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Uporaba kontrolnih kart kontrole kakovosti pri proizvodnji betona

Use of control charts in the production of concrete

Anwendung von Qualitätsregelkarten bei der Herstellung von Beton

Utilisation des chartes de contrôle pour la production du béton

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This Technical Report was approved by CEN on 20 May 2012. It has been drawn up by the Technical Committee CEN/TC 104.

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Foreword

This document (CEN/TR 16369:2012) has been prepared by Technical Committee CEN/TC 104 "Concrete and related products", the secretariat of which is held by DIN.

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Introduction

It is safe to assume that ever since manufacturing commenced, attempts have been made to control the process in order to improve quality and drive down costs. The application of statistical techniques to manufacturing was first developed by physicist Walter A. Shewhart of the Bell Telephone Laboratories in 1924. Shewhart continued to develop the idea and in 1931 he published a book on statistical quality control [1].

Shewhart recognised that within a manufacturing process there were not only natural variations inherent in the process, which affected quality but there were also variations that could not be explained. Shewhart recognised that it is possible to set limits on the natural variation of any process so that fluctuations within these limits could be explained by chance causes, but any variation outside of these limits, special variations, would represent a change in the underlying process.

Shewhart's concept of natural and special variations is clearly relevant to the production of concrete at a ready-mixed plant or precast factory and the requirement to achieve a specified compressive strength. Natural variations exist in the process due to variation in the raw materials (aggregate grading, chemical composition, etc), batching accuracy, plant performance, sampling and testing, etc. Special causes of variation outside of the natural variations could be due to changed constituent materials being used, weigh-scales losing accuracy, a new batcher, problems with testing equipment, etc.

Control charts have found widespread use in the concrete industry in both ready-mixed concrete and precast concrete sectors as a tool for quality control. Control charts can be applied to monitor a range of product characteristics (e.g. cube/cylinder strength, consistence, w/c ratio), constituent materials (aggregate grading, cement strengths, etc.) or production (batching accuracy).

Their most common application of control charts is as a means of continuously assessing compressive strength results in order to:

- check whether target strengths are being achieved;
- measure the variations from target (all products vary);
- identify magnitude of any variation;
- objectively define action required (e.g. change w/c ratio) to get the process back on target;
- identify periods and concretes where the strength was less than specified so that investigations can be carried out and corrective action taken.

The use of control charts should not be treated in isolation from the rest of production control. For example routine checking and maintenance of weigh equipment will minimise the risk of a weigh-scale failure. Control charts provide information about the process, but the interpretation of the information is not a mechanical process. All the information available to the concrete producer should be used to interpret the information and make informed decisions. Did a change in quality occur when a new batch of constituent was first used? Is all the family showing the same trend? Are other plants using similar materials showing a similar trend? Such information leads to the cause of the change in quality being identified and appropriate action being taken. For example a loss of accuracy in the weigh-scales should lead to repair, maintenance and re-calibration and not a change in mix proportions. Where a change in mix proportions is required, the use of control charts can lead to objectively defined changes in proportions.

Effective control of concrete production is more easily achieved when there are good relationships with the constituent material suppliers, particularly the suppliers of cementitious materials. Early warning of a change in performance from the constituent material supplier should be part of the supply agreement, e.g. that stock clinker is being used during the maintenance period, and on the basis of this warning, the producer will decide the appropriate action.

Some producers use changes in cement chemistry to predict changes in concrete strength. Effective production control is about using all this information to produce concrete conforming to its specification. Effective production control, which includes the use of control charts, significantly reduces the risk of non-conformity benefiting both users and producers of concrete.

There are drawbacks to the existing method of assessment of conformity of mean strength adopted in EN 206-1 [3] including not following the CEN Guidance on the evaluation of conformity [2]. It is believed that control charts (already widely used as a quality assurance tool in factory production control) would provide an alternative and better means of ensuring the characteristic strength is achieved and it is a method that follows the CEN Guidance.

1 Scope

This Technical Report reviews various control systems that are currently used in the concrete industry and, by the use of examples, show how the principles are applied to control the production of concrete. This CEN/TR provides information and examples of the use of method C in Clause 8 of prEN 206:2012.

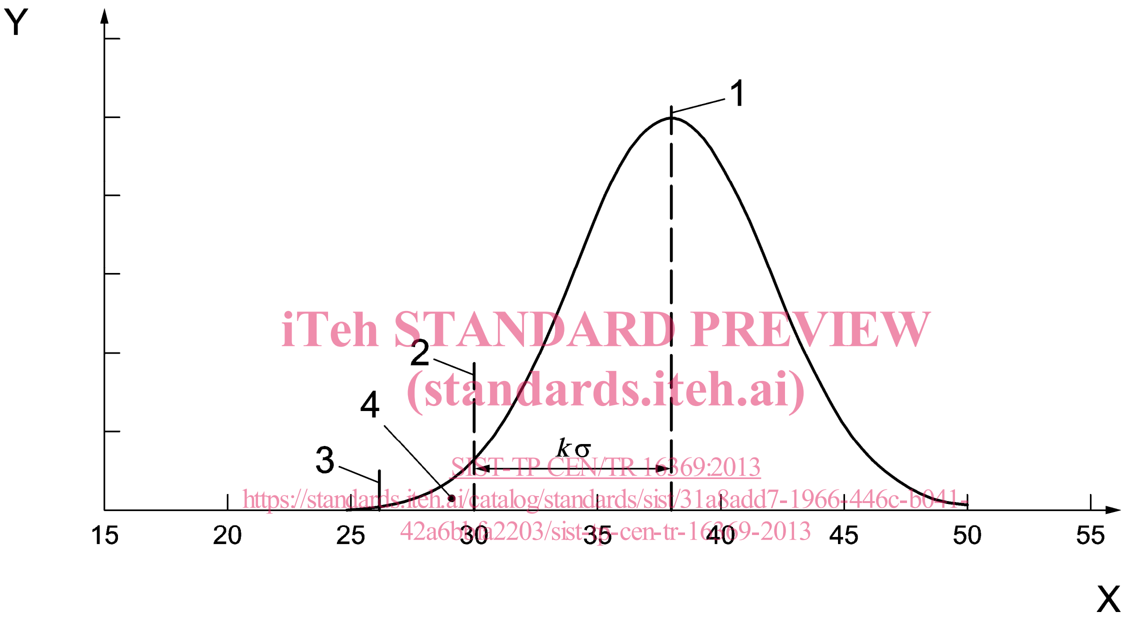
2 Symbols and abbreviations

AOQ	**Average outgoing quality**
AOQL	**Average outgoing quality limit**
C_{mra}	**Constant giving the cement content increase required to produce a 1N/mm^2 increase in strength**
dc	**Change in cement content**
Dl	**Decision interval**
G	**Gradient**
f_{ci}	**Individual test result for compressive strength of concrete**
f_{ck}	**Specified characteristic compressive strength**
f_{cm}	**Mean compressive strength of concrete**
k	**Statistical constant**
L_{l}	**Lower limit**
LCL	**Lower control limit**
LWL	**Lower warning limit**
n	**Number of samples**
q_{n}	**Statistical constant that depends upon *n* and the selected AOQL**
s	**Sample standard deviation**
UCL	**Upper control limit**
UWL	**Upper warning limit**
x_{i}	**Test result** **NOTE According to EN 206-1 [3], a test result may be the mean value of two or more specimens taken from one sample and tested at one age.**
$\bar{x}$	**Mean value of ’n’ test results**
σ	**Estimate for the standard deviation of a population**

3 Statistics for Concrete

3.1 Normal distribution of strength

Compressive strength test results tend to follow a normal distribution as illustrated in Figure 1. A normal distribution is defined by two parameters, the mean value of the distribution and the standard deviation (σ), which is the measure of the spread of results around the mean value. A low standard deviation means that most strength results will be close to the mean value; a high standard deviation means that the strength of significant proportions of the results will be well below (and above) the mean value. The area under the normal distribution between two values of 'x' represents the probability that a result will fall within this range of values. The term 'tail' is used to mean the area under the normal distribution between a value, e.g. a compressive strength, and where the frequency is effectively zero. For strength it is the lower tail, i.e. low strength results, that is important but for other properties, e.g. consistence, both the lower and upper tails are important.



Key

X cube strength, N/mm²

Y frequency

1 target mean strength

2 specified Characteristic strength, f_{ck}

3 minimum strength ($f_{ck} - 4$)

4 tail

Figure 1 — Illustration of concrete strength distribution

At the extremes of the strength range for a given set of constituent materials, the assumption of a normally distributed set of data may not be valid. It is not possible to have strengths less than zero and most concretes have a ceiling strength beyond which they cannot go. In these situations the data set is skewed. However as low strengths are of concern to specifiers, an assumption of normally distributed data does not lead to problems in practice.

3.2 Characteristic strength and target strength

EN 206-1 [3] specifies the characteristic compressive strength of concrete in terms of a standard cylinder test or a standard cube test carried out at 28 days. The characteristic strength is defined in EN 206-1 [3] as the "value of strength below which 5 % of the population of all possible strength determinations of the volume of concrete under consideration, are expected to fall". Put simply this means that if every single batch was tested, 5 % of the results would fall within the lower 'tail' of the normal distribution that starts 1,64σ below the actual mean strength. However the actual mean strength will not be known until the concrete has been produced and tested and therefore the target mean strength (TMS) is usually set at some higher value to ensure the concrete achieves at least the specified characteristic strength.

The target mean strength is given in Equation (1):

$$TMS = f_{\text{ck}} + k \times \sigma \qquad (1)$$

where

TMS = target mean strength

f_{ck} = characteristic compressive strength

σ = estimate for standard deviation of population

k = statistical constant

$k \times \sigma$ = the margin

The fixed point in the distribution is the specified characteristic strength and as the margin increases and/or the standard deviation increases, the target mean strength increases, see the following Example.

EXAMPLE The target mean strength for a specified characteristic strength of C25/30 is given in Table 1. A standard deviation (σ) of 3 N/mm^2 is typical of a concrete with low variability and a value of 6 N/mm^2 represents high variability.

Table 1 — Target mean strength for specified characteristic strength of 30 N/mm^2 (cube)

Margin	**Area in lower tail (i.e. percentage below characteristic strength)**	**Target mean strength (cube), N/mm^2**	
		σ = 3 N/mm^2	**σ = 6 N/mm^2**
1,64σ	5 %	35	**40**
1,96σ	2,5 %	36	**42**
2,00σ	2,28 %	36	**42**
2,33σ	1,0 %	37	**44**
3,0σ	0,13 %	39	**48**
The numbers in this table have been rounded.			

A concrete strength below the characteristic strength is not a failure as statistically 5 % of the results are expected and accepted as to fall below this value. However for structural safety reasons, a batch with a concrete strength significantly below the characteristic strength is excluded, even though it forms part of the expected population. Consequently EN 206-1 [3] specifies a minimum strength requirement for individual results (f_{ci}) of ($f_{\text{ck}} - 4$). Any batch below this strength is a non-conforming batch.

The risk of non-conformity decreases as the margin increases. Statistics are used to quantify that risk. For a given margin the probability of a test result falling below the specified characteristic strength or failing the individual strength criterion is given in Table 2. Table 2 shows that the probability of having a result below the specified characteristic strength is independent of the standard deviation (as the margin is based on the standard deviation) but the risk of failing the criterion for individual batches increases as the standard deviation increases.

Table 2 — Effect of margin on proportion of concrete below characteristic strength; and risk of failing the strength criterion for individual batches

Margin	Probability of a test result being below the characteristic strength	Risk of failing the strength criterion for individual batches	
		σ = 3 N/mm^2	σ = 6 N/mm^2
1,64σ	1 in 20 (5 %)	0,1 %	**1 %**
1,96σ	1 in 40 (2,5 %)	0,05 %	**0,4 %**
2,33σ	1 in 100 (1 %)	0,01 %	**0,1 %**
3,08σ	**1 in 1 000 (0,1 %)**	**0,000 5 %**	**0,01 %**

The definition of ‘characteristic strength’ in EN 206-1:2000 [3] has its complications. For a structural engineer the phrase ‘the volume of concrete under consideration’ may be applied to all the concrete in their structure and to the concrete in a single element of that structure even if this comprises a single batch. For conformity to EN 206-1 [3], the ‘volume under consideration’ is all the concrete in an assessment period. Neither of these interpretations of this phrase is suitable for use in control systems as the process is continual. Caspeele and Taerwe [5] have proposed that if the production achieves an average outgoing quality limit[1] (AOQL) of 5 %, the production can be accepted as having achieved the characteristic strength.

3.3 Standard deviation

The standard deviation of a population will only be truly known if every batch of concrete is tested. However if 35 or more results are available, the estimated standard deviation is likely to be very close to the true standard deviation. This is the reason why EN 206-1 [3] requires 35 results to calculate the initial standard deviation.

When $n \geq 35$, the standard deviation may be estimated using the equation:

Standard deviation,

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{(n-1)}}$$

Alternatively it can be determined through a range of pairs approach where:

$$\text{Mean range of successive pairs} = 1{,}128 \times \text{standard deviation} \qquad (2)$$

or,

$$\text{Standard deviation} = 0{,}886 \times \text{mean range of successive pairs of results}$$

The range is the numerical difference between successive results and the difference is always taken as a positive number, e.g. |2 – 3| = 1. The range of pairs method of calculating the standard deviation is particularly suited for populations where there are step changes in mean strength in the data set, e.g. concrete, as the effect of the step change will be limited to a single pair of results. With concrete production, step changes in mean strength (usually due to a change in a constituent) are more common than drifts in mean strength.

EXAMPLE 1

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[1] From the operating-characteristic curve for the selected sampling plan, the average outgoing quality (AOQ) curve is determined by multiplying each percentage of all possible results below the required characteristic strength in the production by the corresponding acceptance probability.

Table 3 — Calculation of the standard deviation using mean range

Result	Transposed cube strength, N/mm^2	Range, N/mm^2	Calculation of standard deviation
1	54,5		**Estimation of the standard deviation** **= 0,886 × 51/14** **= 0,886 × 3,64 = 3,0 N/mm^2** **(rounded to the nearest 0,5 N/mm^2)**
2	52,5	2,0	
3	49,5	3,0	
4	47,5	2,0	
5	49,0	1,5	
6	43,5	5,5	
7	54,5	11,0	
8	46,5	8,0	
9	50,0	3,5	
10	50,5	0,5	
11	47,0	3,5	
12	48,5	1,5	
13	53,0	4,5	
14	51,5	1,5	
15	48,5	3,0	
Sum of ranges		51,0	
Mean of ranges		**3,64**	

EXAMPLE 2 (copied from Reference [4])

15 random data have been generated assuming a mean strength of 37,0 N/mm^2 and a standard deviation of 3,5 N/mm^2. These have been repeated to give a total of 30 data, see Figure 2a. The standard deviation of the 30 data given in Figure 2a) is:

3,6 N/mm^2 when determined by the standard method;

3,7 N/mm^2 when determined from 0,886 × mean range.

To illustrate the effect of a change in mean strength on the standard deviation, an extreme reduction in mean strength of 5,0 N/mm^2 is introduced at result 16 i.e. data 16 to 30 are all 5,0 N/mm^2 less than in Figure 2a). The dispersion of the data around these mean strengths is unchanged. The standard deviation of the 30 data given in Figure 2b) is:

4,4 N/mm^2 when determined by the standard method;

3,8 N/mm^2 when determined from 0,886 × mean range.

This shows that the standard deviation calculated from the mean range has been less affected by the change in mean strength.

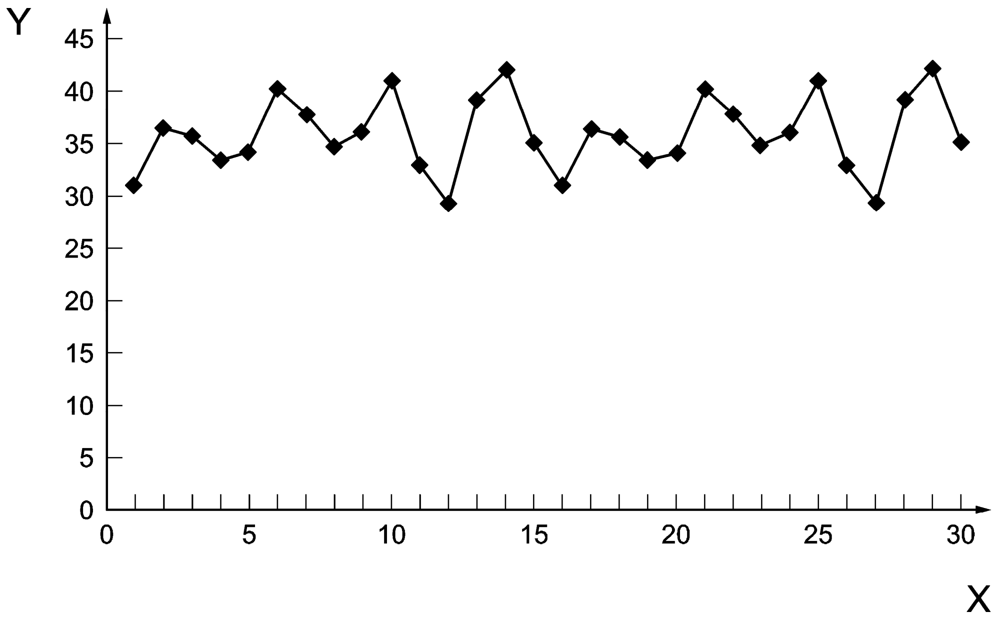


Figure 2a) — Fifteen random data generated assuming a mean strength of 37,0 N/mm2 and a standard deviation of 3,5 N/mm^2 (the first group of 15 results are the same as the second group of 15 results)

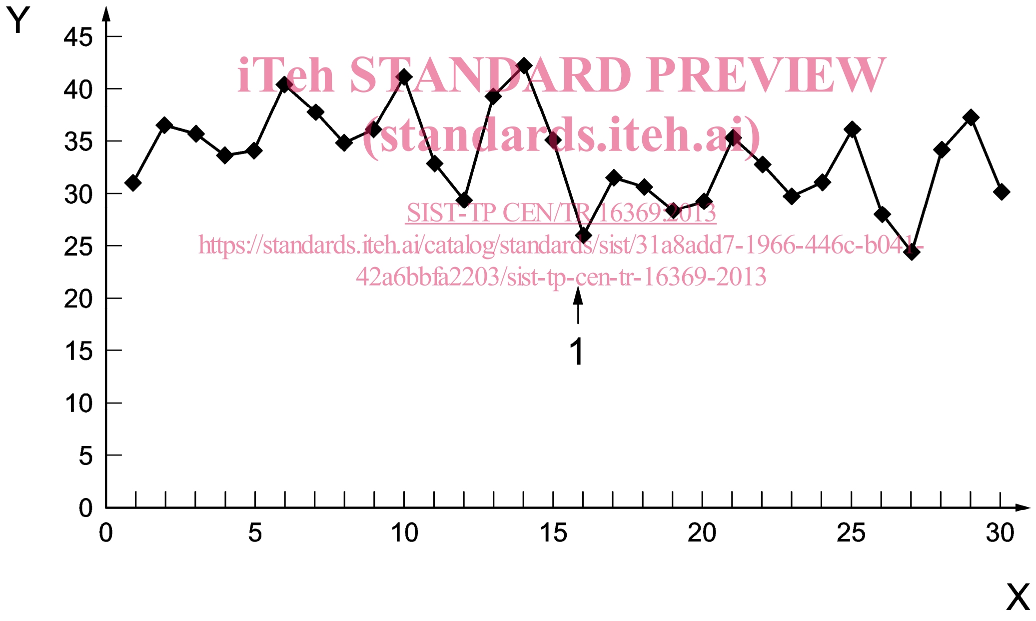


Figure 2b) — The same data as in Figure 6a), but with a reduction in mean strength of 5,0 N/mm^2 introduced at result 16

Key

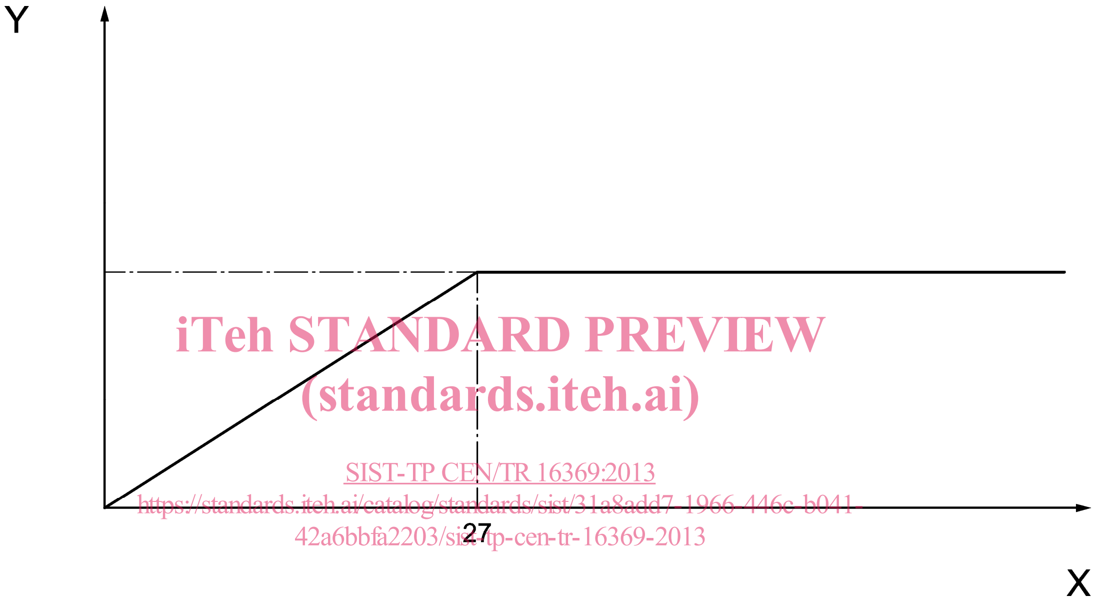
X	result number
Y	compressive strength – N/mm²
1	reduction of 5 N/mm² in the mean strength

Figure 2 — Example of the impact of a step change in mean strength on the calculated standard deviation

The true standard deviation of a population, σ, can only be determined if all the population were to be tested, which is impractical. In practice the population standard deviation is estimated by testing samples. The more samples that are tested, the more reliable the estimated population standard deviation will be. EN 206-1 [3] requires at least 35 results to initially estimate the population standard deviation. Prior to obtaining the estimated population standard deviation, concrete is controlled by more conservative initial testing rules. Without an estimated population standard deviation, it is not possible to use control charts to control the concrete production.

Once the initial population standard deviation has been estimated, EN 206-1 [3] permits two methods for verifying the initial estimate. The first method involves checking that the standard deviation of the most recent 15 results does not deviate significantly from the adopted value. The second method involves the use of continuous control systems.

The standard deviation for strength tends to be constant for medium and high strength mixes but for lower strengths it tends to increase proportionally with mean strength [6] and the relationship illustrated in Figure 3 may be assumed. In practice this means that the standard deviation for concretes that have a characteristic strength of 20 N/mm^2 or more is determined by testing and calculation, while the standard deviation for concrete with a lower strength is interpolated.



Key

X strength (N/mm²)

Y standard Deviation (N/mm²)

Figure 3 — Simplified standard deviation to mean strength relationship

3.4 Setting the target strength

The target strength is set to achieve a balance between the following requirements:

- high probability of achieving a population with at least the specified characteristic strength;
- low risk of failing the minimum strength criterion;
- low consumers risk;
- low producers risk;
- competitive and economic.

The target strength is selected by the producer, but the producer may have to comply with certain minimum values. The target strength should never be lower than (f_{ck} + 1,64σ), but it is normally higher than this value. National requirements, the requirements of a certification body or other requirements (see 10.4) may impose minimum target strengths.