Quarry Products Association

Guidance on the application of the EN 206-1 conformity rules

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Executive summary

For a selected level of risk (probability of non-conformity during an assessment period), the design margin to achieve conformity depends upon the number of test results in the assessment period and the level of auto-correlation. The highest risk of non-conformity is with busy plants with frequent testing.

Increased numbers of test results in an assessment period together with reduced levels of auto-correlation, increase the probability of correctly identifying whether the population conforms or not and thereby reduces the risk to the concrete producer.

The recommended method for deriving the population standard deviation is to use 0.886 times the mean range between consecutive results.

Use Method 2 in BS EN 206-1: 2001 for deriving when the standard deviation changes. Method 1 is too insensitive and where the standard deviation is high, it is very difficult for this system to trigger a change.

Conformity applies to conditions of uniform production. Whilst a change in mean strength or standard deviation indicates a change in the conditions of production i.e. non-uniform conditions, the assessment period should be ended immediately only under certain conditions of change of standard deviation. Guidance is given on where such a change should immediately start a new assessment period.

Assessment periods need not be uniform for all plants or for different concretes within a plant. The producer defines the assessment periods. Where practical, the assessment period for strength of a concrete family should contain at least 35 results. The definition of a typical assessment period for strength would follow the form:

The period for the assessment of compressive strength for a concrete or concrete family is the shortest of:

- period of uniform conditions for production e.g. period of constant standard deviation;
- period needed to obtain 35 results;
- 12 months.

Recommendation are made with respect to conformity for strength to all options given in BS EN 206-1: 2001 (see **3.1**) and for:

- statistical outliers;
- concretes where the maximum w/c ratio or minimum cement content control the strength of the concrete;
- use of prescribed concretes to increase the number of data sets;
- concrete families and individual concretes;
- low volume production;
- authorised addition of water on site.

Guidance on conformity for properties other than strength is given. The requirements that are spread throughout BS EN 206-1 are collated into tables for easy application.

Where a potential non-conformity is indicated, it is strongly recommended that the data are analysed in depth to delimit the period of non-conformity and to determine those members of a family that are in conformity and those that are not. Some guidance is provided in this publication.

Contents

Glossary

The following terms have been explained in the context of this publication.

Auto-correlation: A measure of how related test data are to their adjacent results.

Concrete family: A group of concrete compositions for which a reliable relationship between relevant properties is established and documented.

Conformity: A series of procedures undertaken by the producer to assure the specifier and user that the delivered concrete conforms to its specification and the appropriate requirements of BS EN 206-1 and BS 8500. The procedures are the application of the conformity rules given in BS EN 206-1 and, where appropriate, the conformity rules given in BS 8500 to test data obtained, normally, from samples of the freshly produced concrete.

Non-conformity: The result of an in-depth analysis of a potential non-conformity that shows the concrete did not conform in one or more respects to its specification.

Operating-characteristic curve (O-C curve): A figure that shows the relationship between the quality of concrete supplied and the probability that it will be accepted when it is tested and the conformity rule is applied.

Potential non-conformity: A result of the initial application of a conformity rule to test data from a single concrete or concrete family that indicates non-conformity. This is followed by an in-depth analysis to verify whether the concrete was in conformity and, if not, over what period was it non-conforming.

Producer's risk: The risk that the concrete defined by the specification as of acceptable quality will be deemed as non-conforming when the conformity criteria in BS EN 206-1 are applied.

Specifier's risk: The risk that the concrete defined by the specification as of unacceptable quality will be deemed as conforming when the conformity criteria in BS EN 206-1 are applied.

1. Introduction

This publication is aimed at the technical managers of concrete production facilities. It is assumed that they have some basic knowledge of statistics and that they can interpret and apply the information given in this publication to their particular situations. This is necessary, as there is no uniquely correct solution. However, general recommendations are made.

This publication explains and amplifies the conformity rules for compressive strength given in BS EN 206-1: *Concrete – Part 1: Specification, performance, production and conformity*. Information is given on the margins necessary for achieving a selected probability of acceptance (P_a). In Section 4, the requirements in BS EN 206-1 for conformity for properties other than strength are explained and guidance provided on application of these requirements.

Only the initial analysis of test data for conformity is covered. This leads to the identification of potential non-conformity. Further analysis is necessary to confirm non-conformity. This should include:

- checking that the correct test specimens were tested;
- checking that the test data did not give any justifiable reason for excluding them from the conformity assessment;
- checking for non-uniform conditions;
- an in-depth analysis to determine which members of the family were in conformity and which members were in non-conformity and over what period.

The information and recommendations in this publication are based on statistical theory, analysis based on simulated data and analysis of real production data from a range of concrete production plants. Data from the following types of plant were included in the analysis:

- busy stable plant;
- busy unstable plant;
- low volume, regularly sampled plant;
- low volume, irregularly sampled plant.

This analysis showed that the greatest risk to producers occur in busy plants with high rates of testing. This is because there will be a lot of data generated before any problem is detected and corrected. Very high test rates can cause problems for conformity control due to, for example, increased auto-correlation, see **2.4.4**. Consequently, very-high test rates should be avoided and the desired number of test results, see **2.4.3**, achieved by increasing the length of the assessment period.

Clause 9.1 of BS EN 206-1: 2001 clearly states that the producer of concrete is responsible for verifying that <u>all</u> the concretes they place on the market conform to their specifications. This is demonstrated by application of the conformity rules given in BS EN 206-1. There is also a general principle that non-conforming products should be prevented from reaching the market. With fresh concrete this is not possible and a compromise had to be reached. For example, the European Standardization Body (CEN) wanted strength to be a requirement of designed concrete, but this is not a property of concrete as it is placed on the market. Excluding this requirement from specifications was not acceptable. The compromise was that concrete could be placed on the market with a declared strength class and the producer is required to inform the specifier if subsequent testing shows that this claim is not correct. To avoid unnecessary bureaucracy, it is unnecessary for producers to issue statements saying the claims made on the delivery tickets have been subsequently proven to be correct. This should be assumed unless told otherwise.

The conformity rules in BS EN 206-1 were formulated on the basis that only the producer exercises conformity control. Any change to this approach will require a fundamental re-appraisal of the conformity rules. In recognition that some specifiers may wish to sample and test the delivered concrete, EN 206-1 provides for identity testing.

Clause 9.1 of BS EN 206-1: 2001 states that production control includes conformity. However it also recognises that the producer needs a system for production control that is independent from conformity control. To avoid confusion, this publication uses the term "production control" where it refers to the actions taken to control the production e.g. the Cusum system. For the purposes of this publication, the term "production control" does not include conformity control.

2. Background to the BS EN 206-1 conformity rules for strength

2.1 Requirement for uniform conditions of production

Clause 8.2.1.2 of BS EN 206-1: 2001 states that sampling shall be carried out "under conditions that are deemed to be uniform". The implication of this is that conformity only applies to uniform conditions of production. What constitutes "uniform conditions" is not defined nor is what to do when uniform conditions do not apply. For the reasons given in **3.10**, a significant change in the standard deviation should be taken as the end of a period of uniform production and under certain conditions, should trigger an immediate end to the assessment period. This could be followed by another period of uniform production with a new value for the standard deviation or by a short period where the plant was unstable.

Whether a significant change in the mean strength should trigger the end of a period of uniform production is an open question. In practice, once a significant change in mean strength is detected from production control, the mix proportions are adjusted to achieve the intended mean strength. This will leave a short period of production where a few data sets will have a different mean strength. If this strength were to be lower than expected, analysis of these few data sets is more likely to indicate a non-conformity than if these data were part of a larger population. It is recommended that a change in mean strength be not used to determine the end of a period of uniform production. However, when analysing a potential non-conformity, part of the analysis should include checking for a change in mean strength as this may delimit the period of non-conformity.

A further practical situation needs to be considered. If there is a problem with a plant e.g. a non-uniform fault with the weigh gear, there may be a period where the plant is unstable and the conditions of production are not uniform. In this case, the data obtained prior to and after the short period of unstable conditions may be combined and assessed for conformity in the normal way. The data obtained during the period where the plant was unstable should be removed from the normal conformity assessment and subjected to an in-depth analysis. This should include:

- implications for the strength and durability of the tested concretes;
- implications for the strength and durability of concretes produced during this period but not subjected to conformity testing;
- determining appropriate actions.

2.2 Initial and continuous production

BS EN 206-1 divides conformity for strength into initial production and continuous production. The concept being applied is that during initial production there are insufficient data to take a statistical approach to conformity and rules using fixed margins are applied. Initial production is defined as the period where there are less than 35 test results for an individual concrete or concrete family obtained over a period not exceeding 12 months. This is the minimum number of test results needed to calculate a reliable estimate of the population standard deviation, σ. Where the production of an individual concrete or concrete family has been suspended for more than 12 months, the producer is required to adopt the criteria, sampling and testing plan for initial production e.g. at the start of the production of a lightweight concrete during a period of continuous production of normal-weight concrete.

For concrete having a specified strength requirement, every concrete family and every individual concrete i.e. a concrete that is not a member of a family, has to be tested to verify strength conformity. Management of technicians to obtain these data will be more complex than at present. To reduce the amount of testing, concretes should be grouped into families.

Some special concretes that are outside of a family may never generate sufficient test data to take them into the conditions necessary for continuous production. These may be assessed using the initial production criteria. An alternative approach is given in **3.11**. As shown later, such concretes may require a higher margin than that needed with continuous production. Given the uncertainty associated with low production rates, this is reasonable.

2.3 Initial production for compressive strength

The criteria for the initial production are:

$$f_{ci} \geq f_{ck} - 4$$

and

$$f_{cm,3} \geq f_{ck} + 4$$

where

f_{ci} compressive strength of an individual result
f_{ck} characteristic strength (This becomes the characteristic strength of the Reference Concrete where assessing the mean strength of a concrete family)
$f_{cm,3}$ mean strength of 3 results.

The mean strength of 3 results can be applied in one of two ways:

- to non-overlapping groups of 3 consecutive results;
- to every group of 3 consecutive results (overlapping groups).

In the first case, the last group should comprise the mean of test result numbers 34, 35 and 36. The use of non-overlapping results reduces the risk to the concrete producer and has the logic that each result is only considered once in the assessment of conformity. Also the criteria were formulated by CEN on the basis of non-overlapping groups. It is recommended that non-overlapping groups of 3 consecutive results be used. See Example 1.

Where the initial production relates to a concrete family, the individual criterion applies to the original test result, f_{ci}, and f_{ck} is the specified characteristic strength. For the assessment of the mean of 3 results, each test result, f_{ci}, is transposed to the equivalent value of the Reference Concrete and f_{ck} is the characteristic strength of the Reference Concrete, see Example 2.

Example 1
Table 1 gives the cube data for initial production of an individual concrete of strength class C25/30 ($f_{ck,cube}$ = 30.0 N/mm^2). To avoid loss of sensitivity in production control, the individual cube results and the mean values have not been rounded to the nearest 0.5 N/mm^2. Consequently, the conformity criteria should be modified to:

$f_{ci} \geq f_{ck} - 4.2 = 25.8\ N/mm^2$

and

$f_{cm,3} \geq f_{ck} + 3.8 \geq 33.8\ N/mm^2$

Every result, except for result number10, passed the individual criterion. For the assessment of the mean, the individual failure has not been excluded from the initial analysis (this can only be done where an in-depth investigation shows it to be justifiable). The mean-of-three data are also not rounded to the nearest 0.5 N/mm^2. The figures shown in bold are potentially non-conforming. These data require further checking and investigation to confirm if they are non-conforming.

Table 1. Assessment of initial production for an individual concrete

Data	*Result*	*Non-overlapping groups*	*Overlapping groups*	*Data*	*Result*	*Non-overlapping groups*	*Overlapping groups*
1	43.4			19	33.2		34.1
2	45.8			20	33.5		**33.7**
3	43.6	44.3	44.3	21	35.6	34.1	34.1
4	41.3		43.6	22	39.4		36.2
5	41.7		42.2	23	42.5		39.2
6	37.3	40.1	40.1	24	34.6	38.8	38.8
7	38.5		39.2	25	35.6		37.6
8	32.7		36.2	26	39.8		36.7
9	34.6	35.3	35.3	27	38.7	38.0	38.0
10	**25.0**		**30.8**	28	35.4		38.0
11	39.3		**33.0**	29	32.6		35.6
12	40.1	34.8	34.8	30	30.3	**32.8**	**32.8**
13	43.2		40.9	31	31.9		**31.6**
14	46.4		43.2	32	32.5		**31.6**
15	40.2	43.3	43.3	33	34.7	**33.0**	**33.0**
16	33.3		40.0	34	34.1		33.8
17	34.7		36.1	35	37.9		35.6
18	34.5	34.2	34.2	36	39.3	37.1	

A complication arises in the use of concrete families where the actual strength of the concrete is controlled by requirements for maximum w/c ratio or minimum cement content. The effect will be that the strength of the test result will be higher than that normally associated with the specified strength class. The way in which the individual criterion is assessed is normal ($f_{ci} \geq$ specified strength class - 4).

For the check on the mean strength, the actual cement content is corrected back to those materials and properties of the Reference Concrete and this corrected cement content used to determine the equivalent strength, see Example 2. Adjustments using other parameters, e.g. w/c ratio, is equally acceptable. This equivalent strength is used in the assessment of conformity of the mean-of-three. This method of transposition is necessary if the estimate of standard deviation is to be determined from the mean range of the transposed results, see **3.10**.

The inclusion of prescribed concrete in the family may speed the time when conditions for continuous production have been achieved and testing such concretes for strength provides an indirect check on the cement content, see **3.2** for further information.

Example 2

Reference Concrete C25/30 at 50mm slump (cement content 275 kg/m^3)

*For simplicity of analysis, the relationship between strength and cement content is taken to be linear at a rate of 0.2 N/mm^2 per kg/m^3 up to a cement content of 325 kg/m^3. Higher cement contents are assumed to give no increase in strength, see **3.9**.*

Relationships:

25mm change of slump @ 15 kg/m^3 change in cement content (20 kg/m^3 for pumped concretes)

To change from a concrete with a water reducing admixture (wra) to one without admixture will increase the cement content by 20 kg/m^3

Ref.	Strength class $f_{ck, cube}$	Minimum cement content kg/m^3	Max. w/c ratio	Specified slump, mm	Actual slump, mm	Admixture and additions	Cement content, kg/m^3	Equivalent cement content without wra	Cement content corrected to 50mm slump	Actual 28 day strength, N/mm^2	Equiv. Strength of Ref. Concrete N/mm^2	Range	Actual strength ³ f_{ck} - 4	Mean of three using transposed data ³ 30 + 4
1	35	275	0.6	75	90	--	315	315	300	39	34		Yes	
2	35	275	0.6	75	85	--	315	315	300	40	35	1	Yes	
3	35	275	0.6	75	70	--	315	315	300	38	33	2	Yes	34 Ö
4	35	275	0.6	75	80	--	315	315	300	37.5	32.5	0.5	Yes	
5	35	--	--	90	115	--	335	335	310	43	36	3.5	Yes	
6	ST4[1)]	300	--	50	65	--	300	300	300	46	41	5	See [1)]	36.5 Ö
7	ST4[1)]	300	--	50	70	--	300	300	300	46	41	0	See [1)]	
8	30	--	--	50	65	--	275	275	275	32	32	9	Yes	
9	P390[2)]	390	--	75	90	Fibres	390	390	375	47.5	37.5[3)]	5.5	See[2)]	37 Ö
10	30	330	--	50	65	--	330	330	330	51	41[3)]	3.5	Yes	
11	25	300	0.55	75	80	--	345	345	330	52	42[3)]	1	Yes	
12	30	--	--	75	90	wra	270	290	275	35.5	35.5	6.5	Yes	39.5 Ö
13	ST4[1)]	300	--	75	80	--	300	300	285	39	37	1.5	See [1)]	
14	20	--	--	75	85	--	250	250	235	31	39	2	Yes	
15	20	--	--	50	75	--	235	235	235	22	30	9	Yes	35.5 Ö
16	20	--	--	70	95	--	245	245	235	28	36	6	Yes	
17	20	--	--	70	75	--	245	245	235	28	36	0	Yes	
18	20	--	--	70	90	--	245	245	235	28	36	0	Yes	36 Ö
19	GEN3 (20)	220	--	50	75	--	235	235	235	28	36	0	Yes	
20	30	--	--	50	60	--	275	275	275	43.5	43.5	7.5	Yes	
21	35	--	--	50	55	wra	280	300	300	40	35	8.5	Yes	38 Ö
22	ST5[1)]	340	--	50	60	--	340	340	340	50	40[3)]	5	See [1)]	
23	40	--	--	50	55	--	330	330	330	43.5	33.5[3)]	6.5	Yes	
24	GEN4 (25)	250	0.7	50	55	--	260	260	260	24	27	6.5	Yes	33.5 X[4)]
25	P275[2)]	275	--	50	80	--	275	275	275	34.5	34.5	7.5	See[2)]	

Continued

Example 2 continued

Ref.	Strength class $f_{ck,\ cube}$	Minimum cement content kg/m^3	Max. w/c ratio	Specified slump, mm	Actual slump, mm	Admixture and additions	Cement content, kg/m^3	Cement content corrected wrt wra	Cement content corrected to 50mm slump	Actual 28 day strength, N/mm^2	Equiv. Strength of Ref. Concrete N/mm^2	Range	Actual str. ³ f_{ck} - 4	Mean of three using transposed data ³ 30 + 4
26	GEN4 (25)	250	0.7	50	75	--	260	260	260	33.5	36.5	2	Yes	
27	35	--	--	60	80	--	315	315	310	46	39	2.5	Yes	36.5 Ö
28	GEN4 (25)	250	0.7	50	70	--	260	260	260	37	40	1	Yes	
29	35 (pump)	325	--	75	100	--	325	325	305	43	37	3	Yes	
30	30	275	0.6	60	80	--	300	300	295	39	35	2	Yes	39.5 Ö
31	GEN3 (20)	220	--	50	65	--	235	235	235	30	38	3	Yes	
32	P390[2)]	390	--	50	60	--	390	390	390	47.5	37.5[3)]	0.5	See[2)]	
33	40 (pump)	300	0.5	75	85	--	340	340	320	50	41	3.5	Yes	39 Ö
34	40 (pump)	300	0.5	75	90	--	340	340	320	47.5	38.5	2.5	Yes	
35	40 (pump)	300	0.5	75	85	--	340	340	320	52	43	4.5	Yes	
36	RC35 (35)	300	0.6	50	70	--	300	300	300	44.5	39.5	3.5	Yes	40.5
											Sum of the ranges =	125.5		
											Mean range = 125.5/35	3.586		

Notes

1) Standardized prescribed concrete with no strength requirement.

2) Prescribed concrete with no strength requirement.

3) Cement contents above 325 kg/m^3 are assumed to give no increase in strength with these constituent materials.

4) Marginal failure in mean-of-three, see below for the further analysis.

Standard deviation of the initial production

*The estimate of s (see **3.10**) = 0.886 x 3.586 = 3.18 N/mm^2*

Further analysis of the indicated non-conformity for results 22, 23 and 24

Three concretes were involved, a ST5, C40 and a GEN4. Consider each concrete individually:

ST5 is a standardized prescribed concrete with no requirement for strength. No other batches of ST5 were tested nor where any batches tested with a cement content of 340 kg/m^3. Reference 10 had a cement content of 330 kg/m^3 and a cube strength of 51 N/mm^2. This is close to the 50 N/mm^2 achieved with the ST5. Check the production records for this batch.

C40 is an individual result. The nearest equivalent adjacent results are for the C40 (pumped) results 33 and 35.

Mean of results 23, 33 and 34 = 43.5 + 50 + 47.5 = 47 ³ 40 + 4 \ concrete is acceptable.

The adjacent results for the GEN4 concrete are results 26 and 28.

Mean of results 24, 26 and 28 = 24 + 33.5 + 37 = 31.5 ³ 25 + 4 \ concrete is acceptable.

If there is a mean-of-three non-conformity in the initial production of a concrete family, the further analysis should consider the original data. Each concrete in the non-conforming group should be identified together with other test data on the same concretes taken during the initial production. For each concrete in the non-conforming group, apply ($f_{cm,3} \geq f_{ck} + 4$) to the result in the non-conforming group plus the 2 adjacent results (assuming that only 1 result was in the non-conforming group). Failure to conform to this criterion will indicate non-conformity of that concrete for the initial period of production unless there is evidence to delimit the period of non-conformity.

Brown and Gibb [1994] analysed the risks of non-conformity with the BS EN 206-1 requirements for initial production. These risks are given in Table 2 for non-overlapping results and Appendix A gives the basis on which this analysis is derived.

Table 2. Probability (%) of non-conformity with the strength requirements for initial production

Design margin	Normal distribution			Castellated distribution		
	Standard deviation, N/mm^2			Standard deviation, N/mm^2		
	3	4	5	3	4	5
1.64σ	28.41	11.11	6.25	33.34	16.17	10.11
2.00σ	10.45	3.81	1.62	20.71	8.74	3.99
2.33σ	4.08	1.01	0.25	10.8	3.01	1.11

Data from Brown & Gibb [1994]

The castellated distribution is considered to reflect more accurately the step changes in quality that occur with concrete production. These data show that even with a margin of 2.33σ, there is a significant risk of non-conformity if the standard deviation is low.

The producer may adopt the sampling and testing plan and the criteria for initial production for continuous production (see 8.2.1.1 of BS EN 206-1: 2001). The analysis given in Table 2 indicates that this approach may pose high risks to the producer of having non-conforming concrete. These risks should be compared with those for continuous production, see **2.4**. Where the standard deviation is very low (≤ 3 N/mm^2), the use of the initial production criteria poses higher risks than using the continuous production criteria. Where the standard deviation is higher, the best option depends on the design margin adopted, the level of auto-correlation of the test data and the number of test results. See **3.11** for the application of the initial production criteria to low-volume production.

2.4 Continuous production for compressive strength

2.4.1 Introduction

Once continuous production is established, the conformity criteria for compressive strength of an individual concrete or a concrete family take the form of:

$$f_{ci} \geq f_{ck} - a$$

and

$$f_{cm} \geq f_{ck} + \lambda\sigma$$

where

- f_{ci} compressive strength of an individual result
- f_{cm} mean strength of all the test results for an individual concrete or of all transposed results for a family in an assessment period
- f_{ck} characteristic strength (This becomes the characteristic strength of the Reference Concrete where assessing the mean strength of a concrete family)
- a constant value, N/mm^2 (BS EN 206-1: 2001 has adopted a value of 4 N/mm^2)
- λ statistical coefficient
- σ standard deviation of the population.

As all the concrete in the population is not tested, the true standard deviation of the population is never known. However reliable estimates of its value can be made from a sample of 35 or more results.

The criterion for individual results is best regarded as an engineering requirement that puts an absolute lower limit on the strength of any batch of concrete. In the case of BS EN 206-1, "a" has been given the value of 4 regardless of whether conformity is based on cylinders or cubes. Consequently there are small differences in the requirements. The actual difference varies due to rounding of the numbers in the selection of strength classes.

Example 3
The individual criterion for a C35/45 concrete is:
$35 - 4 = 31$ N/mm^2 where based on 150mm diameter by 300mm cylinders
or
$45 - 4 = 41$ N/mm^2 where based on cubes
A 41 N/mm^2 cube strength is equivalent to 41 x 0.8 = 32.8 N/mm^2 cylinder strength

A compressive strength below the characteristic but equal to or greater than ($f_{ck} - 4$) is an acceptable result and a structure that incorporates such a batch will still be fit for its intended purpose.

The individual test result criterion can influence the target mean strength. Being an absolute criterion i.e. no value below, the target mean strength should be at least 3σ greater than ($f_{ck} - 4$) to give a high probability of passing the conformity criterion.

In BS EN 206-1, the characteristic strength has been defined as the 5% fractile and consequently the mean strength of the total population is required to be:

$$f_{cm} \geq f_{ck} + 1.65\sigma$$

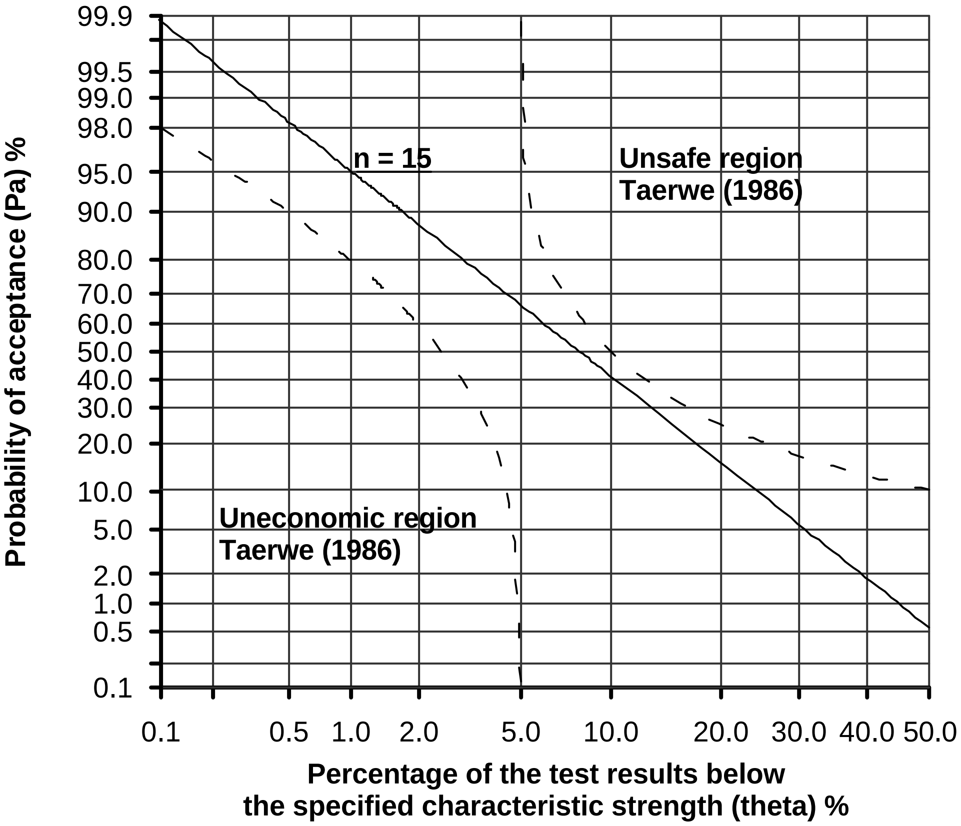
In practice, however, only a sample from the total population is tested. In this case the statistical test applied is one that gives a small risk that the producer will conclude that the concrete is conforming with the specification when the population is non-conforming i.e. f_{cm} is substantially lower than ($f_{ck} + 1.65\sigma$). In the context of BS EN 206-1, the population is all the production of a single concrete or concrete family in an assessment period. Consequently it is possible for all the concrete in a single element or series of elements to contain concrete with strength below the specified characteristic strength, e.g. a single batch of concrete with strength ($f_{ck} - 2$) could be placed in all the columns of a building. Such realities are not new and the former concrete conformity requirements gave the same situation. Current design methods and safety factors result in concrete that is rarely loaded to more than 40% of its characteristic strength and an upper limit of $0.6f_{ck}$ for structural design is recommended in prEN 1992-1: *Design of concrete structures – Part 1: General rules and rules for buildings*.

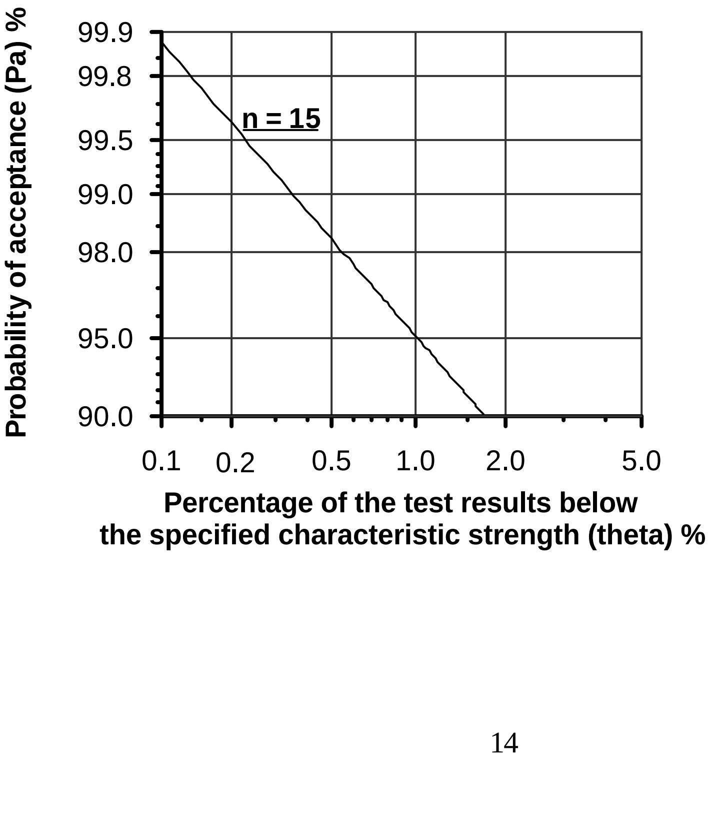
The statistical properties of a conformity rule are conveniently summarised by its "operating characteristic" or "OC curve". This shows the relationship between the quality of the concrete and the probability that it will be accepted when it is tested and the conformity rule is applied to the test results. A concrete producer can use the operating characteristic to determine the level of quality that they have to supply in order to reduce, to an acceptable level, the risks associated with failing to conform. The operating characteristic also shows the protection provided to specifiers by the conformity rule, should poor quality concrete be produced.

The operating characteristics in this publication have been drawn using probability scales for both their axes. They then appear as straight lines. An example is shown in Figure 1.

Figure 1. The operating characteristic for the conformity rule used with continuous production in BS EN 206-1.

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The operating characteristic shown in the figure has been obtained by simulation, and applies when the data are auto-correlated (according to Taerwe's model with parameters 0.4 and 0.2), the mean is calculated from 15 test results, and the standard deviation is established beforehand (from 35 test results).





The vertical axis in Figure 1 shows the probability of acceptance, Pa, as a percentage. If one considers a single application of the conformity rule, i.e. one assessment period, in which some number (15 in the case of Figure 1) of test results are obtained, then this probability indicates the chance that the concrete produced in that period will be deemed to be acceptable. Alternatively, this probability can be interpreted as the percentage of the concrete that will be deemed to be acceptable if the conformity rule is applied repeatedly over a series of assessment periods.

The horizontal axis in Figure 1 shows the quality of the concrete. Here quality is defined as the percentage of the whole population that would give test results below the specified characteristic strength, if the whole population were to be tested. Theta (q) is used to represent this percentage. With the characteristic strength defined as a 5% fractile, the value of 5% on this axis represents the borderline between concrete of satisfactory and unsatisfactory quality.

A concrete producer will design the concrete using a "margin" that is the difference, in N/mm^2, between the target mean strength and the specified characteristic strength. In terms of the plant standard deviation, s, the margin may be written:

$$\text{margin} \quad = \quad k \times s \quad \text{N/mm}^2$$

Table 3 shows how the multiplier k is related to the quantity q %.

Table 3. Multipliers used to calculate the producer's margin (percentage points of the Normal distribution).

Percentage below specified characteristic strength q **%**	Multiplier used to calculate the producer's margin ***k***
5.00	1.645
2.50	1.960
1.00	2.326
0.50	2.576
0.25	2.807
0.10	3.090

Ideally, concrete that has a quality marginally better than the borderline value of q = 5% should have a high probability of acceptance (close to 100%), and if it has a quality marginally worse than the borderline value then it should have a low probability of acceptance (close to 0%). This ideal can be achieved only by carrying out very large numbers of tests. In practice the cost of sampling and testing concrete is such that only limited numbers of test results are available for conformity assessment. If 15 test results are obtained in an assessment period, then the conformity rule

$$f_{cm} \quad \geq \quad f_{ck} \quad + \quad 1.48s \qquad (1)$$

has the operating characteristic shown in Figure 1, in the circumstances described under the title of the figure. As noted above, a concrete producer can use such an operating characteristic to determine the level of quality that they have to supply in order to reduce, to an acceptable level, the risks associated with failing to conform.

For example, suppose that a concrete producer aims at the borderline level of quality q = 5% (i.e. the quality is such that 5% of the test results will fall below the specified characteristic strength in the long run). From Table 3 it can be seen that the margin in this case is 1.645s. Then, according to Figure 1, they can expect the concrete to be deemed to conform on only about 70% of occasions.

If the producer adopts a higher margin of, say, 2s, then Table 3 shows that this is equivalent to q = 2.5%, and Figure 1 then shows that the probability of acceptance increases to about 85%.

To achieve a probability of acceptance better than 98%, in the circumstances to which Figure 1 applies, producers need to aim at a quality better than q = 0.5%. This requires margins larger than 2.576s N/mm^2.

Figure 1 applies when the test results are auto-correlated and when 15 test results are obtained in an assessment period. Where data are auto-correlated they are related to adjacent results, see **2.4.4**. Later sections of this publication explain how the population is more likely to be correctly classified and the producer's risks reduced if a larger number of tests are obtained in the assessment period, or if the test results are independent (not auto-correlated).

Specifiers can be assured that the conformity rule provides them with adequate protection should poor-quality concrete be supplied. According to Figure 1, if a producer supplied concrete continuously with a quality such that 10% of the test results fell below the specified characteristic strength, the probability of acceptance is only 40%. Thus, in the circumstances to which Figure 1 applies, the conformity rule provides specifiers with a high degree of protection against poor quality. As shown later, increases in "n" or reductions in the level of auto-correlation, increase the protection given to specifiers by the BS EN 206-1 conformity rules for strength.

2.4.2 Historical background to the conformity rule

Comparisons of the rules for judging the quality of concrete used in different European countries led to the formulation of boundaries for "unsafe" and "uneconomic" regions on figures that show operating characteristics (CEB, 1975). These regions were later given a mathematical basis and justification (Taerwe, 1986).

Taerwe's definition of the boundary of the "unsafe" region is:

$$q \times P_a = 500$$

and of the "uneconomic" region is:

$$\frac{q}{100 - P_a} = 0.05$$

These boundaries are shown on Figure 1 as dashed lines.

If a conformity rule gives an operating characteristic that passes through the unsafe region then the protection it gives the specifier would be too weak. If a rule gives an operating characteristic that passes through the uneconomic region it causes producers to use excessively large margins and, even then, accept high risks of non-conformity.

The rule

$$f_{cm} \geq f_{ck} + 1.48 s_{15} \qquad (2)$$

gives an operating characteristic that just touches the unsafe region, when the test results are auto-correlated according to the model discussed in **2.4.4**, and where s_{15} is a standard deviation derived from the same 15 test results that are used to calculate f_{cm}.

This is the reason for the use of the multiplier of 1.48 in the rule used in BS EN 206-1. However, after it was adopted, it was decided to allow the standard deviation to be derived from a run of at least 35 test results, obtained in advance of the assessment period. Hence the operating characteristic for Equation (1) passes near the unsafe region, but does not touch it.

2.4.3 Effect of increasing the number of test results above 15

Figure 2 shows operating characteristics for conformity rules in which different numbers of test results are used to calculate the mean, f_{cm}. Apart from the value of *n*, these operating characteristics apply to the same circumstances as that shown in Figure 1, and the one for *n* = 15 is the same as that shown in Figure 1. Note that they intersect at a point corresponding to a probability of acceptance of 50%.

The figure shows that increasing the number of test results used to assess conformity:

- increases the probability of accepting a conforming population for which $q < 5\%$;
- increases the probability of rejecting a non-conforming population for which $q > 10\%$.

BS 8500 clarifies that more than 15 test results may be collected during an assessment period and used to assess conformity using the same criterion.

Tables 4 and 5 provide some detailed results to illustrate the effect of the number of test results on conformity. Table 4 gives the producer's margins required to achieve a 98% probability of acceptance when differing numbers of test results are used to assess conformity.

Table 4. The effect of the number of test results used to assess conformity on the producer's margin.

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The data are auto-correlated (according to Taerwe's model with parameters 0.4 and 0.2), the mean is calculated from 6, 15, 35 or 70 test results, and the standard deviation is established beforehand (from 35 test results).

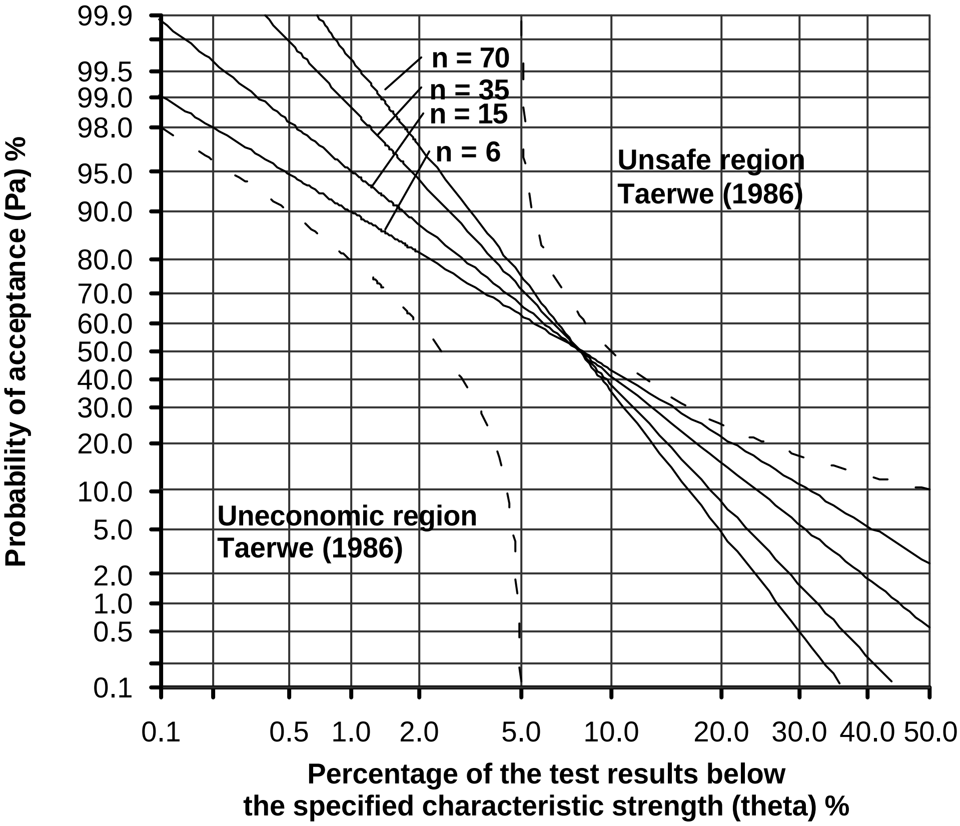
Number of test results used to assess conformity *n*	Probability of acceptance P_a %	Percentage below specified characteristic strength q %	Multiplier used to calculate the producer's margin *k*
6	98.0	0.2	2.9
15	98.0	0.5	2.5
35	98.0	1.2	2.2
70	98.0	1.8	2.1

Table 5 gives the specifier's risks when differing numbers of test results are used to assess conformity, and in the situation when concrete is supplied from a population for which q =10%. Table 5 shows that increasing the number of test results increases the protection provided by conformity assessment even in this situation when the concrete is only marginally non-conforming.

Appendix D gives examples of conformity based on 15 or 35 results using site data for a family. It should be noted that these concretes were not designed for conformity to BS EN 206-1.

Figure 2. The effect of increasing "n" on the operating characteristic for the conformity rule used with continuous production in BS EN 206-1.

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The operating characteristics have been obtained by simulation and apply when the data are auto-correlated (according to Taerwe's model with parameters 0.4 and 0.2), the mean is calculated from 6, 15, 35 or 70 test results, and the standard deviation is established beforehand (from 35 test results).



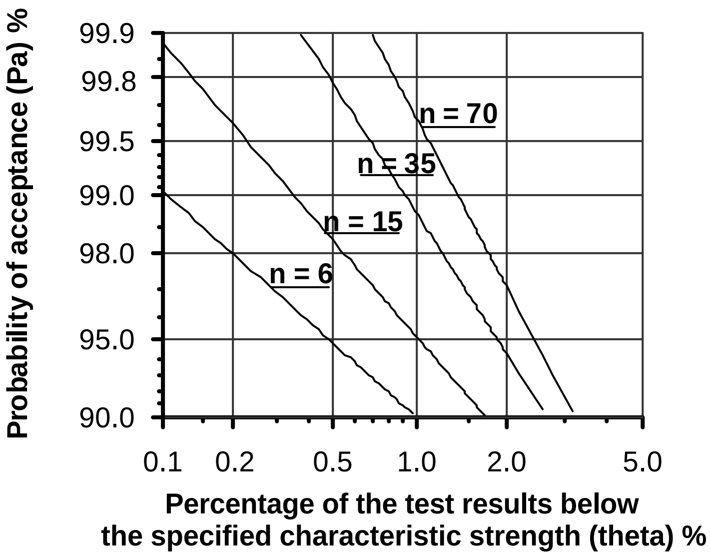


Table 5. The effect of the number of test results used to assess conformity on the specifier's risk.

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The data are auto-correlated (according to Taerwe's model with parameters 0.4 and 0.2), the mean is calculated from 6, 15, 35 or 70 test results, and the standard deviation is established beforehand (from 35 test results).

Number of test results used to assess conformity ***n***	Probability of acceptance P_a **%**	Percentage below specified characteristic strength q **%**	Multiplier used to calculate the producer's margin ***k***
6	43.1	10.0	1.3
15	41.0	10.0	1.3
35	38.2	10.0	1.3
70	35.9	10.0	1.3

2.4.4 Effect of auto-correlation

"Auto-correlation" means that successive results in a series of test results are correlated. For example, in the case of positive auto-correlation, which is the case of interest with concrete, it means that if one test result is higher than the average for the series, then the next test result is more likely to be higher than the average than lower than the average.

Appendix B contains a description of some methods that may be used to test data for auto-correlation. It is recommended that previous production data be checked for auto-correlation prior to establishing design margins.

Taerwe (1987) examined five series of concrete test results and concluded that the results could be modelled by:

$$(X_n - m) = 0.4(X_{n-1} - m) + 0.2(X_{n-2} - m) + e_n$$

Here

μ is the long-term average of the test results

X_1 , X_2 , X_3 , ... , X_n are successive test results

ε_n (n = 1, 2, ...) are random deviations (normally distributed with mean zero and constant variance)

Roberts (1988) showed that under typical United Kingdom conditions, test results are not auto-correlated. The analysis of UK data used in the development of this publication gave some level of auto-correlation, but less than that assumed by Taerwe.

Figure 3 illustrates the effect of auto-correlation. The two operating characteristics shown with solid lines are for auto-correlated results that follow Taerwe's model (and are the same as two of the lines shown in Figure 2). The two broken lines apply to the same circumstances as the first two, but when the test results are independent, not auto-correlated.

The figure shows that if the test results are independent, this:

- increases the probability of accepting a conforming population for which $q < 5\%$;
- increases the probability of rejecting a non-conforming population for which $q > 10\%$.

Table 6 shows the effect on the producer's margin of auto-correlation. It is clearly advantageous for the producer to try to ensure that the test results are not auto-correlated, particularly if the number of test results available to assess conformity is only 15.

Table 6. The effect of auto-correlation on the producer's margin.

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The data are independent, or auto-correlated (according to Taerwe's model with parameters 0.4 and 0.2), the mean is calculated from 15 or 35 test results; and the standard deviation is established beforehand (from 35 test results).

Number of test results used to assess conformity *n*	Producer's design margin ks	Probability of non-conformity, %
6 (independent)	2.0σ	12.5
6 (auto-correlated)	2.0σ	20.4
15 (independent)	2.0σ	4.7
15 (auto-correlated)	2.0σ	14.2
35 (independent)	2.0σ	1.5
35 (auto-correlated)	2.0σ	7.4
6 (independent)	2.326σ	2.9
6 (auto-correlated)	2.326σ	10.0
15 (independent)	2.326σ	0.3
15 (auto-correlated)	2.326σ	4.8
35 (independent)	2.326σ	0.02
35 (auto-correlated)	2.326σ	1.2

The probability of non-conformity given in Table 6 should be compared with Table 2. For the particular situation (number of test results and the level of auto-correlation), a decision can be taken as to whether the use of the continuous production conformity criteria or continued use of the initial production conformity criteria give the lower risk of non-conformity.

2.5 Conformity of tensile splitting strength

The conformity criteria for tensile splitting strength follow the same pattern as the criteria for compressive strength. The criteria are given in 8.2.2 of BS EN 206-1: 2001. BS EN 206-1 does not permit the concept of concrete families to be applied to the conformity of tensile splitting test data. As it is likely that a tensile splitting strength requirement will only be specified for relative large quantities of a single pavement concrete, the inability to use families is not a serious problem. It is recommended that tensile splitting test data be not used for production control. If appropriate, these concretes may be incorporated into a family for production control purposes using their compressive strength.

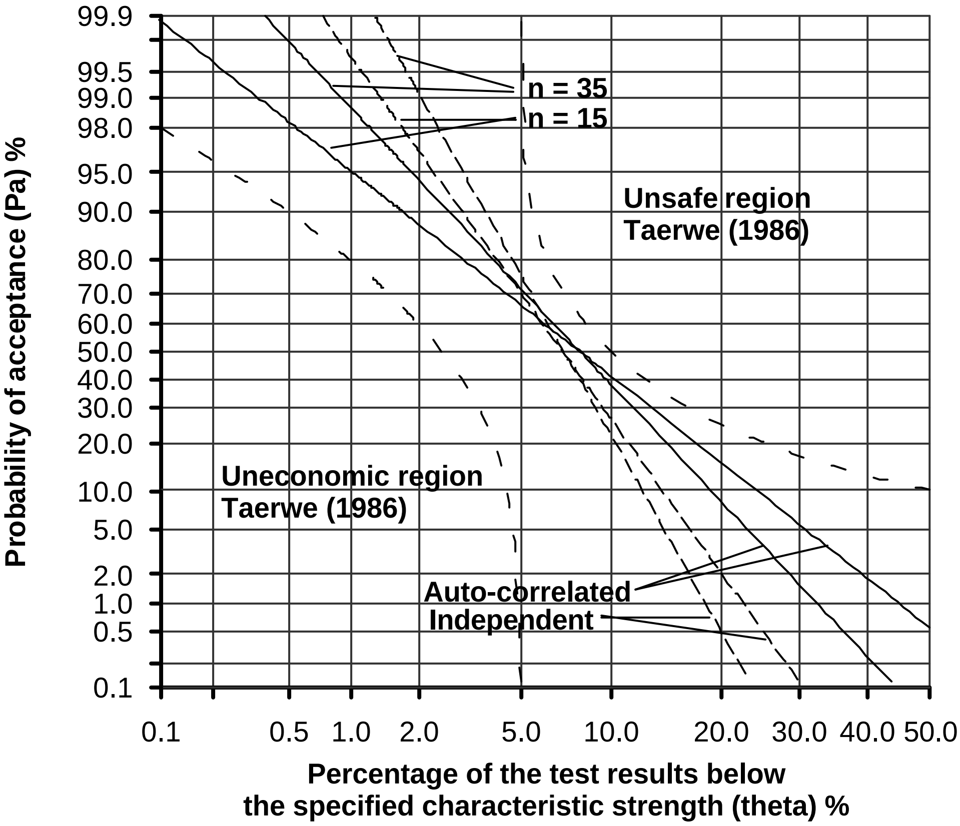
With the exception of the recommendations related to families, the advice given for conformity of compressive strength will be equally applicable to tensile splitting strength. Where there is frequent testing of pavement concrete, the level of auto-correlation is likely to be high. Another point to note is that the repeatability of the tensile splitting test (and the flexural test) is relatively poor and this will increase the standard deviation of the test data.

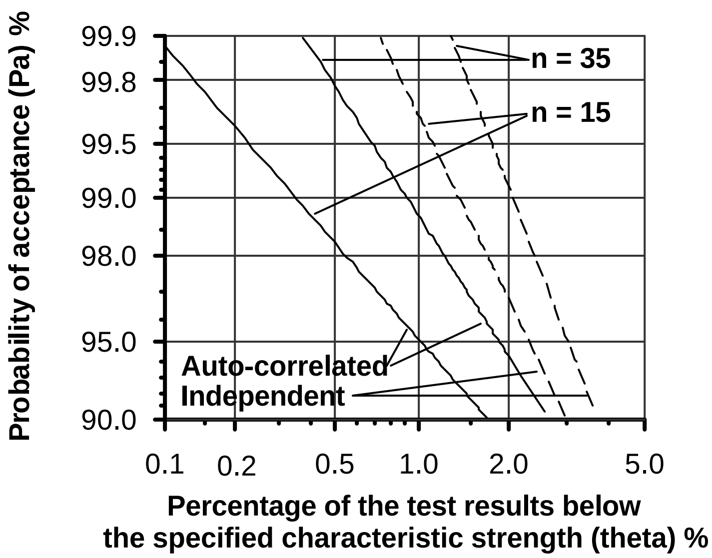
2.6 Conformity of flexural strength

The draft European standard prEN 13877-1 *Concrete pavements – Part 1: Materials* contains classes for flexural strength and cites BS EN 206-1 for the conformity criteria. However BS EN 206-1 does not contain conformity criteria for flexural strength. Until this problem is resolved, the conformity criteria should be agreed on a contract-by-contract basis.

Figure 3. The effect of test results being either independent or auto-correlated on operating characteristics.

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The operating characteristics have been obtained by simulation, and apply when the test results are either independent or auto-correlated (according to Taerwe's model with parameters 0.4 and 0.2), the mean is calculated from 15 or 35 results, and the standard deviation is established beforehand (from 35 results).





3. Guidance on the application of the conformity rules for compressive strength

3.1 Introduction

In general, BS EN 206-1 fixes the rules for concrete conformity of strength. However in a number of places, they do permit the producer and, in a few cases, the specifier to select from a given number of options.

Options are given for:

- relevant test data;
- point of sampling;
- number of specimens per test result;
- age at testing;
- assessment period;
- higher sampling rates;
- overlapping or non-overlapping results;
- use of concrete families;
- estimation of the standard deviation.

In addition to providing guidance on these choices, there are a number of practical issues where guidance may be helpful and this is provided. There is no uniquely correct answer to these issues and therefore this publication provides guidance on the considerations that need to be taken into account when making choices. Where possible, general recommendations are made.

3.2 Relevant test data

The requirements of BS EN 206-1: 2001 are:

From 8.1 *Where tests for production control are the same as those required for conformity control, they shall be permitted to be taken into account for the evaluation of conformity. The producer may also use other test data on the delivered concrete in the conformity assessment.*

It makes commercial sense to use strength test data for both production and conformity control. The inclusion of other test data e.g. that obtained from the customer by identity testing, is the producer's choice. There can be differences in data produced by a different organisation using different test machines and, possibly, different specimen shapes. The producer has no control over how well these specimens are made, cured and tested. In most cases, the sampling frequency for identity testing is likely to be lower than that required for conformity testing. As a general rule, the best option is to use only the producer's data, but there may be exceptions to this advice. For example, when the producer is controlling a single concrete and it is unlikely that sufficient data will be obtained to qualify for continuous production. In this case it may be of benefit to use identity test data.

Where concrete families are used and the strength of a concrete is controlled by maximum w/c ratio or minimum cement content, transposing the test result on the basis of the specified strength class will distort the production and conformity control systems by inflating the standard deviation and mean strength. In these cases, the individual criterion is unchanged i.e. ($f_{ci} \geq$ specified characteristic strength – 4). However, for the check on the mean strength, the actual cement content should be corrected back to those materials and properties of the Reference Concrete and this corrected cement content used to determine the equivalent strength. Adjustments using other parameters, e.g. w/c ratio, is equally acceptable. This equivalent strength is used in the assessment of conformity of the mean strength.

Where a family containing such data indicates a potential non-conformity, further analysis of the data should compare concretes with their specified characteristic strength.

The inclusion of data from prescribed concretes should be considered. Testing such concretes for strength provides an indirect check on their cement content and where data from designed concrete are scarce, these data will shorten the assessment period. If these data are included, the individual criterion is not applicable. The actual cement content is corrected back to those materials and properties of the Reference Concrete and this corrected cement content used to determine the target strength. This target strength is used in the assessment of conformity of the mean strength.

Where water is added on site under the instructions of the specifier/user and signed for, the producer may take this as a change in specification. The producer should have documentary evidence showing the effect on strength of these site additions of water. This information may be used to determine the appropriate lower (specified) characteristic strength or used to adjust the actual strength to reflect the strength without this addition of water. This adjusted strength may be used in conformity assessment.

For production control purposes, it is normal to exclude statistical outliers. These are normally defined as results that are greater than or equal to ($\pm 3\sigma$) from the target mean strength. However, if this approach were to be applied to conformity control, the effect would be to eliminate results that may fail the individual criterion. The conformity control system should identify all outliers and each one should be investigated. Unless there is a valid reason for rejecting the result, low outliers should be included in the conformity assessment but excluded from the check on standard deviation. Producers may eliminate high outliers from the conformity analysis, but if the high result is caused by requirements other than the specified strength controlling the actual strength e.g. maximum w/c ratio, these data should be included using the procedure described above.

3.3 Point of sampling and sampling rate

The requirements of BS EN 206-1: 2001 are:

From 8.1 *The place of sampling for conformity tests shall be chosen such that the relevant concrete properties and concrete composition do not change significantly between the place of sampling and the place of delivery. In the case of lightweight concrete produced with unsaturated aggregates, the samples shall be taken at the place of delivery.*

From 8.2.1.2 *The minimum rate of sampling and testing of concrete shall be in accordance with table 13 of BS EN 206-1 : 2001 at the rate that gives the highest number of samples for initial or continuous production, as appropriate.*

Not withstanding the sampling requirements in 8.1 of BS EN 206-1: 2001, the samples shall be taken after any water or admixtures are added to the concrete under the responsibility of the producer, but sampling before adding placticizer or superplasticizer to adjust the consistence (see 7.5 of BS EN 206-1: 2001) is permitted where there is proof by initial testing that the plasticizer or superplasticizer in the quantity to be used has no negative effect on the strength of the concrete.

From Table 13 *Where the standard deviation of the last 15 test results exceeds 1,37 s, the sampling rate shall be increased to that required for initial production for the next 35 test results.*

BS EN 206-1 permits, as an alternative to sampling on site, sampling at the plant provided water is not added at site under the responsibility of the producer. The exception to this is where lightweight concrete with unsaturated aggregates is supplied.

The attractions of sampling at the plant are:

- lower costs per test result;
- the ability to test at a higher rate;
- simpler to test the first load of air entrained concrete.

However there may be practical problems with sampling at the plant with some production systems, particularly in respect of safety and obtaining a representative sample. Where the concrete is centrally mixed, sampling is carried out by discharging a sample from the truckmixer. It should be noted that in this case the sample does not fully conform to the requirement in BS EN 12350-1 *Testing fresh concrete – Part 1: Sampling* for incremental sampling. Where the concrete is truckmixed, the first part of the discharge is not considered as being representative of the batch and should not be used for strength testing.

Table 13 of BS EN 206-1: 2001 uses the terms "production day" and "production week" without defining what these terms mean. Consequently, the draft BS 8500-2 includes the following definitions:

> **production day:** Day in which 20m^3 or more of designed or designated concrete has been produced or, on days where less than 20m^3 of designed or designated concrete have been produced, the day on which a cumulative 20m^3 has been produced shall be regarded as one production day. The sequence is restarted on a new day for each occasion when a production day is counted.
>
> **production week:** A period of 7 consecutive days comprising at least 5 production days or alternatively, the period taken to complete 5 production days, whichever is the longer period.

The rate of sampling is given in Table 13 of BS EN 206-1: 2001. The volume rates should be taken as the prime sampling rate and only where this rate does not give sufficient test results, should the time rate of sampling be applied. Where this is applied, the volume at the end of the production week/day (as appropriate) is taken as 0. The volume rates are not time dependent e.g. where there is continuous production of 410m^3 of concrete from a concrete family in 1 production week, the minimum rate of sampling is 1 and the last 10m^3 of production starts the next 400m^3 of production.

In order to achieve a desired number of test results in an assessment period, it is better to extend the time taken than to increase the rate of testing as an increased rate of testing may increase auto-correlation.

The note in Table 13 of BS EN 206-1: 2001 to increase the rate of sampling only applies where there is a step change in the standard deviation greater than 1.37σ. In **3.10**, it is recommended that more sensitive systems are used to detect changes in standard deviation and in practice the standard deviation should be changed prior to a change of 1.37σ. With such changes in the standard deviation based on the more sensitive system, there is no requirement to increase the rate of testing even if a series of step changes has exceeded 1.37σ.

Example 4
Example of testing rates with continuous production and production control certification. The minimum rates of sampling given in Table 13 of BS EN 206-1: 2001 are 1/400 m^3 or 1/production week.

Minimum rate of sampling for a concrete family					
Production week	*Volume of production in production week*	*Carry-over volume of production from previous production week*	*Carry-over volume of production plus actual volume of production*	*Minimum rate of sampling for the concrete family*	*Comments*
1	*350*	*0*	*350*	*1*	*1/week*
2	*370*	*0*	*370*	*1*	*1/week*
3	*440*	*0*	*440*	*1*	*1/400 m^3*
4	*565*	*40*	*605*	*1*	*1/400 m^3*
5	*630*	*205*	*835*	*2*	*1/400 m^3*
6	*840*	*35*	*875*	*2*	*1/400 m^3*
7	*790*	*75*	*865*	*2*	*1/400 m^3*
8	*375*	*65*	*440*	*1*	*1/400 m^3*

3.4 Number of specimens per test result

The requirements of BS EN 206-1: 2001 are:

From 8.2.1.2 *The test result shall be that obtained from an individual specimen or the average of the results when two or more specimens made from one sample are tested at the same age.*

Where two or more specimens are made from one sample and the range of the test values is more than 15 % of the mean then the results shall be disregarded unless an investigation reveals an acceptable reason to justify disregarding an individual test value.

The number of specimens to be made from one sample is decided by the producer. Where two or more specimens are made, it is possible to run a check on how well the specimens were made and tested. Where there is a low-test result based on a single specimen, it will be more difficult to justify its exclusion from the conformity control. There may, however, be a requirement for greater carrying capacity in vans and larger curing tanks where two specimens are taken.

3.5 Age at test

The requirements of BS EN 206-1: 2001 are:

From 8.2.1.1 *If the strength is specified for a different age, the conformity is assessed on specimens tested at the specified age.*

In theory this permits the specifier to specify strength at earlier or later ages. If large volumes of a single concrete are to be produced, it may be practical to run separate production and conformity control systems for the specified age. In most cases this will not be the situation and the concrete will be required to be part of a family with additional conformity testing at the specified age. If the concrete comes from a family or individual concrete that is in continuous production, the criteria in BS EN 206-1 for continuous production may be applied to the strength assessment at the different age.

Where testing at later ages is specified, a better solution is to provide strength development data for the specified concrete and to agree with the specifier a method for calculating an equivalent concrete strength at 28 days and use this for the assessment of conformity.

Where a strength requirement of less than 28 days is required, additional testing will be required at the specified age. Where there is no requirement for a 28 day strength, consideration should be given to testing at 28 days and treating the results in an identical way to those from prescribed concrete, see **3.2**.

Where concretes are tested at one or two days, the temperature of the constituent materials at batching will significantly affect the strength result. It should be noted that the 2-day strength requirements in 7.2 of BS EN 206-1: 2001 are based on laboratory tests at 20°C where the constituent materials should have been stored in the laboratory for several days prior to use. Test data from site samples cannot be used to verify conformity with any specified $f_{cm,2}/f_{cm,28}$ strength ratio.

3.6 Assessment period

The requirements of BS EN 206-1: 2001 are:

From 8.2.1.3 *Conformity assessment shall be made on test results taken during an assessment period that shall not exceed the last twelve months.*

In Table 14, the criteria are only given where the number "n" of test results for compressive strength in the group is 15.

An assessment period is established for every concrete family and every individual concrete not within a family. Assessment periods may be different for each concrete family and individual concrete. Obviously, if a particular concrete is not produced during an assessment period, there is no requirement to verify conformity. Conversely, every produced concrete family and every produced individual concrete not within a family is required to be sampled and tested for conformity. There is no requirement to test every member of a concrete family, only for tests to be taken at random from the family.

The number of test results in each assessment period required by BS EN 206-1 is not defined. During the development of BS EN 206-1, it was understood that the continuous criteria would apply to 15 or more results obtained in an assessment period. Early drafts of BS EN 206-1, including the CEN Enquiry version, contained the words “not less than 15”. However in the voting version of BS EN 206-1, the words “not less than” had been deleted. This creates uncertainty over the conformity provisions, as there is no requirement for “n” to be 15 and no defined requirements for conformity where “n” is not equal to 15. In the view of BSI, this change had not been agreed by the CEN committee responsible for BS EN 206-1 and was an error. Unfortunately to correct this error will require an amendment to BS EN 206-1 that will take some time to pass its formalities. For the intermediate period, 8.2.1.3 of BS 8500-2 (at present at the public comment stage) contains the words:

The criteria given in tables 14 and 16 of BS EN 206-1: 2001 for n=15 apply to higher values of “n”.

This restores clarity to the conformity criteria when $n \geq 15$. See **3.11** for guidance when $n < 15$ in an assessment period.

Whenever possible, try to avoid individual concretes and link any specials to an existing family e.g. link the sulfate-resisting Portland cement concretes to the Portland cement family with the same aggregates.

There is no requirement for the assessment period to be defined in terms of time, only that the assessment period shall not exceed 12 months. The assessment period may be different for certain concretes or families. Different assessment periods may apply to different aspects of conformity e.g. strength and cement content. The assessment periods within a company do not have to be constant; they may vary from plant to plant. This flexibility is essential as the assessment period for, say, a busy urban plant is likely to be different to a rural plant producing mainly prescribed concrete.

Methods of defining the assessment period include:

- defined volume of concrete;

- number of test results;
- period of uniform conditions for production e.g. period of constant standard deviation.

All the above methods require the proviso that the resulting period does not exceed 12 months. Composites of the above are permitted and recommended. Where practical, the number of results from strength testing for a concrete family should be set at a value ≥ 35. For the reasons given in **3.10**, under certain conditions, a significant change in standard deviation should trigger the end of an assessment period. With a maximum period of 12 months, these criteria are recommended as the basis for defining the assessment period for strength.

Example 5
The period of assessment period of compressive strength for a concrete or concrete family is the shortest of:

- *period of uniform conditions for production e.g. period of constant standard deviation;*
- *period needed to obtain 35 results;*
- *12 months.*

As explained in **2.1**, a period of uniform production can be the sum of 2 periods separated by a period where the plant was unstable.

See **4.2** for guidance on assessment periods for properties other than strength.

Conformity has to be declared only at the end of each defined assessment period. Prior to this the producer should be keeping a watch on the likelihood of achieving conformity and where this is in doubt, taking appropriate corrective measures.

The producer has no requirement to declare conformity for the period of supply for a particular contract. As it is more common to supply a multiplicity of contracts during any period of time, this declaration is not a practical option. It would be satisfactory for the producer to declare any proven non-conformity within a reasonable time after the end of each relevant assessment period.

3.7 Higher sampling rates

The requirements of BS EN 206-1: 2001 are:

From 8.1 *If higher sampling rates are required by the specifier, this shall be agreed in advance.*

The sampling rates given in Table 13 of BS EN 206-1: 2001 are <u>minimum</u> sampling rates for conformity testing, but to ensure full production control, the producer may need to select higher rates. Avoid very high rates of testing as this will increase auto-correlation and the risk of non-conformity where “n” is relatively low. Where “n” is set at 35, testing at rates of 8 to 16 per month i.e. at current QSRMC rates, would provide a reasonable compromise between the need for control of the production and conformity assessment.

The specifiers option to increase the sampling rate is not helpful. One assumes that this means a higher <u>minimum</u> sampling rate and that it only applies to the concrete production going to that specifier. Where the concrete is produced on site with a dedicated plant, a change in the minimum sampling rate can be accommodated. However, where the specifiers requirements represent a small part of the output from a ready mixed concrete plant, it is not a very easy requirement to satisfy and it could skew the random testing of the production (a requirement of BS EN 206-1). Again there are exceptions to this general advice. Where high strength concrete for critical elements is produced, the specifier may require each load to be tested. These concretes cannot form part of a family and the higher rate of testing may be needed to qualify for continuous production.

3.8 Non-overlapping and overlapping results

The requirements of BS EN 206-1: 2001 are:

From 8.2.1.3 *Conformity of concrete compressive strength is assessed on:*

– groups of "n" non-overlapping or overlapping consecutive test results f_{cm} *(criterion 1);*

– each individual test result f_{ci} *(criterion 2).*

NOTE: The conformity criteria are developed on the basis of non-overlapping test results. Application of the criteria to overlapping test results increases the risk of rejection.

The note warns of the increased risk of non-conformity if the overlapping test results are used. The producer, not the specifier, selects which method of analysis to apply to the data and it does not appear very sensible to select a method of analysis that increases the risk of non-conformity. Therefore the selection of the non-overlapping groups is strongly recommended.

3.9 Use of concrete families

The requirements of EN 206-1: 2000 are:

From 8.2.1.1 *For normal-weight and heavyweight concrete of strength classes from C8/10 to C55/67 or lightweight concrete up to and including class LC55/60, sampling and testing shall be performed either on individual concrete compositions or on concrete families of established suitability as determined by the producer unless agreed otherwise. The family concept shall not be applied to concrete with higher strength classes. Lightweight concrete shall not be mixed into families containing normal-weight concrete. Lightweight concrete with demonstrably similar aggregates may be grouped into its own family.*

NOTE: For guidance for the selection of concrete families, see Annex K of BS EN 206-1: 2001. More detailed information for the application of the concrete family concept is given in CEN Report (CR13901: 2000).

In the case of concrete families, the producer shall achieve control over all family members and sampling shall be carried out across the whole range of concrete compositions produced within the family.

Where conformity testing is applied to a concrete family, a reference concrete is selected which is either that most commonly produced or one from the mid-range of the concrete family. Relationships are established between each individual concrete composition of the family and the reference concrete in order to be able to transpose test results for compressive strength from each individual concrete test result to the reference concrete. The relationships shall be reviewed on the basis of original compressive strength test data at every assessment period and when there are appreciable changes in the production conditions. In addition, when assessing conformity for the family, it has to be confirmed that each individual member belongs to the family (see 8.2.1.3 of BS EN 206-1: 2001).

From 8.2.1.2 *Sampling shall be carried out on each family of concrete produced under conditions that are deemed to be uniform.*

From 8.2.1.3 *Where conformity is assessed on the basis of a concrete family, criterion 1 is to be applied to the reference concrete taking into account all transposed test results of the family; criterion 2 is to be applied to the original test results.*

To confirm that each individual member belongs to the family, the mean of all non-transposed test results (f_{cm}) for a single family member shall be assessed against criterion 3 as given in table 15 of BS EN 206-1: 2001. Any concrete failing this criterion shall be removed from the family and assessed individually for conformity.

The producer is free to select the membership of the family, but they have to be able to justify the selection and provide relationships to the Reference Concrete. For those not experienced in the use of concrete families, Annex K of BS EN 206-1: 2001 provides guidance on the selection of the family. It is recommended that less common concretes e.g. 10mm maximum upper aggregate size, are included within a family.

Whilst theoretically and in the UK experience, normal-weight concrete with $f_{ck,\ cube}$ > 67 N/mm^2 could form part of a family. However, the pragmatic judgement was made that these concretes would be subjected to frequent testing and therefore the UK accepted the majority view that they should be assessed as single concretes.

It is permitted to use air entrained and non-air entrained data in a single family. For conformity control purposes, it may be better to separate air entrained concretes from non-air entrained concretes. Minor changes in air content will affect strength and these concretes may have a higher standard deviation.

The relationship between strength and cement content takes an "S" shape. Modern systems take this shape into account when transposing data. However in some cases, a linear approximation of the strength v cement content relationship may be taken for the central part of this relationship in the transposition of the test result to an equivalent value of the Reference concrete, see Example 2. In this case, the upper limit of the linear relationship should be defined. Values of cement content above this value will have a decreasing effect on strength until the point is reached where an increase in cement content gives no increase in strength. At very high cement contents, the effect of using a linear relationship between strength and cement content is to over-estimate the reduction in strength. Ideally the strength v cement content relationship should be used to make the necessary adjustment, Figure 4, but in some cases this could be approximated to a bi-linear equation, Figure 5.

Each member of the family is checked to confirm that it belongs to the family at each assessment period using the confirmation criteria given in Table 15 of BS EN 206-1: 2001. Any family member failing to satisfy the confirmation criteria is removed from the family and assessed separately. Where there is only a single result for a family member in the assessment period, the individual criterion in BS EN 206-1 is applied. BS EN 206-1 does not give requirements for the confirmation criterion when there are more than 6 test results for the family member. In this situation, CEN Report 13901: 2000 recommends the following. Where the number of test results is ≥ 15, apply the criterion:

Mean of the family member ≥ $f_{ck} + 1{,}48\sigma$

When the number of test results is in the range 7 to 14, apply linear interpolation between the requirement for 6 test results and ($f_{ck} + 1{,}48\sigma$).

Example 6
There are 9 test results for a C25/30 concrete giving a mean strength of 37 N/mm^2 (cube). The family standard deviation is 4.5 N/mm^2.
For 6 results the confirmation criterion is:

$$f_{cm} \geq f_{ck} + 3 \geq 33\ N/mm^2$$

For 15 results the confirmation criterion is:

$$f_{cm} \geq f_{ck} + 1.48\sigma \geq 36.7\ N/mm^2$$

By interpolation, the requirement for 9 results is:

$$f_{cm} \geq f_{ck} + 3 + (6.7 - 3)(9 - 6)/(15 - 6) \geq 34.2\ N/mm^2$$

As f_{cm} is 37 N/mm^2, this concrete is accepted as belonging to the family.

Failure to satisfy the confirmation criteria will result in that concrete failing to satisfy the conformity criteria when assessed as an individual concrete.

In addition to the conformity assessment, at each assessment period, the original results of each family member shall be inspected to verify that the relationship with the Reference Concrete and the design margin is still valid. One-way of doing this is given in CEN Report 13901: 2000. It recommends calculation of, for each family member, the mean strength for all the original test data taken during the assessment period and check that it is $\geq (f_{ck} + 1{,}48\sigma)$. In this case f_{ck} is the specified strength except where the strength of the concrete is controlled by requirements for maximum w/c ratio or minimum cement content. In these cases an equivalent (higher) f_{ck} should be used. This check is not applied to any prescribed concretes that are within the family. If it satisfies this criterion, no further action is needed. If it fails this criterion, a more detailed investigation of the relationship is needed. This should involve the consideration of data from previous assessment periods and what was happening to the general production when this concrete was produced. This check on relationships is not part of the determination of conformity and consequently other systems could be used e.g. for each concrete within the family, a comparison between the design target strength and the actual mean strength.

Where the check on relationships is combined with the conformity assessment, it may be used as a filter for the application of the confirmation criterion. If a concrete passes the assessment of relationships (a more severe test) then it is deemed to have satisfied the confirmation test (criterion 3 in BS EN 206-1: 2001). Only where the data for a particular concrete fails this assessment of relationships is the confirmation check applied.

Where an inspection or certification body is involved, it is required to check the results of the conformity assessment by the producer. For site made concrete where there is no third party involvement, the second party should take on this role.

It should not be assumed that the use of concrete families reduces the risk of non-conformity. An increase in risk occurs where the number of results to detect a significant change plus those awaiting testing represent a high proportion of the test results in the assessment period.

Figure 4. Transposition of high cement content data (Cement content of the Reference Mix is 275 kg/m^3)

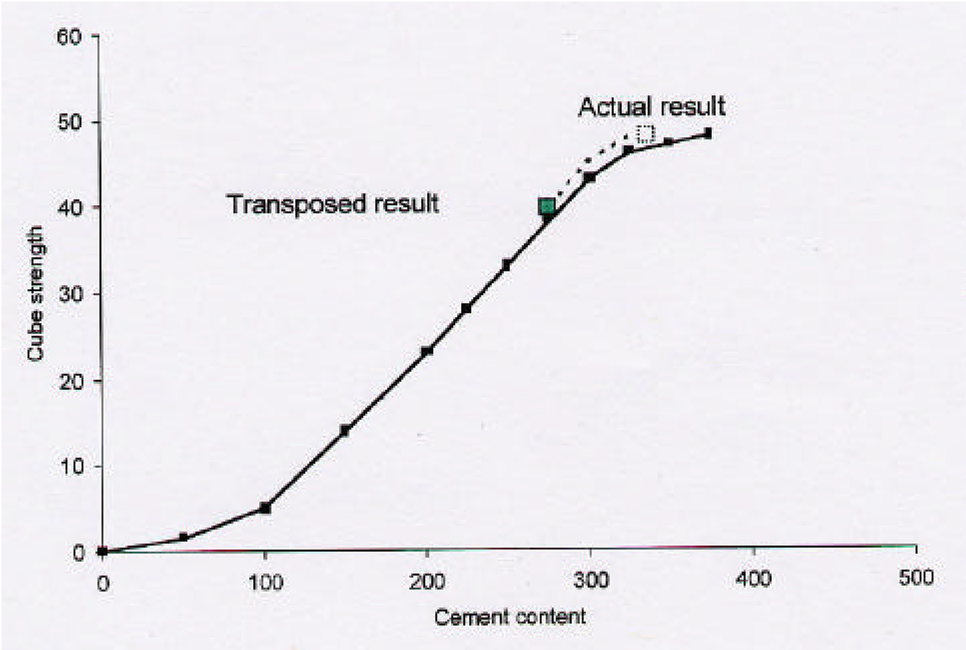
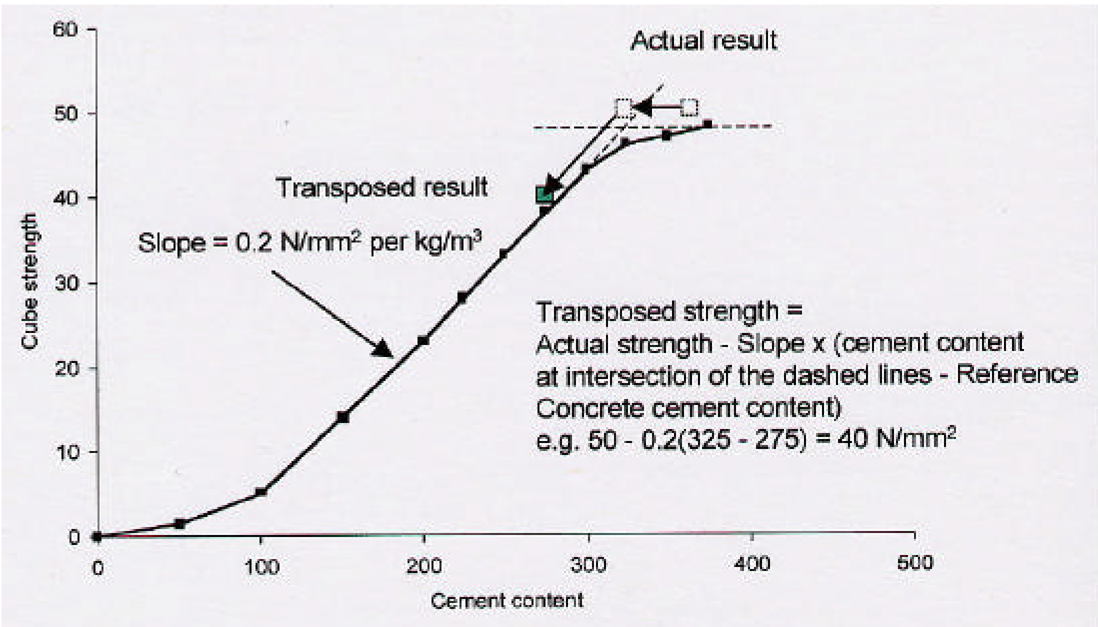


Figure 5. Approximate method for transposing high cement content test data (Cement content of the Reference Mix is 275 kg/m^3)



3.10 Estimation of the standard deviation

BS EN 206-1 provides no guidance on the method for determining the estimate of the population standard deviation. The traditional way of estimating and the method programmed into most calculators is the square root of the sum of the squared deviations of individual results from the mean divided by the number of results less one (RMS method). However such a method is not appropriate where the process average can change, as is the case with concrete production. In the case of concrete production, the estimate of the standard deviation should be based upon:

Estimated standard deviation = 0.886 x mean range of successive pairs of results.

The derivation of this equation can be found in standard statistical works on production control such as Oakland, 1986. The mean range is widely used to provide the measure of dispersion used in process control charts, such as the Cusum system, and so has stood the test of widespread practical use. Oakland makes the point "the chart indicates to operatives and first line supervisors when they should be taking action or alternatively when they should leave the process alone". The conventional method of deriving the standard deviation can have a masking effect on changes.

See Example 7 for the estimate of standard deviation by this method.

Example 7

Table 7. Calculation of the standard deviation

Result	*Transposed cube strength, N/mm²*	*Range, N/mm²*	*Calculation of standard deviation*
1	*54.5*		*Estimation of the standard deviation* *= 0.886 x 51/14* *= 0.886 x 3.64 = 3.0 N/mm² (rounded to the nearest 0.5 N/mm²)*
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*	

The standard deviation estimated from the mean range is to be preferred over the conventional sample standard deviation as a method of estimating the population standard deviation where the data contain outlying results. This is because the mean range method is less affected by such results than the sample standard deviation method. In the calculation of the sample standard deviation, the squares of a few large deviations will outweigh those of the other smaller deviations. The estimation of the population standard deviation from the mean range does not involve squaring so the effect of the outlying results is smaller.

Likewise, the use of the mean range method is to be preferred over the sample standard deviation where the data contain changes in the process mean with time. The sample standard deviation is calculated using the deviations of the results from the arithmetic mean of all the results. Therefore, if the results contain a shift in the process mean at some point in time, all these deviations will be inflated and the sample standard deviation will give an inflated estimate of the dispersion of the data. Where the mean range method is used, such a shift will affect only the one range, or ranges, that spans the shift. Hence the population standard deviation estimated from the mean range will be less affected by such a shift in mean strength than the standard deviation derived from the sample, see Example 8.

Example 8
15 random data have been generated assuming a mean strength of 37.0 N/mm² and a standard deviation of 3.5 N/mm². These have been repeated to give a total of 30 data, see Figure 6a. The standard deviation of the 30 data given in Figure 6a is:

3.6 N/mm² when determined by the standard method;
3.7 N/mm² when determined from 0.886 x 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/mm² is introduced at result 16 i.e. data 16 to 30 are all 5.0 N/mm² less than in Figure 6a. The dispersion of the data around these mean strengths is unchanged. The standard deviation of the 30 data given in Figure 6b is:

4.4 N/mm² when determined by the standard method;
3.8 N/mm² when determined from 0.886 x mean range.

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

In the context of conformity assessment, both outlying results, and shifts in the process mean during an assessment period, are to be expected.

The standard deviation to be applied to the first period of assessment of continuous production is estimated from at least 35 results from the period exceeding 3 months that immediately precedes the assessment period. At least every assessment period, the standard deviation is checked to confirm that it has not changed significantly. BS EN 206-1 permits two methods of verifying the estimate.

Method 1 calculates the standard deviation of the latest 15 results, s_{15}, and compares this with the current estimate of the standard deviation, σ. If the standard deviation is not within:

$$0.63\sigma \leq s_{15} \leq 1.37\sigma$$

a new estimate of σ is calculated using the latest 35 results. This new value of the standard deviation is applied to the next assessment period. As shown in Table 8, this method of detecting changes in the standard deviation is relatively crude and insensitive. With this method where the standard deviation is high, it is very difficult to trigger a change in the standard deviation.

With Method 1, particular care is needed when the standard deviation is reducing and a lower value is adopted immediately for production. If the target-mean strengths are reduced to reflect the lower margin, there could be an increase in risk of non-conformity as the assessment is based on the previous (higher) standard deviation. With low initial standard deviations, further reductions in the standard deviation can result in the target mean strength being lower than the conformity limit, i.e. negative values as shown in Table 9. A lower value of standard deviation should not be adopted until the assessment period is closed.

Figure 6a. 30 random data generated assuming a mean strength of 37.0 N/mm^2 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).

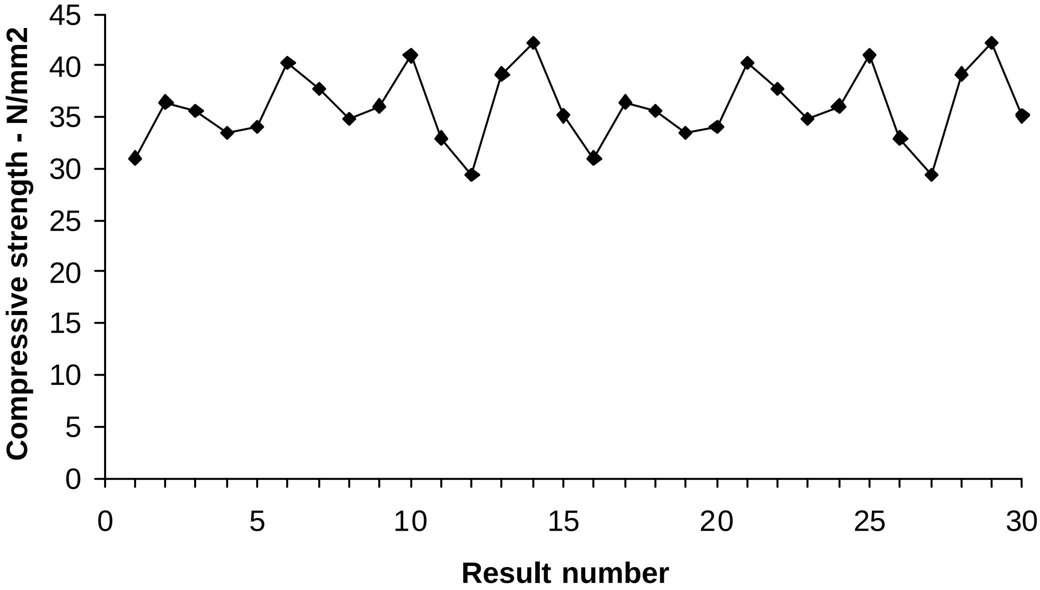


Figure 6b. The same data as in Figure 6a, but with a reduction in mean strength of 5.0 N/mm^2 introduced at result 16.

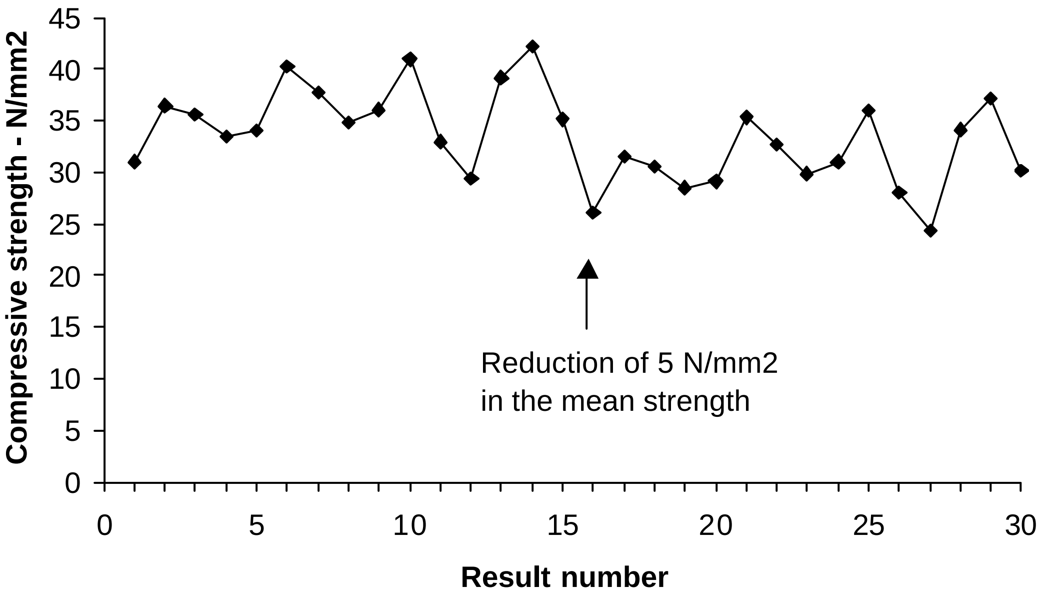


Table 8. Limits on s_{15} outside of which a new estimate of the standard deviation is required.			
Current s, N/mm^2	**Lower limit, N/mm^2**	**Upper limit, N/mm^2**	**Range, N/mm^2**
2	1.27	2.73	± 0.73
3	1.90	4.10	±1.1
4	2.53	5.47	±1.47
5	3.16	6.84	±1.84
6	3.79	8.21	±2.21
7	4.42	9.58	±2.58

Whilst Table 9 shows that it is safe to adopt increases in standard deviation immediately for production, adoption of the new value of standard deviation increase the margin. However, certification bodies are likely to take the view that if the producer has evidence that the standard deviation has increased, they should immediately adopt the new value for production.

Users of the Cusum technique would probably regard a 0.50 N/mm^2 real change in standard deviation as being significant and consequently Method 2 was introduced into BS EN 206-1 allowing the use of continuous systems, such as Cusum R, for checking the estimate of standard deviation. The sensitivity of such systems has to be at least as good as that given by Method 1. Method 2 is not restricted to systems such as Cusum.

Table 9. Difference between the target mean strength and the conformity limit where the standard deviation has changed and this new value adopted for production, but where conformity is based on the previous value of the standard deviation[1)]

Change in s, N/mm^2	**Design margin, N/mm^2**	**Difference, N/mm^2 Previous value of s, N/mm^2**			
		3	**4**	**5**	**6**
+ 1.5	1.64σ	2.94	3.10	3.26	3.42
	2.00σ	4.56	5.08	5.60	6.12
	2.33σ	6.05	6.90	7.75	8.6
+ 1.0	1.64σ	2.12	2.28	2.44	2.6
	2.00σ	3.56	4.08	4.6	5.12
	2.33σ	4.88	5.73	6.58	7.43
+ 0.5	1.64σ	1.30	1.46	1.62	1.78
	2.00σ	2.56	3.08	3.60	4.12
	2.33σ	3.72	4.57	5.42	6.27
0	1.64σ	0.48	0.64	0.80	0.96
	2.00σ	1.56	2.08	2.60	3.12
	2.33σ	2.55	3.40	4.25	5.1
- 0.5	1.64σ	- 0.34	- 0.18	- 0.02	0.14
	2.00σ	0.56	1.08	1.60	2.12
	2.33σ	1.39	2.24	3.09	3.94
- 1.0	1.64σ	- 1.16	- 1.00	- 0.84	- 0.68
	2.00σ	- 0.44	- 0.08	0.60	1.12
	2.33σ	0.22	1.07	1.92	2.77
- 1.5	1.64σ	- 1.98	- 1.82	- 1.66	- 1.5
	2.00σ	- 1.44	- 0.92	- 0.40	1.12
	2.33σ	- 0.95	- 0.10	0.76	1.61

Notes
[1)] See Appendix C for the method of calculation.

A further advantage of using Method 2 with a sensitivity greater than that of Method 1, is the requirement to increase the rate of testing to that used in initial production only applies where the change in standard deviation is > 1.37σ.

Where the Cusum technique is used for production control, there may be cut–off lower and upper limits on standard deviation within the production control system. The system should be modified to ensure that cut-off values are not used for conformity assessment.

A significant change in the standard deviation is an indication that the production conditions have changed (8.2.1.2 of BS EN 206-1: 2001 requires them to be uniform). Thus a change in the standard deviation should indicate the end of one assessment period and the start of the next. This can create a practical problem when the start of a new assessment period creates a period with less than the expected number of sets of compressive strength test results e.g. there are less than 15 results from the end of the last assessment and the time when a change in standard deviation was detected. The following procedure is recommended where the normal number of results in an assessment period has been set at a value ≥ 15.

There are three decisions that have to be taken:

- whether to use the new standard deviation or the old standard deviation for production control in the rest of the assessment period;
- whether to use the new standard deviation or the old standard deviation to assess conformity in the current assessment period;
- whether to use the “n” results to assess conformity immediately or to wait until the normal number of results are available.

Table 10 gives recommendations on what actions should be taken and the following comments give the basis for these recommendations. Appendix D gives an example of the application of these recommendations.

Table 10. Recommendations on actions to be taken where a change in standard deviation has been indicated part way through an assessment period

	New s smaller than old s		**New s larger than old s**	
Number of results obtained prior to the detection of a change in the standard deviation plus the number of test results awaiting testing	**n £ 6**	**n > 6**	**n £ 6**	**n > 6**
	Case 1	**Case 2**	**Case 3**	**Case 4**
Standard deviation to be used for production control in the rest of the assessment period	New σ	Old σ	New σ	New σ
Standard deviation to be used to assess conformity in the current assessment period	New σ	Old σ	New σ	Old σ
Assess conformity using the “n” results or wait until the normal number of results are available	Wait	Wait[1)]	Wait	Use “n” results
Notes [1)] Until at least some defined number of test results have been obtained.				

Case 1: When the change in σ is signalled just a small number of results into an assessment period, it is likely that the change actually took place before the start of the period, so the new σ will be the correct one to use for both production control and conformity assessment.

Case 2: When the change in σ is signalled some way into an assessment period, the change may have actually taken place during the assessment period, and neither the old σ nor the new σ will be the correct one to use for conformity assessment. Using the old σ for conformity assessment gives the smaller risk to the specifier, so the producer should retain the old σ for production control until the end of the assessment period to avoid increasing his risk. So that benefit can be taken from the lower standard deviation, the producer may opt to terminate the assessment period after some defined number of test results.

Case 3: When an increase in σ is signalled, the new value should be adopted for production control immediately. As in Case 1, the new σ is likely to be the correct one to use for both production control and conformity assessment. However, using the new σ to assess conformity will increase the producer's risk because the "n" results will have been obtained at a lower target average strength than that given by the new σ. In Case 3, this increase in the producer's risk is limited because the "n" results will be a small part of the ≥ 15 results used to assess conformity. (Note that the actions as given in Table 10 are the same for Cases 1 and 3.)

Case 4: BS EN 206-1 embodies the philosophy that the standard deviation used to assess conformity is known prior to production and therefore it is unreasonable to use the new, larger, σ to assess conformity when most or all of the results in an assessment period relate to concrete produced using a target average calculated using the old, smaller, σ. Consequently, the old σ is used to assess conformity in Case 4. On the day the change in σ is detected, the closure date for the assessment period is fixed as the day the last cubes awaiting testing are tested, and conformity is assessed using the "n" results available at that time.

In all cases, the new value of standard deviation is used in the next assessment period for both production control and conformity.

3.11 Low volume production

BS EN 206-1 is not clear on the issue of low volume production for special individual concretes. Whilst BS EN 206-1 permits the application of the initial production criteria to continuous production, it has no requirement to apply these criteria to concretes that have less than 15 results in an assessment period. Special concretes commonly use at least some of the constituent materials used in the concrete families. In these cases, the special concrete should be linked to the family and the confirmation criteria and the assessment of relationships should provide adequate control. Where this is not possible they should be treated as individual concretes.

When BS EN 206-1 was being drafted the word "and" was often used to include the option "or" which can create confusion to English speakers. Clause 8.2.1.1 of BS EN 206-1: 2001 contains the words *"During continuous production, the producer may adopt the sampling and testing plan and the criteria for initial production"*. Does this clause mean that if the producer opts to use the initial production conformity criteria for continuous production, they also have to test at a higher rate? The alternative interpretation (the "or" option) would mean that the producer could apply the initial production criteria to continuous production at the continuous production rates of testing. This seems reasonable, as there is no sound technical reason why the higher rate of testing should be applied.

In the case of low-volume production, one option is to apply the initial production criteria to this concrete, but this may require high margins and still pose a significant risk of non-conformity. The following is an alternative procedure where the concrete families within a plant are in continuous production. It is based on the assumption that the standard deviation is mainly a function of the plant.

1. Apply the initial production criteria to the first assessment period.

2. For the second and subsequent assessment periods:
    - where n = 1 or 2, apply the individual result criterion;
    - where n is in the range 3 to 6, apply the initial production criteria to the first three and last three results;

- where there are more then 6 test results, apply the criteria for continuous production using the main family standard deviation.

Inspection of Figure 2 shows that where there are over 6 test results, the operational-characteristic does not enter the unsafe region. However the risk to producers is increased where there are low numbers of test results and it is recommended that the producer apply a suitable margin with these concretes to reduce the risk of non-conformity. It can be argued that a high margin is reasonable in these situations to cope with uncertainty associated with a low production rate and the special nature of the individual concrete.

Special concretes are often produced intermittently and tested frequently during these periods of intermittent production. This may give a high level of auto-correlation of the test results and a low standard deviation. The low standard deviation will increase the risk of non-conformity if the initial production criteria are applied and the high level of auto-correlation will increase the risk if the continuous production criteria are applied.

The risk of non-conformity associated with using the initial production conformity criteria and the alternative procedure can be compared by examination of Tables 2 and 6. This shows that there is no simple answer and the option that minimises the risk of non-conformity depends upon the design margin, level of auto-correlation, standard deviation and the number of test results.

4. Conformity of concrete for properties other than strength

4.1 Basis of the method

For properties other than strength, BS EN 206-1 uses the method of attributes to assess conformity based on the running production over the assessment period that shall not exceed 12 months. As an alternative, BS EN 206-1 also permits a requirement based on testing by variables in accordance with ISO 3951 where the acceptance quality limit (AQL) is equal to 4%. There is no equivalent table in ISO 3951 for testing by variables where the AQL is 15% and therefore it is not an option for consistence testing where the AQL is 15%.

The method of attributes counts the number of results that are outside the specified limiting values, class limits or tolerances on target values as appropriate and provided this number is not greater than the acceptance number given in Table 19 of BS EN 206-1: 2001, conformity is confirmed. In addition, each individual result is compared with the maximum allowable deviation given in Table 17 or 18 of BS EN 206-1: 2001 and if it exceeds this value, the individual result is declared as non-conforming.

Tables 11 & 12 show that the percentage of results outside the specified limiting values, class limits or tolerances on target values is not a constant. Higher sample sizes reduce the risk to both the specifier and the producer. Some of the acceptance numbers in Tables 11 & 12 agree with ISO 2859-1: 1999 and others are interpolations. In Table 11 (Table 19a of BS EN 206-1: 2001) the interpolations are acceptable. This cannot be said for some of the interpolations in Table 12 (Table 19b of BS EN 206-1: 2001).

The term “running production” needs clarification. With continual assessment of conformity, production can move from non-conformity to conformity and back to non-conformity. This is clearly an unsatisfactory position for both specifiers and producers. “Running” should be taken to mean random sampling through the assessment period and conformity is established once at the end of the assessment period.

The minimum rates of sampling for the assessment of conformity are given in Tables 17 and 18 of BS EN 206-1: 2001.

Table 11. Permitted percentage of results outside of class limits/ tolerances where Table 19a of BS EN 206-1 applies		
Number of results	**Acceptance number**	**Percentage outside of class limits/ tolerances**
≤ 12	0	0
13 19	1 1	7.7 5.3
20 31	2 2	10.0 6.5
32 39	3 3	9.4 7.7
40 49	4 4	10.0 8.2
50 64	5 5	10.0 7.8
65 79	6 6	9.2 7.6
80 94	7 7	8.8 7.4
95 100	8 8	8.4 8.0
Notes 1. The step changes between two consecutive numbers of results are caused by the structure of Table 19a in BS EN 206-1: 2001. 2. This Table applies to conformity of properties other than compressive strength and consistence.		

Table 12. Permitted percentage of results outside of class limits/ tolerances where Table 19b of BS EN 206-1 applies		
Number of results	**Acceptance number**	**Percentage outside of class limits/ tolerances**
≤ 2	0	0
3 4	1 1	33.3 25.0
5 7	2 2	40.0 28.6
8 12	3 3	37.5 25.0
13 19	5 5	38.5 26.3
20 31	7 7	35.0 22.6
32 49	10 10	31.6 20.4
50 79	14 14	28.0 17.7
80 100	21 21	26.3 21.0
Notes 1. The step changes between two consecutive numbers of results are caused by the structure of Table 19b in BS EN 206-1: 2001. 2. This Table applies to conformity of consistence.		

4.2 Assessment periods for properties other than strength

The producer is free to select assessment periods for properties other than strength and they need not be the same for each property. As consistence is likely to be measured each time samples are taken for strength testing, aligning the assessment periods may be appropriate. A similar logic could be followed for density of lightweight concrete. However other properties such as minimum cement content, maximum w/c ratio and air content, have different frequencies of testing and other factors should influence the setting of the acceptance period.

Table 11 shows that if the number of results is ≤ 12, no result is permitted outside of the class limits or tolerances on target value. Consequently avoid assessment period with less than 13 results. A reasonable assessment period would be 20 results for all these properties except for maximum chloride content, see **4.3.6**.

4.3 Conformity requirements for properties other than strength and consistence

4.3.1 General

The conformity requirements for properties other than strength and consistence are spread in various clauses in BS EN 206-1. Class limits are given in clause 4, tolerances on target values in clause 5 and maximum deviations from these class limits or tolerances given in Table 17 of BS EN 206-1: 2001. Table 13 combines these requirements and gives the number of results that have to fall within the class limits or tolerances on target values where the assessment period is defined as 20 consecutive non-overlapping results. If a different assessment period is selected, the last column of Table 13 is not applicable.

Where limits are not given in Table 17 of BS EN 206-1: 2001, the specification may introduce limits. Only exceptional cases would warrant the introduction of additional limits. It should be noted that this permission is to introduce limits where none are given in Table 17 of BS EN 206-1: 2001, not introduce different limits to those given.

Comment is given in the following sub-sections on some of these requirements.

4.3.2 Density of heavyweight concrete

There are no density classes for heavyweight concrete and therefore it will be specified as a target density. BS EN 12390-7: *Testing hardened concrete – Part 7: Density of hardened concrete*, permits three conditions for measuring density, as-received, water saturated and oven-dried. The definitions of heavyweight concrete are based on the oven-dry condition and consequently this condition should be assumed unless another condition is specified.

There is no upper limit for individual results, but there is an upper tolerance limit of +100 kg/m^3 on the target value. There is a lower tolerance limit on the target value of –100 kg/m^3 and a lower limit for individual results of –130 kg/m^3.

Table 13. Conformity requirements for properties other than strength and consistence

Property	Individual criterion	Class limits/ tolerances on target value	Minimum number of results within class limits/ tolerances per 20 consecutive non-overlapping results
Density of heavyweight concrete	≥ target density – 130 kg/m^3	≥ target density – 100 kg/m^3 ≤ target density +100 kg/m^3	18
Density of lightweight concrete where specified as a target value	≥ target density – 130 kg/m^3 ≤ target density + 130 kg/m^3	≥ target density – 100 kg/m^3 ≤ target density +100 kg/m^3	18
Lightweight concrete classes			
D1,0	≥ 770, ≤ 1030 kg/m^3	≥ 800, ≤ 1000 kg/m^3	18
D1,2	> 970, ≤ 1230 kg/m^3	> 1000, ≤ 1200 kg/m^3	18
D1,4	> 1170, ≤ 1430 kg/m^3	> 1200, ≤ 1400 kg/m^3	18
D1,6	> 1370, ≤ 1630 kg/m^3	> 1400, ≤ 1600 kg/m^3	18
D1,8	> 1570, ≤ 1830 kg/m^3	> 1600, ≤ 1800 kg/m^3	18
D2,0	> 1770, ≤ 2030 kg/m^3	> 1800, ≤ 2000 kg/m^3	18
W/C ratio (designed concrete)	≤ maximum w/c ratio + 0.02	≤ maximum w/c ratio	18
W/C ratio (prescribed concrete)	Specified value ± 0.04	Specified value ± 0.04	18
Cement content (designed concrete)	≥ minimum cement content – 10 kg/m^3	≥ minimum cement content	18
Cement content (prescribed concrete)	≥ 97% specified cement content – 10 kg/m^3	≥ 97% specified cement content ≤ 103% specified cement content	18
Air content specified as a minimum value	≥ specified air content – 0.5% ≤ specified air content + 5.0%	≥ specified air content ≤ specified air content + 4.0%	18
Chloride content of concrete	≤ maximum chloride content	≤ maximum chloride content	20 i.e. all results ≤ maximum chloride content[1)]

Notes
[1)] See **4.3.6**.

4.3.3 Density of lightweight concrete

This may be specified by a density class from Table 9 of BS EN 206-1: 2001 or by target density. Density class is based on the oven-dry condition when tested in accordance with BS EN 12390-7. Where concrete is specified by density class and the average concrete density for the constituent materials to be used is near a class limit, it is recommended that the producer proposes to supply to a target density.

Example 9
A density class of D2,0 has been specified and, say, the average density of a suitable lightweight concrete is 1830 kg/m^3. The class limits are ³ 1800 and £ 2000 kg/m^3 with individual results being ³ 1770 and £ 2030 kg/m^3. If the specification were to be changed to a target density of 1830 kg/m^3, the tolerances on the target value are ³ 1730 and £ 1930 kg/m^3 with individual results being ³ 1700 and £ 1960 kg/m^3.

The definitions of lightweight concrete are based on the oven-dry condition and consequently where a target density is specified, the oven-dry condition should be assumed unless another condition is specified.

4.3.4 Maximum w/c ratio and minimum cement content

Clause 5.4.2 of BS EN 206-1: 2001 gives the methods of verification of conformity to specified maximum water/cement ratio and minimum cement content.

The reference method for the determination of cement content is by inspection of the autographic records or, where there is no autographic recorder, by inspection of the production records. Conformity is established using the method of attributes and the single result criterion is that the determined cement content shall not be less than 10 kg/m^3 below the specified minimum cement content. For most results, the determined cement content has to be equal to or higher than the specified minimum cement content, see Table 13.

With prescribed concrete, the target cement content is specified and not the minimum. Clause 8.3 of BS EN 206-1: 2001 requires this to be batched within ± 3% and Table 17 of BS EN 206-1: 2001 allows a small percentage of the results to be within the (target cement content - 3%) and the (target cement content – 3% - 10kg/m^3).

The reference method for determination of water/cement ratio is by calculation using the determined cement content and the effective water content (see 5.4.2 of BS EN 206-1: 2001). Conformity is established using the method of attributes and the single result criterion is that the determined water/cement ratio shall not be greater than 0.02 above the specified maximum value.

The requirements for the w/c ratio of prescribed concrete are given in 8.3 of BS EN 206-1: 2001. The ± 0.04 of the specified value should be taken as the tolerance on the specified value to which the maximum allowed deviation of single test results given in Table 17 of BS EN 206-1: 2001 apply.

Clause 8.2.3.2 of BS 8500-2: 2001 provides an alternative method for demonstrating conformity to the specified maximum water/cement ratio and minimum cement content. In principle, the strengths associated with the maximum water/cement ratio and minimum cement content become the required characteristic strengths associated with these criteria. The highest characteristic strength from those needed to satisfy the strength class, the maximum water/cement ratio and the minimum cement content becomes the characteristic strength on which conformity of the concrete is based. This alternative method requires the target strength to have a margin of at least 2 standard deviations.

For the following analysis, the following approximations are made:

25 kg/m^3 change in cement content ≅ 5 N/mm^2 change in cube strength;

0.05 change in water/cement ratio ≅ 5 N/mm^2 change in cube strength.

On the basis of these relationships, the single result criteria transpose to:

Maximum w/c ratio + 0.02 ≅ $f_{ck} – 2$;

Minimum cement content – 10 kg/m^3 ≅ $f_{ck} – 2$.

This is less severe than the (f_{ck} – 4) permitted for the single result criterion for strength.

Assuming a standard deviation of 4.0 N/mm^2, the required margin of 2 standard deviations gives:

Target strength = f_{ck} + 8 ≅ Maximum water/cement ratio – 0.08

≅ Minimum cement content + 40 kg/m^3.

In conclusion, the alternative method of demonstrating conformity to the specified maximum water/cement ratio and the minimum cement content is significantly more onerous than the reference method. However, where strength is the controlling factor in the mix design, this method may have no penalties other than the criterion for single results.

4.3.5 Air content

The approach in BS EN 206-1 is to specify a minimum air content and not a target air content as in BS 5328. The requirements of BS EN 206-1 are effectively the same as BS 5328 although expressed in a different way. In BS EN 206-1 the term “absolute value” is used in context of the conformity requirements. This means that the tolerances are given in differences in air content expressed as a percentage of the total volume.

Example 10
A minimum air content of3.5% is specified. The tolerances on this value are – 0% absolute and + 4% absolute i.e. ³ 3.5% and £ 7.5%. Individual results are required to be ³ 3.0% (3.5% - 0.5% absolute) and £ 8.5% (7.5% + 1.0% absolute).

4.3.6 Chloride content of concrete

Clause 5.2.7 of BS EN 206-1: 2001 gives the method for calculating the chloride content of concrete. For each constituent material, either the maximum permitted or declared chloride ion content is used in the calculation or the chloride ion content is calculated from the last 25 monthly measurements plus 1.64 times the standard deviation of these results. If the calculated value exceeds the maximum value, the mix proportions are adjusted or materials from alternative sources are used. Due to the built-in margin, the fact that the calculated value exceeds the maximum value does not give rise to non-conformity. Conformity by the method of attributes is not applicable with this system.

Conformity by the method of attributes is only applicable to the situation where the chloride ion content is measured on samples taken from the production.

4.4 Conformity criteria for consistence

Consistence may be specified by class or in special cases (not defined) by a target value. Sampling may be representative or taken from the initial discharge. This gives 4 sets of conformity criteria for each of the 4 test methods. Tables 14 to 17 give the conformity criteria where the assessment period is 20 consecutive non-overlapping results. Where the assessment period is defined in a different way, the last column of each table does not apply.

Non-conformity of consistence should be obvious at delivery and consequently where non-conformity is established, the producer needs to review the procedures/ mix designs, but has no requirement to inform the specifier and user.

Table 14. Conformity requirements for slump

Property	Individual criterion	Class limits/ tolerances	Minimum number of results within class limits/ tolerances per 20 consecutive non-overlapping results
Slump classes measured on representative sample			
S1	≤ 60mm	≥ 10mm, ≤ 40mm	13
S2	≥ 40mm, ≤ 110mm	≥ 50mm, ≤ 90mm	13
S3	≥ 90mm, ≤ 170mm	≥ 100mm, ≤ 150mm	13
S4	≥ 150mm, ≤ 230mm	≥ 160mm, ≤ 210mm	13
S5	≥ 210mm	≥ 220mm	13
Slump classes measured on initial discharge			
S1	≤ 70mm	≥ 10mm, ≤ 40mm	13
S2	≥ 30mm, ≤ 120mm	≥ 50mm, ≤ 90mm	13
S3	≥ 80mm, ≤ 180mm	≥ 100mm, ≤ 150mm	13
S4	≥ 140mm, ≤ 240mm	≥ 160mm, ≤ 210mm	13
S5	≥ 200mm	≥ 220mm	13
Slump specified as a target value and measured on representative sample			
Target slump ≤ 40mm	≥ Target slump – 20mm ≤ Target slump + 30mm	Target slump ± 10mm	13
Target slump 50 to 90mm	≥ Target slump – 30mm ≤ Target slump + 40mm	Target slump ± 20mm	13
Target slump ≥ 100mm	≥ Target slump – 40mm ≤ Target slump + 50mm	Target slump ± 30mm	13
Slump specified as a target value and measured on initial discharge			
Target slump ≤ 40mm	≥ Target slump – 30mm ≤ Target slump + 40mm	Target slump ± 10mm	13
Target slump 50 to 90mm	≥ Target slump – 40mm ≤ Target slump + 50mm	Target slump ± 20mm	13
Target slump ≥ 100mm	≥ Target slump – 50mm ≤ Target slump + 60mm	Target slump ± 30mm	13

Table 15. Conformity requirements for Vebe

Property	**Individual criterion**	**Class limits/ tolerances**	**Minimum number of results within class limits/ tolerances per 20 consecutive non-overlapping results**
Vebe classes measured on representative sample			
V0	≥ 27	≥ 31 seconds	13
V1	≤ 32s, ≥ 17s	30 to 21 seconds	13
V2	≤ 22s, ≥ 7s	20 to 11 seconds	13
V3	≤ 12s, ≥ 2s	10 to 6 seconds	13
V4	≤ 7s, ≥ 0s	5 to 3 seconds	13
Vebe classes measured on initial discharge			
V0	≥ 25s	≥ 31 seconds	13
V1	≤ 34s, ≥ 15s	30 to 21 seconds	13
V2	≤ 24s, ≥ 5s	20 to 11 seconds	13
V3	≤ 14s, ≥ 0s	10 to 6 seconds	13
V4	≤ 9s, ≥ 0s	5 to 3 seconds	13
Vebe specified as a target value and measured on representative sample			
Target value ≥ 11 seconds	≥ Target value– 7s ≤ Target value + 5s	Target value ± 3 seconds	13
Target value 10 to 6 seconds	≥ Target value – 6s ≤ Target value + 4s	Target value ± 2 seconds	13
Target value ≤ 5 seconds	≥ Target value – 5s ≤ Target value + 3s	Target value ± 1 second	13
Vebe specified as a target value and measured on initial discharge			
Target value ≥ 11 seconds	≥ Target value – 9s ≤ Target value + 7s	Target value ± 3 seconds	13
Target value 10 to 6 seconds	≥ Target value – 8s ≤ Target value + 6s	Target value ± 2 seconds	13
Target value ≤ 5 seconds	≥ Target value – 5s ≤ Target value + 5s	Target value ± 1 second	13

Table 16. Conformity requirements for degree of compactability			
Property	**Individual criterion**	**Class limits/ tolerances**	**Minimum number of results within class limits/ tolerances per 20 consecutive non-overlapping results**
Degree of compactability classes measured on representative sample			
C0	≥ 1.41	≥ 1.46	13
C1	≤ 1.48, ≥ 1.21	1.45 to 1.26	13
C2	≤ 1.28, ≥ 1.06	1.25 to 1.11	13
C3	≤ 1.13, ≥ 0.99	1.10 to 1.04	13
Degree of compactability classes measured on initial discharge			
C0	≥ 1.39	≥ 1.46	13
C1	≤ 1.50, ≥ 1.19	1.45 to 1.26	13
C2	≤ 1.30, ≥ 1.04	1.25 to 1.11	13
C3	≤ 1.15, ≥ 0.97	1.10 to 1.04	13
Degree of compactability specified as a target value and measured on representative sample			
Target value ≥ 1.26	≥ Target value – 0.15 ≤ Target value + 0.13	Target value ± 0.10	13
Target value 1.25 to 1.11	≥ Target value – 0.13 ≤ Target value + 0.11	Target value ± 0.08	13
Target value ≤ 1.10	≥ Target value – 0.10 ≤ Target value + 0.08	Target value ± 0.05	13
Degree of compactability specified as a target value and measured on initial discharge			
Target value ≥ 1.26	≥ Target value – 0.17 ≤ Target value + 0.15	Target value ± 0.10	13
Target value 1.25 to 1.11	≥ Target value – 0.15 ≤ Target value + 0.13	Target value ± 0.08	13
Target value ≤ 1.10	≥ Target value – 0.12 ≤ Target value + 0.10	Target value ± 0.05	13

Table 17. Conformity requirements for flow			
Property	**Individual criterion**	**Class limits/ tolerances**	**Minimum number of results within class limits/ tolerances per 20 consecutive non-overlapping results**
Flow classes measured on representative sample			
F1	≤ 370mm	≤ 340mm	13
F2	≥ 335mm, ≤ 440mm	350 to 410mm	13
F3	≥ 405mm, ≤ 510mm	420 to 480mm	13
F4	≥ 475mm, ≤ 580mm	490 to 550mm	13
F5	≥ 545mm, ≤ 650mm	560 to 620mm	13
F6	≥ 615mm	≥ 630mm	13
Flow classes measured on initial discharge			
F1	≤ 380mm	≤ 340mm	13
F2	≥ 325mm, ≤ 450mm	350 to 410mm	13
F3	≥ 395mm, ≤ 520mm	420 to 480mm	13
F4	≥ 465mm, ≤ 590mm	490 to 550mm	13
F5	≥ 535mm, ≤ 660mm	560 to 620mm	13
F6	≥ 605mm	≥ 630mm	13
Flow specified as a target value and measured on representative sample			
All target flow diameters	≥ Target flow – 45mm ≤ Target flow + 60mm	Target flow ± 30mm	13
Flow specified as a target value and measured on initial discharge			
All target flow diameters	≥ Target flow – 55mm ≤ Target flow + 70mm	Target flow ± 30mm	13

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Appendix A: Basis for the analysis of the risks associated with the criteria for initial production

Computer simulation was used to estimate the risks of non-conformity. The program used a random number generator linked to input of the required mean strength and the standard deviation of the test results for a steady state normal distribution.

Two distributions of results were analysed:

- a steady state normal distribution;

- a random castellated distribution judged [Barber & Sym, 1983] to simulate the typical distribution of concrete results. This is a basic normal distribution with the superimposition of a random change in mean with a standard deviation of 2 N/mm^2 occurring with a probability of 0.15.

Assessments were carried out for groups using 10,000 individual results linked to a characteristic strength of 35 N/mm^2. The design mean strengths were based on margins of 1.64, 2.00 and 2.33 standard deviations. These margins would generate nominally 5, 2.3 and 1% respectively of results below the characteristic strength.

Appendix B. Auto-correlation in concrete test results

B.1 Interpretation of auto-correlation

"Auto-correlation" will occur in practice if there is a reason why successive test results should be close together. For example, if several test results are obtained within a short period of time and all on the same mix, they would be expected to be similar. If a producer adopts a test rate such that this is a common occurrence, then his test results are likely to be auto-correlated. (Auto-correlation could be interpreted as an indication that the frequency of testing is unnecessarily high.)

Where production data are plotted as a time series (as in Figure B.1) it may be possible to see that they are auto-correlated. With auto-correlated results, they tend to follow each other, so that they give the impression that the process average is meandering up and down.

Figure B.1 shows data (generated using Taerwe's model) that display varying degrees of auto-correlation. Taerwe's model contains two parameters, a_1 and a_2, that control the amount of auto-correlation in data generated by the model. Figure B.1 shows two examples of data for each of three cases:

a_1 = 0.3 and a_2 = 0.1;

a_1 = 0.4 and a_2 = 0.2;

a_1 = 0.6 and a_2 = 0.2.

These represent progressively greater degrees of auto-correlation.

Auto-correlation is measured by correlation coefficients at different "lags". Thus:

r_1 = correlation between test results "at lag 1", i.e. between results one result apart;
r_2 = correlation between test results "at lag 2", i.e. between results two results apart;
r_3 = correlation between test results "at lag 3", i.e. between results three results apart;
and so on.

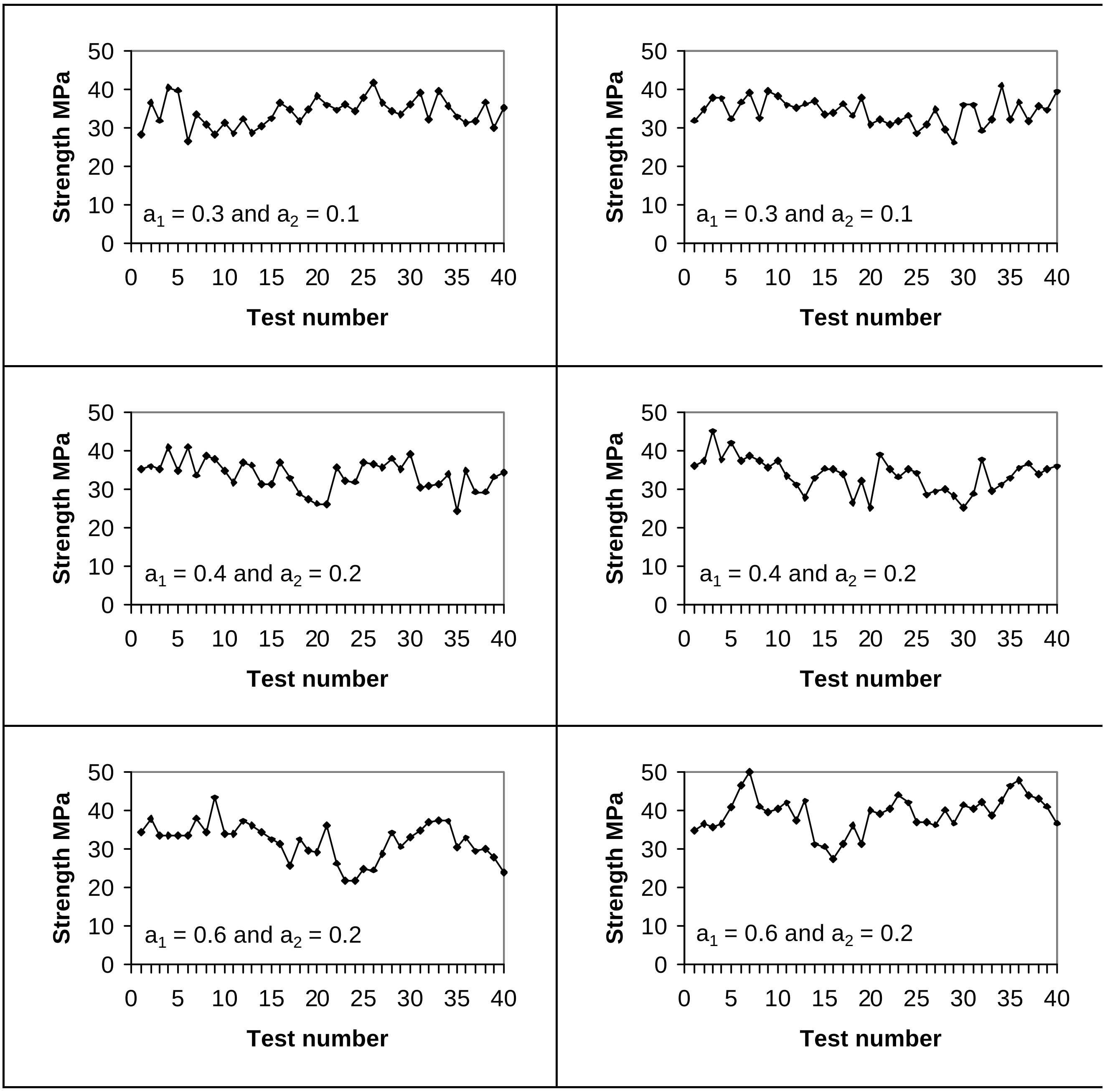
(The relation between these correlation coefficients and the parameters in Taerwe's model is given in B.4.)

Correlation coefficients can take values no larger than 1.0, so a correlation coefficient of 0.0 indicates no auto-correlation (independent results), and a correlation coefficient of 1.0 indicates totally-auto-correlated results.

With simulation, it is possible to show how auto-correlation affects the producer's margin. Table B.1 gives results when conformity is assessed using n = 15 or 35 test results, and the producer wishes to use a margin such that the probability of acceptance is P_a = 98.0%. (Table B.1 amplifies the results shown in Table 6.) With conformity assessed using n = 35 test results, the effect of auto-correlation on the producer's margin is not very dramatic. The effect is larger if conformity is assessed using n = 15 test results.

Figure B.1. Auto-correlated test results generated using Taerwe's model:

$$(X_n - m) = a_1 \times (X_{n-1} - m) + a_2 \times (X_{n-2} - m) + e_n$$



B.2 Confidence limits for correlation coefficients

Estimates of correlation coefficients may be calculated from production data by the method set out in B.3.

Approximate 95% confidence limits for these correlation coefficients may be calculated as $\pm 2.0/\sqrt{n}$, where n is the number of test results. (Tables of factors to use to calculate exact confidence limits exist, similar to those for the "t-distribution", but this formula is an adequate approximation for $n > 30$.)

These confidence limits may be used in two ways.

(1) They may be applied to correlation coefficients calculated from production data to show if enough data have been used in the calculation.

For example, if a correlation coefficient of 0.35 is obtained from $n = 30$ test results, then approximate 95% confidence limits are $0.35 \pm 2.0/\sqrt{30} = 0.35 \pm 0.37$. This is not a useful result because the limits are larger than the estimate. This shows that more than 30 results are needed to estimate correlation coefficients.

It is suggested that at least $n = 100$ test results will be needed in practice to obtain useful estimates of correlation coefficients.

(2) A correlation coefficient calculated from production data has to be larger than $2.0/\sqrt{n}$ for one to be able to conclude that there is a statistically significant degree of auto-correlation in the data.

For example, if a correlation coefficient is calculated from $n = 100$ test results, then it has to be larger than $2.0/\sqrt{100} = 0.2$ before it provides convincing evidence that auto-correlation really exists.

Table B.1. The effect of auto-correlation on the producer's margin

The conformity rule is $f_{cm} \geq f_{ck} + 1.48s$. The data are auto-correlated (according to Taerwe's model with parameters a_1 and a_2), the mean is calculated from 15 or 35 test results; and the standard deviation is established beforehand (from 35 test results).

Number of test results used to assess conformity n	Probability of acceptance P_a %	Taerwe's model parameter a_1	Taerwe's model parameter a_2	Auto-correlation coefficient r_1	Auto-correlation coefficient r_2	Percentage below specified characteristic strength q %	Multiplier used to calculate the producer's margin k
15	98.0	0.0	0.0	0.00	0.00	1.7	2.1
15	98.0	0.1	0.0	0.10	0.01	1.5	2.2
15	98.0	0.2	0.0	0.20	0.04	1.4	2.2
15	98.0	0.2	0.1	0.22	0.14	1.2	2.3
15	98.0	0.3	0.0	0.30	0.09	1.2	2.3
15	98.0	0.3	0.1	0.33	0.20	1.0	2.3
15	98.0	0.3	0.2	0.38	0.31	0.7	2.4
15	98.0	0.4	0.0	0.40	0.16	1.0	2.3
15	98.0	0.4	0.1	0.44	0.28	0.8	2.4
15	98.0	0.4	0.2	0.50	0.40	0.5	2.5
15	98.0	0.4	0.3	0.57	0.53	0.4	2.7
35	98.0	0.0	0.0	0.00	0.00	2.4	2.0
35	98.0	0.1	0.0	0.10	0.01	2.3	2.0
35	98.0	0.2	0.0	0.20	0.04	2.1	2.0
35	98.0	0.2	0.1	0.22	0.14	2.0	2.1
35	98.0	0.3	0.0	0.30	0.09	2.0	2.1
35	98.0	0.3	0.1	0.33	0.20	1.8	2.1
35	98.0	0.3	0.2	0.38	0.31	1.5	2.2
35	98.0	0.4	0.0	0.40	0.16	1.8	2.1
35	98.0	0.4	0.1	0.44	0.28	1.5	2.2
35	98.0	0.4	0.2	0.50	0.40	1.2	2.2
35	98.0	0.4	0.3	0.57	0.53	1.0	2.3

B.3 Calculation of auto-correlations

Auto-correlations may be calculated using Excel by the following method.

Step 1

See Table B.2. (Note that only 10 test results are shown in Table B.2 to keep the example simple. In practice, a series of at least 100 test results should be used to calculate auto-correlations.)

Enter the test results and their identification into two columns of an Excel spreadsheet. In Table B.2, the identifications are shown simply as test numbers 1, 2, 3 and so on. The first column of test results should be headed "Lag 0" as shown in Table B.2.

Step 2

Copy the test results into the next few columns of the spreadsheet as shown in Table B.2. Note that the test results are displaced downwards by one cell as one goes from one column to the next.

Add headings to the columns "Lag 1", "Lag 2", "Lag 3", and so on, as shown in Table B.2.

Step 3

Use the "Correlation" function in the menu "Tools/Data analysis" to calculate the auto-correlations:

(1) Set the "Input range" to be the array of test results, including the headings "Lag 0" to "Lag 5". With the data as shown in Table B.2 the input range includes 6 columns (Lag 0 to Lag 5), and 16 rows (the headings plus 15 rows of data).

(2) Select "Grouped by" to be "Columns".

(3) Tick the "Labels in first row" box.

(4) Select a cell for the "Output range" away from the data.

(5) Press "OK".

The auto-correlations will be calculated and presented in a table as shown in Table B.3.

Step 4

The auto-correlations may then be read from the column headed "Lag 0" in the table as:

$r_0 = 1.00$ $r_1 = 0.05$ $r_2 = -0.21$ $r_3 = -0.07$ $r_4 = -0.42$ $r_5 = -0.33$

Table B.2. Example of calculation of auto-correlations						
Test number	**Lag 0**	**Lag 1**	**Lag 2**	**Lag 3**	**Lag 4**	**Lag 5**
1	53.0					
2	47.6	53.0				
3	49.2	47.6	53.0			
4	48.9	49.2	47.6	53.0		
5	48.5	48.9	49.2	47.6	53.0	
6	44.5	48.5	48.9	49.2	47.6	53.0
7	46.6	44.5	48.5	48.9	49.2	47.6
8	41.9	46.6	44.5	48.5	48.9	49.2
9	45.6	41.9	46.6	44.5	48.5	48.9
10	55.3	45.6	41.9	46.6	44.5	48.5
11		55.3	45.6	41.9	46.6	44.5
12			55.3	45.6	41.9	46.6
13				55.3	45.6	41.9
14					55.3	45.6
15						55.3

Table B.3. Auto-correlations calculated from the data in Table B.2						
	Lag 0	**Lag 1**	**Lag 2**	**Lag 3**	**Lag 4**	**Lag 5**
Lag 0	1.00					
Lag 1	0.05	1.00				
Lag 2	-0.21	0.05	1.00			
Lag 3	-0.07	-0.21	0.05	1.00		
Lag 4	-0.42	-0.07	-0.21	0.05	1.00	
Lag 5	-0.33	-0.42	-0.07	-0.21	0.05	1.00

B.4 Taerwe's model

Correlation coefficients may be calculated from the parameters in Taerwe's model as shown in Table B.4. (It will be of interest to compare these correlation coefficients with those calculated from production data to see if the production data behave similarly to results generated by Taerwe's model.)

Table B.4. Auto-correlations for Taerwe's model

Lag	Formula	Correlation coefficient when $a_1 = 0.4$, $a_2 = 0.2$
0	$r_0 = 1.00$	1.00
1	$r_1 = a_1/(1.0 - a_2)$	0.50
2	$r_2 = a_1 \times r_1 + a_2 \times r_0$	0.40
3	$r_3 = a_1 \times r_2 + a_2 \times r_1$	0.26
4	$r_4 = a_1 \times r_3 + a_2 \times r_2$	0.18
5	$r_5 = a_1 \times r_4 + a_2 \times r_3$	0.13
>5	*and so on*	

The parameters of Taerwe's model may be calculated from correlation coefficients using the following formulae, should this ever be necessary:

$$a_1 = \frac{r_1 \times (1 - r_2)}{1 - r_1^2} \qquad a_2 = \frac{r_2 - r_1^2}{1 - r_1^2}$$

B.5 An example

Figure B.2 shows the 127 test results obtained for a concrete family by a concrete plant over a period of six months.

Figure B.3 shows correlation coefficients for the auto-correlation of these data, and compares them with the correlation coefficients for data that follow Taerwe's model (from Table B.4). Lines representing values calculated using the approximate formula for 95% confidence limits for correlation coefficients are shown as $0.0 \pm 2.0/\sqrt{n}$, with $n = 127$, so that the coefficients that are significantly greater than zero can be identified.

For this plant, the correlation coefficients for lags 1 and 2 are statistically significant, but smaller than those for Taerwe's model, so that the degree of auto-correlation is not as large as that expected from Taerwe's model. This plant would have to:

either take account of the auto-correlation when deciding how many test results to collect in an assessment period;

or try to reduce the auto-correlation by not collecting bunches of test results on the same mix.

Figure B.2. 127 test results obtained at a concrete plant over a period of 6 months

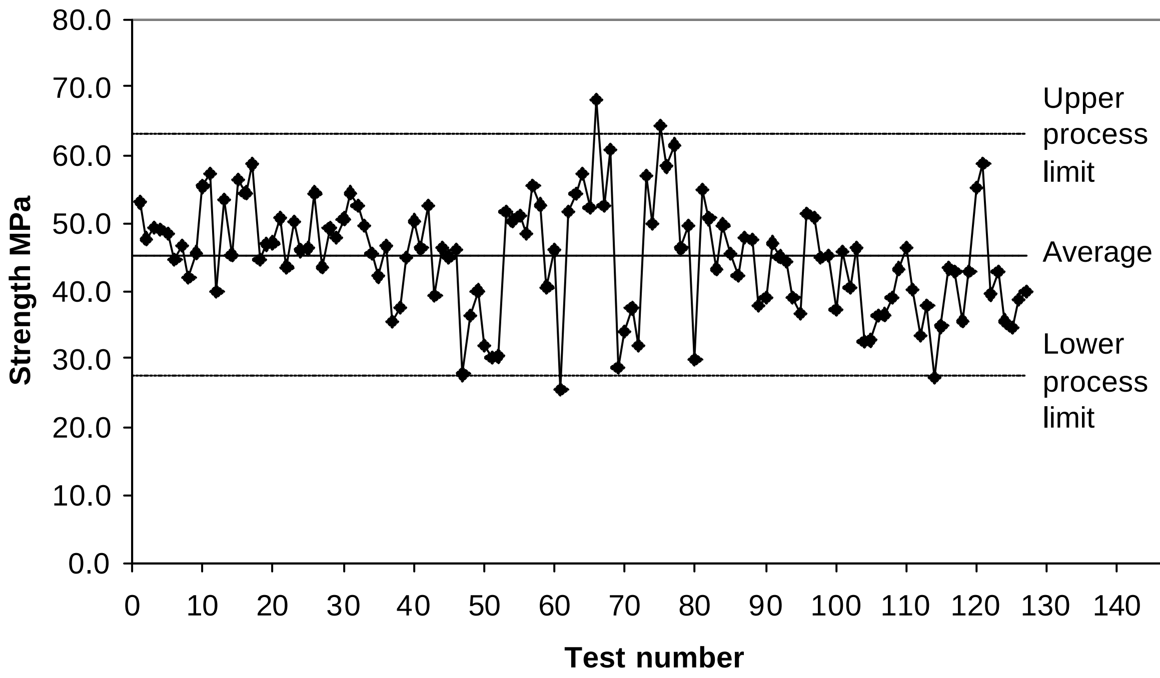
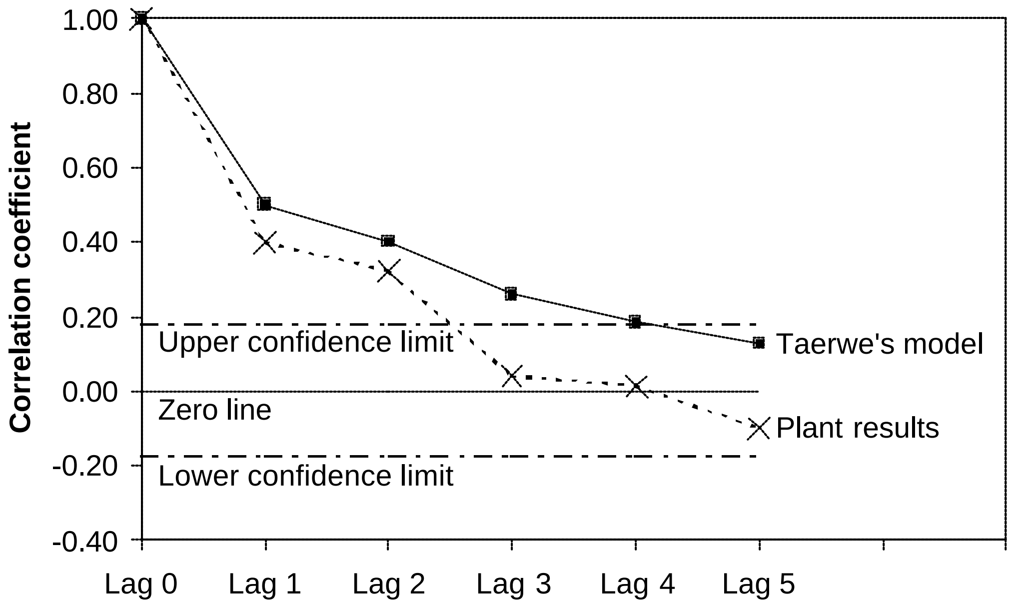


Figure B.3. The auto-correlation of the results in Figure B.2



Appendix C: Derivation of the difference between the target mean strength and the limits for conformity

The target mean strength is given by:

$$f_{ck} + k\sigma_c$$

where σ_c is the current standard deviation.

The conformity criteria can be either:

$$\text{Mean strength} \geq f_{ck} + 1.48\sigma_p \qquad \text{Equation 1}$$

where σ_p is the standard deviation calculated from the previous 35 results,

or, if the new value of the standard deviation, σ_c, is adopted immediately:

$$\text{Mean strength} \geq f_{ck} + 1.48\sigma_c \qquad \text{Equation 2}$$

Case 1

The difference between the target mean strength and the conformity limit based on equation 1 and the new value of the standard deviation being adopted for production is:

$$f_{ck} + k\sigma_c - (f_{ck} + 1.48\sigma_p) \qquad \text{Equation 3}$$

If the change in standard deviation is Δ:

$$\sigma_c = \sigma_p + \Delta$$

substituting and simplifying, Equation 3 becomes:

$$\sigma_p(k - 1.48) + k\Delta \qquad \text{Equation 4}$$

Case 2

The difference between the target mean strength and the conformity limit based on equation 2 is:

$$f_{ck} + k\sigma_c - (f_{ck} + 1.48\sigma_c) \quad = \sigma_c(k - 1.48)$$

Appendix D: Example of the application of the recommendations where the standard deviation changes part way through an assessment period

D.1 Key to the figures

Figures D.1 to D.3 show three sets of data where conformity is normally assessed on groups of 15 results. Figures D.4 to D.6 show the same three sets of data but where conformity is normally assessed on groups of 35 results.

The x-axis shows the dates when conformity is assessed, and each vertical grid line passes through the last point used in an assessment.

The values for the standard deviation are derived from the Cusum control system.

The solid line shows the Target Mean Strength, calculated as the specified characteristic strength for the reference concrete plus two times the standard deviation.

The dashed lines are set at +/-3.0 standard deviations above and below the Target Mean Strength.

The standard deviation used to calculate the Target Mean Strength and the position of the solid lines is that used for production control. Thus the steps in the dashed and solid lines show when this standard deviation changes. According to the rules given in **3.10**, there can be occasions when the Cusum control system signals a change in the standard deviation part way through an assessment period, but the new standard deviation is not adopted for production control until the end of an assessment period is reached. When this happens the steps in the solid and dashed lines coincide with the vertical grid lines.

"Fail" is shown on the Figures when a group of results fails to conform to the BS EN206-1 conformity criterion for mean strength. This has been applied by assuming that the specified characteristic strength of the Reference Concrete is 35.0 N/mm^2.

D.2 Commentary on the Figures D.1 to D.6

Figure D.1. 26 October 1998. The Cusum control system has signalled a reduction in the standard deviation n=12 results into the assessment period. According to the rules for "Case 2", the old standard deviation is retained for production control until the end of the assessment period, and also used to assess conformity for the period.

Figure D.1. 10 February 1999. Similar to the 26 October 1998 event.

Figure D.1. 6 March 2000. The Cusum control system has signalled an increase in the standard deviation just at the end of an assessment period. According to the rules for "Case 4", the new standard deviation is adopted immediately for production control, but the old value is used to assess conformity for the period.

Figure D.2. 16 March 1999. The Cusum control system has signalled a reduction in the standard deviation just one result into the assessment period. According to the rules for "Case 1", the new standard deviation is adopted immediately for production control and also used to assess conformity for the period.

Figure D.2. 1 June 2000. The Cusum control system has signalled an increase in the standard deviation n=8 results into the assessment period. According to the rules for "Case 4", the new standard deviation is adopted for production control immediately, but the old standard deviation is used to assess conformity by applying the BS EN206-1 criterion to the n=8 results. A new assessment period is then started to coincide with the adoption of the new standard deviation for production control.

Figures D.3, D.4 and D.5. These figures contain further examples of changes in the standard deviation like those seen in Figures D.1 and D.2.

Figure D.6. Final assessment period. This shows an example of "Case 3", where an increase in the standard deviation has been signalled by the Cusum control system just n=4 results into the assessment period. The new standard deviation is adopted for production control immediately, and is also used to assess conformity for the period.

Figure D.1. Analysis of data set 1 where "n" is normally 15
Specified characteristic strength = 35 N/mm2, Producer's margin = 2*SD N/mm2

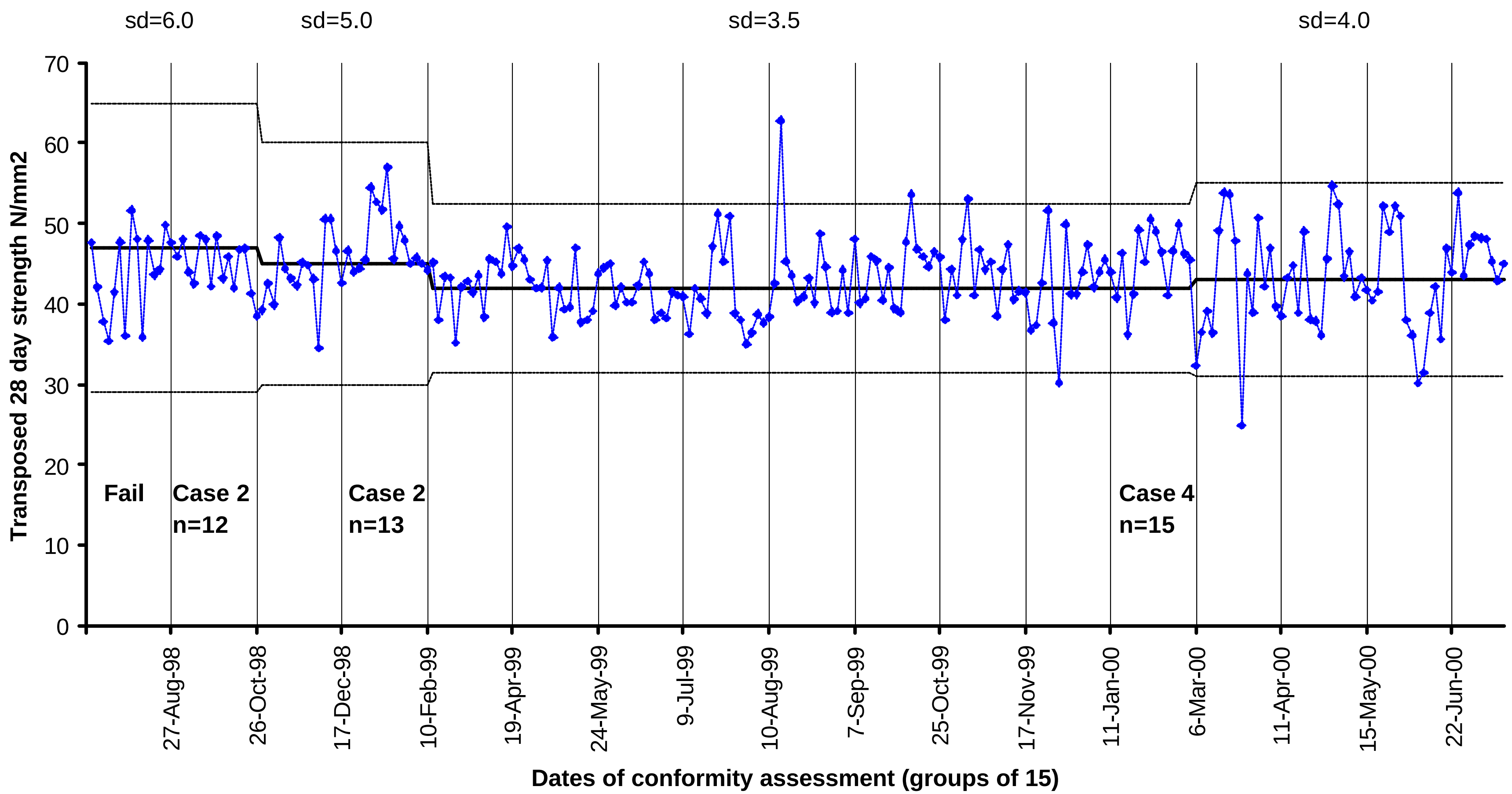


Figure D.2.Analysis of data set 2 where "n" is normally 15
Specified characteristic strength = 35 N/mm², Producer's margin = 2*SD N/mm²

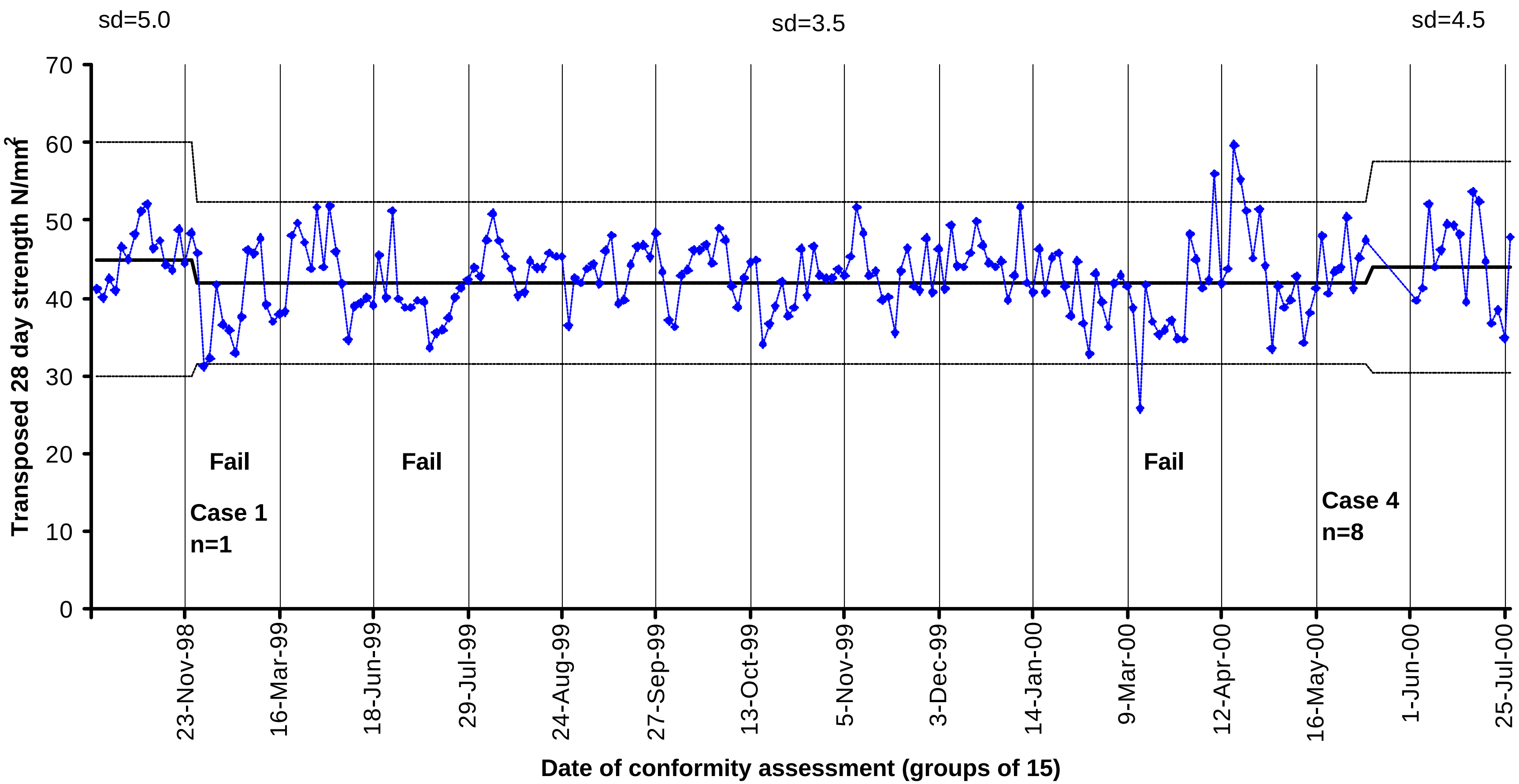


Figure D.3. Analysis of data set 3 where "n" is normally 15
Specified characteristic strength = 35 N/mm^2, Producer's margin = 2*SD N/mm^2

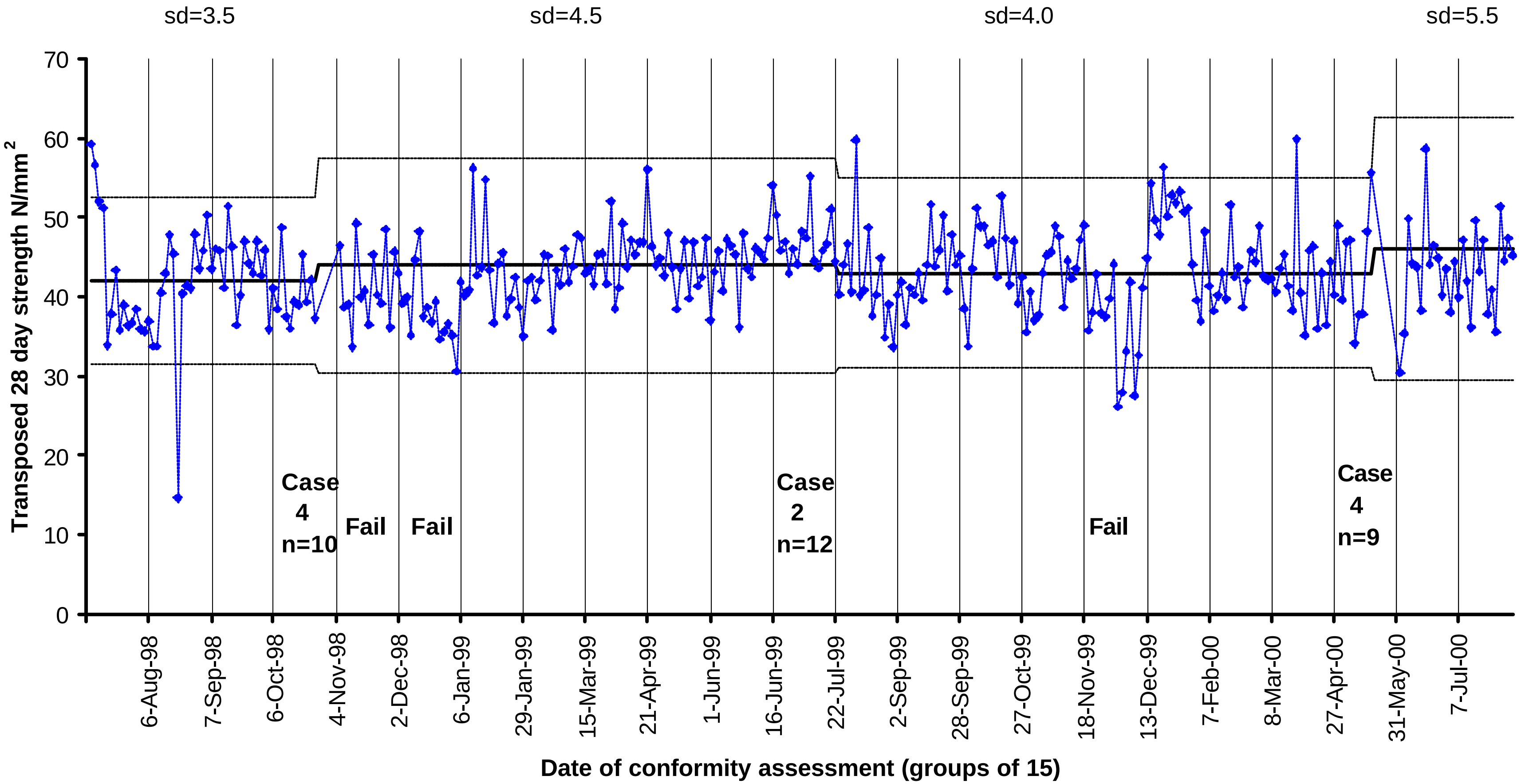


Figure D.4. Analysis of data set 1 where "n" is normally 35
Specified characteristic strength = 35 N/mm^2, Producer's margin = 2*SD N/mm^2

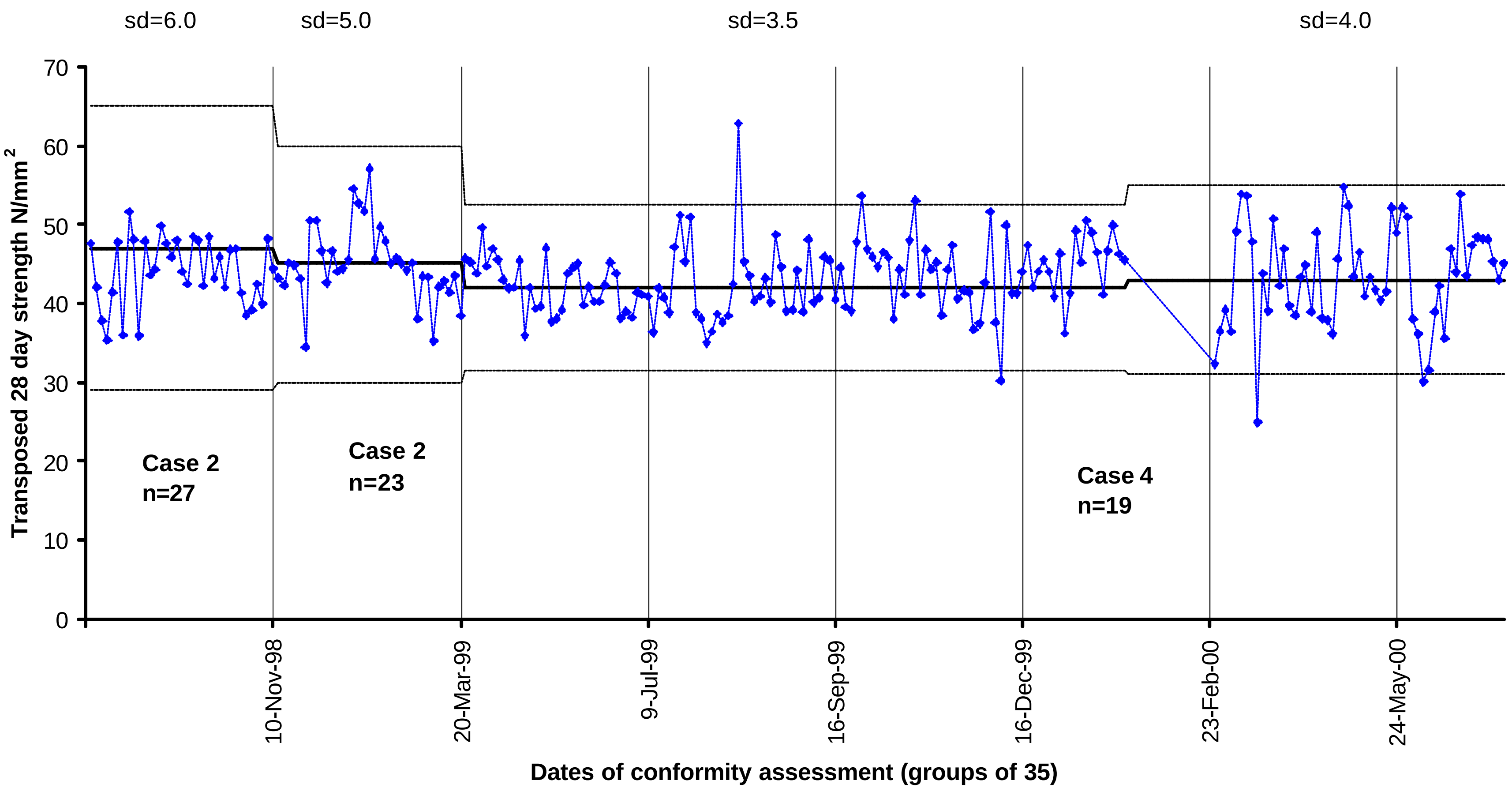


Figure D.5. Analysis of data set 2 where "n" is normally 35
Specified characteristic strength = 35 N/mm², Producer's margin = 2*SD N/mm²

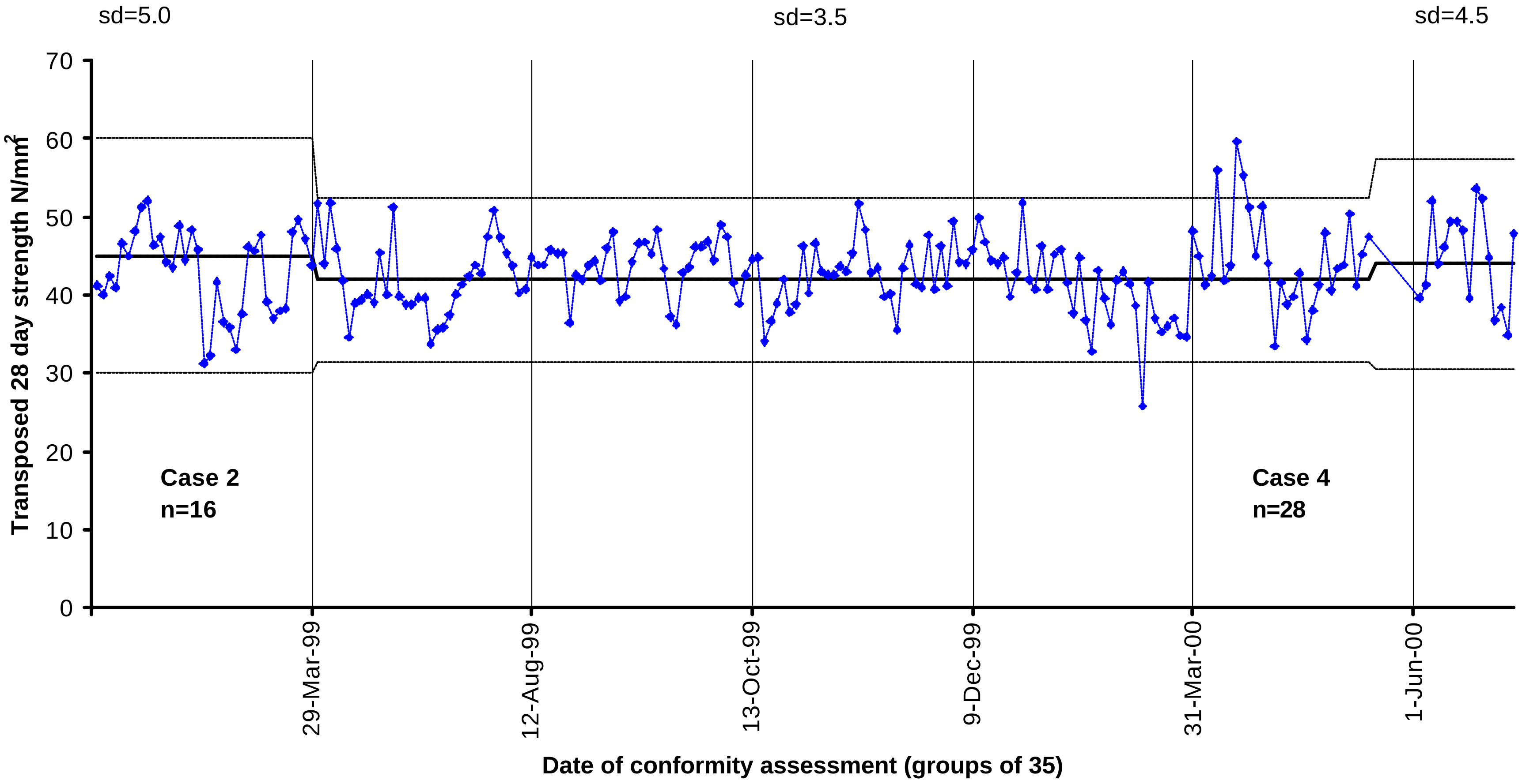


Figure D.6. Analysis of data set 3 where "n" is normally 35
Specified characteristic strength = 35 N/mm², Producer's margin = 2*SD N/mm²