Techniques of quality control

There are two aspects to controlling concrete quality:

1. The avoidance of failures and
2. Reduce variability.

Obviously low variability will be of assistance in avoiding failures.

Equally there will be no failures if there is an adequate margin between the average quality level and the specified minimum.

It is even possible that some of the same factors can fit into both categories, e.g. sand grading is unlikely to be identical from truck to truck but there may be a more substantial change from time to time as extraction location or conditions change.

It is a difference between variability about the same mean value and a change in mean value. If a change in mean value remains undetected it causes an apparent increase in basic variability.

The **continuous basic variability** can be thought of as a feature of the **production process**.
The *early detection* and reversal of occasional *change* is a feature of the control system.

So the control system measures the *basic variability* and detects *change points*.

Apparent *overall variability* is also increased by the *error in testing* or *recording data*.

**Structurally defective and contractually defective**

*Structurally defective* concrete is that which is unable to serve its intended purpose and must be removed from the structure or supplemented in some way. It is absolutely imperative that no such concrete whatever be produced (it is not practicable to allow some to be produced and then attempt to ensure its exclusion from the structure).
**Contractually defective** concrete is that which, while capable of serving its intended purpose, is not quite of the specified quality. A small proportion of such concrete may be incorporated in the structure with little detriment.

There is usually a substantial margin between the two and if no contractually defective concrete is accepted without some **penalty** or substantial expense and inconvenience to the contractor, **no** structurally defective concrete is produced. However, if contractually defective concrete is supplied with **impunity**, structurally defective concrete is likely to follow.
**Factors causing variability**

Graham and Martin (1946) were the first to publish an attempt to locate and quantify sources of variability on an actual project. The project was Heathrow Airport, UK, on which 0.5 million cubic yards of concrete were produced and controlled in an exemplary manner.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Possible range</th>
<th>% of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of cement</td>
<td>2100 psi</td>
<td>48.2%</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td>800 psi</td>
<td>18.4%</td>
</tr>
<tr>
<td>Sampling &amp; making cubes</td>
<td>500 psi</td>
<td>11.5%</td>
</tr>
<tr>
<td>Testing cubes</td>
<td>600 psi</td>
<td>13.8%</td>
</tr>
<tr>
<td>Mixing time</td>
<td>200 psi</td>
<td>4.6%</td>
</tr>
<tr>
<td>Varying SG of aggregate</td>
<td>150 psi</td>
<td>3.5%</td>
</tr>
<tr>
<td>Total variability</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

They concluded that cement was responsible for 48.2% of the variation of strength that occurred at Heathrow. (And therefore that this was not under site engineers’ control).
Types of variation

1. **Random variation** with no assignable cause. As control improves, the extent of such variation diminishes and an assignable cause is anticipated for any substantial variation.

2. **Isolated or non-sustained changes** having an assignable cause, e.g. an isolated high slump producing a reduced strength.

3. **Sustained changes** in mean strength.

4. **Changes due to testing procedures** (i.e. false changes) which again can be either sustained or isolated

[Diagram showing changes in mean strength with change points and basic variability]
The typical extent of a change is of the order of 2 to 5 MPa (which probably only means that changes of much less than 2 MPa are not generally detectable)

**Quality assurance**

QA is necessarily pre-planned and documented as to both procedures and their execution. QA provides an assurance, in the form of certified records, that the established QC procedures have been carried out in full. It is intended that the system should be sufficiently comprehensive to necessarily ensure the acceptable quality of the output. While QC may also include the same procedures, this is not necessarily the case.

The days of controlling by reacting to whether or not failures are being experienced are hopefully long past (although of course failures cannot be ignored).

Statistical analysis is used to establish whether production has been satisfactory over some period of time.
**Pareto’s principle**

**Vilfredo Pareto** was an Italian economist (1848–1923) engaged in traveling from town to town in an attempt to identify the country’s sources of wealth. He came to realize that the 4 or 5 wealthiest men in a town almost invariably controlled Pareto’s principle over half its wealth. Therefore his survey could most efficiently be conducted by first seeking out the right men and then asking his questions, rather than attempting a random survey of a few per cent of the population.

This principle is of great value in QC of all kinds, certainly including concrete QC, that is, while there may be 100 or more factors causing variability in concrete strength, 70 or 80% of the total variability is often caused by only 2 or 3 of the 100 possible causes. Often only one single factor will cause more than half of the total variability. It will not be the same principal factor in all cases, nor even the same ‘short list’ of 2 or 3, but the following list is likely to include the major factors in most cases:

1 Slump (misjudgment or deliberate variation)

2 Temperature

3 Air content
4 Fine aggregate silt content

5 Fine aggregate organic impurity

6 Fine aggregate grading

7 Coarse aggregate dust content

8 Coarse aggregate bonding characteristics

9 Cement quality

10 Admixture quality, dosage or interaction

11 Fly-ash quality (especially carbon content)

12 Time delays

13 Coarse aggregate strength

14 Fine aggregate grain quality

15 Sampling and testing procedures (namely: segregation, compaction, curing, capping, centering in testing machine, lubrication of spherical seating, planeness of platens, stiffness of machine frame, alignment of ram and spherical seating, rate of loading, operator fear of explosive failure or desire to maintain specimen in one piece).
The mechanism of the effect on strength is via increased water requirement in many cases, specifically in items 1, 2, 4, 6, 7 and 12.

**Finding the principal causes of variability**

It may be fairly obvious in some cases which of these causes is likely to predominate.

Rather than make a guess, or spread control either too thinly or too expensively over too many factors, it is better to follow the advice of the master of QC, J. M. Juran (Juran, 1951) and “ask the process”.

This can be done in *two distinct stages*:

1. Compare actual and predicted strength and if there is a discrepancy, track it down. This may provide a firm lead on what is most likely to affect strength on the particular project.

2. Monitor strength and a selected number of ‘related variables’ using Cusum analysis.

The selected variables will usually include slump, air content and concrete temperature. If reasonably reliable water content is available from any source, this is certainly very important. The strength results will be particularly examined for pair differences and 7 to 28 day gain as a kind of internal consistency test.
It is important to realize that low strengths do not ‘just happen’ they are usually caused by either high water content, low cement content, incomplete compaction, defective curing and testing, or reduced cement quality.

The art or science of QC is to establish which of these is the cause by a logical examination of the pattern of results.

**For example:**

Difference in cement quality from one delivery to another is not a reasonable explanation for isolated low results or for a period of low strength extending for a shorter or longer period than that between the two deliveries.

High water content will not explain low 28 day results if 7 day results from the same sample were normal. Certainly the possibility that the concrete is normal and the testing defective, should be adequately considered as it is frequently encountered.
CONTROL CHARTS

Plotting results on a graph provides an appreciation of a situation far more rapidly than a table of results.


The purpose of a control chart is to detect any departure of the process from the “in control” state; any such movement is said to be due to assignable causes of variation. The decision making aspect of control charts is centred on the problem of deciding whether a sample observation is due only to the expected, inherent unassignable causes of variation (in which case no action is required) or whether it is due to the effect of some additional, assignable variation (in which case corrective action is usually required).’

Shewhart control charts

There are two main types of Shewhart (1931) control charts. These are:

I. Charts for variables and
II. Charts for attributes.

The latter type, which is concerned with counting the number of samples which are defective, or have some other particular attribute, is not used in concrete quality
control. Charts for **variables** are concerned with **variations in measured characteristics**. This is the kind of chart which is useful in concrete quality control.

![Shewhart control chart](image)

Shewhart control chart.

The concept first proposed by Shewhart in 1924 (Shewhart, 1931) was to plot a chart (see the figure below) with time or sample number as a horizontal axis and the value of a measured parameter (e.g. strength) as the vertical axis. Horizontal limit lines were drawn on the chart. It is important to understand that these limits were not **specification limits**. Their function was not to indicate whether the result plotted was **acceptable**, but to indicate whether it was **unusual**. The intention was not to decide whether to accept or reject the product represented by the result, but
to detect whether there has been any **change in the process** producing the product. This concept has proved very difficult to promote but is still the basis needed to achieve good quality control.

The limits were calculated from a statistical analysis of previous results. Statistical tables provide factors by which the standard deviation is to be multiplied to calculate the limit outside which a selected proportion of the individual results can be expected to lie. A factor of 3.09 (effectively 3.00) times the standard deviation ($\sigma$) gives the 1 in 1000 limit, i.e. theoretically one result in every 1000 should be expected to differ from the mean of all results by more than three times the standard deviation of those results. Putting this another way, if a result outside the 3$\sigma$ limit occurs, there is only one chance in 1000 that the mean strength and standard deviation of current production remains unchanged. It may be of interest to show the (+ and −) 3$\sigma$ limits on a control chart as an indication that **a change definitely has occurred.** However it would take a very large number of results (on average almost 500) before a small change in mean strength would cause a result to infringe such a limit. Closer limits are therefore selected to give a faster, if less certain, indication of a change, e.g. if the lines are drawn a distance 1.65$\times$ the standard deviation above and below the mean line, there will be one chance in 20 of a result lying outside each limit without a change having occurred. Such a result can be taken as a **warning** that a change **may** have occurred.
Cusum charts

‘Cusum’ is a contraction of ‘Cumulative Sum’ (of the difference between each successive result and a target value, preferably the previous mean). By definition the cumulative sum of differences from the mean is zero. So if the previous mean continues to be the mean, a graph of the cusum will have temporary divergences (the extent depending upon the variability of the concrete) but will remain basically horizontal.

However if the mean changes, even by a very small amount, each successive point on the graph will, on average, differ from the previous point by this amount. The graph will still show the same temporary divergences about a straight line, but the line will now make an angle with the horizontal and the angle will be an accurate measure of the change in the mean, and the point of intersection of the best straight line before and after the change will pinpoint the time of occurrence (Fig. 2).
The mathematical significance of any particular change of slope can be accurately and simply assessed by the use of a ‘V-mask’ (Fig. 3).

The lead point of the V is placed over the last point on the graph and if the graph cuts the V, a significant change has occurred. The V-mask can be a sheet of transparent material carrying a whole family of Vs, each indicating a different degree of significance.

Whether the cusum technique is effective or not depends on a number of factors:

1. The most basic factor is whether changes in mean tend to be isolated ‘step’ changes or to gradually increase in magnitude.
2 The change points will be much more clearly visible if the general scatter of points is reduced.

3 A significant change, as previously explained, results in a change of slope. An isolated error, or non-significant change, appears as an offset to the slope and can usually be readily discounted by eye examination (Fig. 4).

![Figure 4: Cusum graph exhibiting both real and non-significant changes.](image)

4 Obviously the number or frequency of tests and the time delay between testing and interpretation are also significant factors in the rapid detection of change.

5 Finally, as previously explained, the confirmation of change detection need not rely on the mathematical analysis of results on the variable in question. If cusum graphs of ‘related variables’ such as density, slump and temperature are also
drawn, and show a change explaining the change in the primary variable at the same point in time, then the change is certainly confirmed.

**Example:** The following results are the concrete strength for the previous and current months. Draw Cusum control chart and indicate the change point?

<table>
<thead>
<tr>
<th>Strength</th>
<th>Previous month (N/mm²)</th>
<th>Current month (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No.</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Solution:**

\[ \bar{x} = \frac{(34+35+32+33+35.......+34)}{10} = 34 \text{ N/mm}^2 \]

<table>
<thead>
<tr>
<th>previous month</th>
<th>Current month</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_i )</td>
<td>( x_i - \bar{x} )</td>
</tr>
<tr>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>32</td>
<td>-2</td>
</tr>
<tr>
<td>33</td>
<td>-1</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>37</td>
<td>3</td>
</tr>
<tr>
<td>33</td>
<td>-1</td>
</tr>
<tr>
<td>32</td>
<td>-2</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>34</td>
<td>0</td>
</tr>
</tbody>
</table>
Home work:

Re-solve the previous example but with the following data?

<table>
<thead>
<tr>
<th>Strength</th>
<th>Previous month (N/mm²)</th>
<th>Current month (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>29 30 27 28 30 28 27 30 29</td>
<td>28 27 28 29 27 28 26 27 26 25</td>
</tr>
<tr>
<td>Sample No.</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td>1 2 3 4 5 6 7 8 9 10</td>
</tr>
</tbody>
</table>
Quality control for fresh concrete:

Quality control guidance on *placing and compaction* is given in the following [BSI 8110-1-97].

a) Care should be taken to avoid displacing reinforcement, tendon, ducts and anchorages, or formwork, and damage to the faces of formwork, particularly when the concrete is allowed to fall freely through the depth of lift. In such cases a cohesive, non-segregating mix is required. The depth of lift to be concreted should be agreed and consideration given to the effect of lift height in massive sections on the temperature rise of the concrete.

b) Concrete should not be moved across the surface of open textured formwork by means of internal vibration as this may lead to localized honey-combing and inadequate bonding between the concrete and the reinforcement.

c) No concrete should be placed in flowing water. Under water, concrete should be placed in position by tremies or by pipeline from the mixer and never allowed to fall freely through the water unless specifically designed for this purpose.

d) Concrete should be thoroughly compacted by vibration or other means during placing, and worked around the reinforcement, tendons or duct formers, embedded fixtures and into corners of the formwork to form a solid void-free mass having the required surface finish. When vibrators are used, vibration should be applied until the expulsion of air has practically ceased and in a manner that does not promote segregation. Over-vibration should be avoided to minimize the risk of forming a weak surface layer.
e) Air-entraining admixtures and plasticizing admixtures can improve the handling and placing characteristics of fresh concrete.

f) When external vibrators are used, the design of formwork and disposition of vibrators should be such as to ensure efficient compaction and to avoid surface blemishes.

g) Where permanent formwork is incorporated in the structure, its energy absorption should be taken into account when deciding on the method of vibration to be used. Extra care is required to ensure full compaction of the concrete since this cannot be checked when the formwork is removed.

Quality control guidance on curing is given in the following [BSI 8110-1-97].

Curing is the process of preventing the loss of moisture from concrete whilst maintaining a satisfactory temperature regime and preventing the development of high temperature gradients within the concrete.

Curing and protection should start immediately after the compaction of the concrete to protect it from:
a) premature drying out, particularly by solar radiation and wind;
b) leaching out by rain and flowing water;
c) rapid cooling during the first few days after placing;
d) high internal thermal gradients;
e) low temperature or frost;
f) vibration and impact which may disrupt the concrete and interfere
with its bond to the reinforcement.

**Minimum periods of curing and protection**

Surfaces should normally be cured for a period not less than that given in Table 6.1. Depending on the type of cement, the ambient conditions and the temperature of the concrete, the appropriate period is taken from Table 6.1 or calculated from the last column of that table. During this period, no part of the surface should fall below a temperature of 5 °C.

<table>
<thead>
<tr>
<th>Type of cement</th>
<th>Ambient conditions after casting</th>
<th>Minimum periods of curing and protection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Days</td>
</tr>
<tr>
<td>CEM I 42.5 or CEM I 52.5 to BS EN 197-1</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>SRPC 42.5 to BS 4027</td>
<td>Poor</td>
<td>6</td>
</tr>
<tr>
<td>All cements indicated in Table A.6 of BS 8500-1:2006 except for CEM I 42.5 or CEM I 52.5 to BS EN 197-1, SRPC 42.5 to BS 4027 and supersulfated cement.</td>
<td>Average</td>
<td>6</td>
</tr>
<tr>
<td>All</td>
<td>Poor</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 6.1 — Minimum periods of curing and protection**

<table>
<thead>
<tr>
<th>Type of cement</th>
<th>Ambient conditions after casting</th>
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<td>Average</td>
<td>6</td>
</tr>
<tr>
<td>All</td>
<td>Poor</td>
<td>10</td>
</tr>
</tbody>
</table>

**NOTE 1**  Abbreviations for the type of cement used are as follows:

- CEM I 42.5: Portland cement (class 42.5) (see BS EN 197-1);
- CEM I 52.5: Portland cement (class 52.5) (see BS EN 197-1);
- SRPC 42.5: Sulfate-resisting Portland cement (class 42.5) (see BS 4027).

**NOTE 2**  Ambient conditions after casting are as follows:

good: damp and protected (relative humidity greater than 80%, protected from sun and wind);
average: intermediate between good and poor;
poor: dry or unprotected (relative humidity less than 50%, not protected from sun and wind).
Curing methods

The most common methods of curing are:

a) maintaining formwork in place;
b) covering the surface with an impermeable material such as polyethylene, which should be well sealed and fastened;
c) spraying the surface with an efficient curing membrane;
d) covering the surface with a damp absorbent material;
e) by continuous or frequent applications of water to the surface, avoiding alternate wetting and drying and the application of cold water to warm concrete surfaces;

NOTE  Methods d) and e) should not be used when there is the possibility of freezing conditions.
Quality control requirements for concreting in cold weather

In cold weather, consideration should be given to the following:

a) prevention of freezing of the immature concrete;
b) extended stiffening times which may lead to increased formwork pressures and delays in finishing;
c) low rate of concrete strength development which may lead to delays in subsequent construction operation such as striking formwork.

To provide confidence that the concrete can resist permanent damage from freezing the temperature of the concrete should, at no point, fall below 5 °C until the concrete in the structural element reaches a strength of 5 N/mm² nor should water curing be applied in conditions where freezing of the concrete is anticipated. This should apply regardless of the air temperature at the point of placing. The 5 N/mm² strength requirement may be assessed by tests on cubes cured, as far as possible, under the same conditions as the concrete in the element (see 6.1).

Measures which can be adopted for fresh concrete:

a) increase the specified minimum temperature of the fresh concrete

b) incorporation of an accelerating admixture

c) use of cement that hardens more rapidly;

d) increase in cement content to raise the heat of hydration
Measures can be adopted during the construction sequences:

a) all surfaces with which the fresh concrete will come into contact including those of formwork, reinforcement, prestressing steel and hardened concrete, should be free from snow, ice and frost and preferably be at a temperature close to that of the fresh concrete. Special care is needed when small quantities of fresh concrete are placed against larger quantities of hardened concrete at a lower temperature, or in frozen ground;

b) covering the faces, particularly the exposed top faces of slabs and beams, with insulating materials;

c) shielding newly placed concrete from the wind;

d) using a heated enclosure, completely surrounding the freshly placed concrete, care being taken to prevent excessive evaporation of water or surface carbonation by the products of combustion;

e) using heated formwork panels, precautions being taken to prevent excessive evaporation of water.
Specification for Hot Weather Concreting

(ACI 305.1-06)

Definitions

Evaporation retardant: a material that generates a continuous thin film when spread over water on the surface of fresh concrete and thus retards the evaporation of bleed water.

Hot weather: job-site conditions that accelerate the rate of moisture loss or rate of cement hydration of freshly mixed concrete, including an ambient temperature of 27 °C (80 °F) or higher, and an evaporation rate that exceeds 1 kg/m²/h, or as revised by the Architect/Engineer.

Hot weather concreting: operations concerning the preparation, production, delivery, placement, finishing, protection, and curing of concrete during hot weather.

Moist: slightly damp but not quite dry to the touch; “wet” implies visible free water, “damp” implies less wetness than “wet,” and “moist” implies not quite dry.

Protection period: the required time during which the concrete is protected against thermal cracking due to rapid temperature drops.
**Temperature of fresh concrete:** the temperature measured during the discharge and placement in accordance with ASTM C 1064/C 1064M.

**Submittal of procedures**

Before hot weather concreting and the preplacement conference, submit to Architect/Engineer for review and comment detailed procedures, including production, placement, finishing, curing and protection of concrete during hot weather concreting.

**Preplacement conference**

1. At least 15 days before the start of the concrete construction schedule, hold a preplacement conference for the purpose of reviewing hot weather concreting requirements and mix designs.

2. Send a preplacement conference agenda on hot weather operations and procedures to representatives of concerned parties not less than 10 days before the scheduled date of the conference.

3. Preplacement conference shall include, but is not limited to, representation of Contractor, Concrete Subcontractor, Testing Agency, Pumping Contractor, and Ready-Mixed Concrete Producer.
EXECUTION

1. Do not place concrete against surfaces of absorbent materials that are dry.

   Do not place concrete against surfaces that have free water.

2. Prepare all materials required for accepted evaporation control measures and have them available on site.

Maximum allowable concrete temperature

Limit the maximum allowable fresh concrete temperature to 35 °C (95 °F), unless otherwise specified, or unless a higher allowable temperature is accepted by Architect/Engineer, based upon past field experience or preconstruction testing using a concrete mixture similar to one known to have been successfully used at a higher concrete temperature.

Concrete production and delivery

1. Concrete shall be produced at a temperature such that its maximum temperature at discharge will not exceed the specified maximum allowable concrete temperature. Acceptable production methods to reduce the temperature of the concrete include: shading aggregate stockpiles, sprinkling
water on coarse aggregate stockpiles; using chilled water for concrete production; substituting chipped or shaved iced for portions of the mixing water; and cooling concrete materials using liquid nitrogen. The submittals for hot weather concreting shall indicate which methods will be used and in what order they will be initiated when multiple methods are to be used. The substitution of other cooling methods will be considered by the Architect/Engineer when requested in the submittal and accompanied by satisfactory supporting data.

2. Unless otherwise specified, deliver concrete in accordance with ASTM C 94/C 94M, which requires the concrete to be discharged within 1-1/2 hours or before the truck-mixer drum has revolved 300 revolutions, whichever comes first.
QC requirements for transport of concrete

BS 5328-3:1990

General:

Concrete shall be transported from the mixer to the point of placing as rapidly as practicable by methods that will maintain the required workability and will prevent segregation, loss of any constituents or ingress of foreign matter or water. The concrete shall be deposited as close as practicable to its final position to avoid rehandling or moving the concrete horizontally by vibration.

1- Time of transport:

Concrete shall be discharged from the delivery vehicle within 2 h after the time of loading, when concrete is transported in truck mixers or agitators, or within 1 h after the time of loading when non-agitating equipment is used unless a shorter time is specified or a longer time permitted by the purchaser. The time of loading shall start from the first contact between cement and aggregates or, when these are surface dry, between cement and added water.

2- Quantity of concrete

The basis of supply shall be by the cubic metre of fresh, fully compacted concrete. The volume of a given batch of concrete shall be calculated from the total mass of the batch divided by the mass per cubic metre

3- Transport of concrete

Concrete shall be transported in a truck mixer unless the purchaser agrees to the use of non-agitating vehicles. When non-agitating vehicles are used, the mixed concrete shall be protected from gain or loss of water.

4- Additional water

No water, other than any amount required to produce the specified workability, shall be added to the truck mixer drum before discharge unless specifically required and signed for by the purchaser. The water added shall be recorded on the delivery ticket.
5- Delivery ticket

Before discharging the concrete at the point of delivery, the supplier shall provide the purchaser with a delivery ticket for each batch of concrete on which is printed, stamped or written the following minimum information:

a) the name or number of the ready-mixed concrete depot;
b) the serial number of the ticket;
c) the date;
d) the truck number;
e) the name of the purchaser;
f) the name and location of the site;
g) the grade or mix description of the concrete;
h) the specified workability;
i) the minimum cement content, if specified;
j) the type and, if specified, the standard strength class or sub-class of the cement or combination;

k) the limiting proportions of ggbs or pfa, if specified;
l) the maximum free water/cement ratio, if specified;
m) the nominal maximum size of aggregate;
n) the type or name of admixture, if included;
o) the quantity of concrete in cubic metres;
p) the time of loading.
The following information shall be added to the delivery ticket on site:
q) the time of completion of discharge;
r) the water added to meet the specified workability;
s) the extra water added at the request of the purchaser of the concrete, or his representative, and his signature.

NOTE Space should be provided for any additional items.
QC requirements for Formwork

BS 5328-3:1990

1- Design and construction

The design and construction of formwork should take account of safety and of the surface finish required. The formwork should be sufficiently rigid and tight to prevent loss of grout or mortar from the fresh concrete. Consideration should be given to the need to nominate a falsework coordinator whose duties would be similar to those outlined in BS 5975.

Formwork and its supports should maintain their correct position and be to correct shape and profile so that the final concrete structure is within the limits of the dimensional tolerances specified. They should be designed to withstand the worst combination of self-weight, reinforcement weight, wet concrete weight, concrete pressure, construction and wind loads, together with all incidental dynamic effects caused by placing, vibrating and compacting the concrete. Guidance on these loadings is given in The Concrete Society Manual Formwork — Guide to good practice\(^9\), and in CIRIA Report 108, Concrete Pressure on Formwork,\(^10\) and in BS 5975.

Before permanent formwork is used in the structure, its durability and compatibility with adjoining concrete should be established. It should be properly anchored to the concrete.

Formwork spacers left in-situ should not impair the desired appearance or durability of the structure, e.g. by causing spalling, rust staining or allowing the passage of moisture. Recommendations for space
The formwork should be capable of being dismantled and removed from the cast concrete without shock, disturbance or damage. Where necessary, the arrangement should be such that the soffit form, properly

2- Cleaning and treatment of forms

Rubbish should be removed from the interior of the forms before the concrete is placed. The faces of the forms in contact with the concrete should be clean and treated with a suitable release agent, where applicable.

Release agents should be applied so as to provide a thin uniform coating to the forms without contaminating the reinforcement.

3- Striking of the formwork

The time at which formwork is struck will be influenced by the following factors:

a) concrete strength;

b) stresses in the concrete at any stage in the construction period which, in the case of precast units, includes the stresses induced by disturbance at the casting position and subsequent handling;

c) curing

d) subsequent surface treatment requirements;

e) presence of re-entrant angles requiring formwork to be removed as soon as possible after concrete has set, to avoid thermal cracking.
The formwork should be removed without shock, as the sudden removal of wedges is equivalent to an impact load on the partially hardened concrete.

Materials and plant should not be placed on any new construction in such a manner as to cause damage.

2- Striking period for cast in-situ concrete

In the absence of other information the recommended periods before striking formwork given in Table 6.2 may be used for concrete made with Portland or sulfate-resisting Portland cements of strength class 42.5 or higher. Table 6.2 relates to the surface temperature of the concrete but, when this cannot be obtained, air temperatures may be used. Table 6.2 should not be used if accelerated curing methods or sliding forms are used.

<table>
<thead>
<tr>
<th>Type of formwork</th>
<th>Minimum period before striking</th>
<th>Surface temperature of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16 °C and above</td>
<td>t °C (any temperature between 0 °C and 18 °C)</td>
</tr>
<tr>
<td>Vertical formwork to columns, walls and large beams</td>
<td>12 h</td>
<td>( \frac{300}{t + 10} ) h</td>
</tr>
<tr>
<td>Soffit formwork to slabs</td>
<td>4 days</td>
<td>( \frac{100}{t + 10} ) days</td>
</tr>
<tr>
<td>Soffit formwork to beams and props to slabs</td>
<td>10 days</td>
<td>( \frac{250}{t + 10} ) days</td>
</tr>
<tr>
<td>Props to beams</td>
<td>14 days</td>
<td>( \frac{360}{t + 10} ) days</td>
</tr>
</tbody>
</table>

**NOTE** This table can be applied to CEM I and SRPC of higher cement strength classes.

It may be possible to use shorter periods before striking formwork by determining the strength of the concrete in the structural element. Formwork supporting cast in-situ concrete in flexure may be struck when the strength of the concrete in the element is 10 N/mm² or twice the stress to which it will be subjected, whichever is the greater, provided that striking at this time will not result in unacceptable deflection\(^{11}\).

This strength may be assessed by test on cubes cured, as far as possible, under the same conditions as the concrete in the element (see 6.1).
When formwork to vertical surfaces, such as beam sides, walls and columns, is removed at early ages, care should be exercised to avoid damage to the concrete especially to arises and features. If necessary, the provision of relevant curing methods should immediately follow the removal of the vertical formwork at such early ages and the concrete should be protected from low or high temperatures by means of suitable insulation (see 6.2.3.3).

11) Unacceptable deflection may be defined as deflection that is harmful for the member concerned.

Construction joints and movement joints

1- Construction joints

The number of construction joints should be kept to the minimum necessary for the execution of the work. Their location should be carefully considered and agreed before concrete is placed. They should normally be at right angles to the general direction of the member.

The concrete at the joint should be bonded with that subsequently placed against it, without provision for relative movement between the two. Concrete should not be allowed to run to a feather-edge and vertical joints should be formed against a stop end. High quality workmanship is necessary when forming the joints to insure that the load-bearing capacity of the concrete in the area of the joint is not impaired.

The top surface of a layer of concrete should be level and reasonably flat unless design considerations make this undesirable. If a kicker, i.e. a starter stub, is used, it should be at least 70 mm high and carefully constructed. It is sometimes necessary for a kicker to be cast with the previous concrete.
Care should be taken that the joint surface is clean immediately before the fresh concrete is placed against it. It may need to be slightly wetted prior to the new concrete being placed, to prevent excessive loss of mix water into it by absorption. Particular care should be taken in the placing of new concrete close to the joint to ensure that it has an adequate fines content and is fully compacted and dense.

Care should be taken that the joint surface is clean immediately before the fresh concrete is placed against it. It may need to be slightly wetted prior to the new concrete being placed, to prevent excessive loss of mix water into it by absorption. Particular care should be taken in the placing of new concrete close to the joint to ensure that it has an adequate fines content and is fully compacted and dense.

2- Movement joints

When forming movement joints, any joint filler should be fixed firmly to the first-placed concrete.

It is essential that the concrete on both sides of the joint, when placed, is thoroughly compacted to form a dense uniform mass. Where stop ends comprise more than one element, particular care is necessary to ensure that joints between elements are sufficiently tight to allow no grout loss through them during compaction of the concrete. Alternatively, contraction joints may be introduced by the use of crack inducers.

Where flexible water stops are used, they should be fixed so as to ensure that they are not displaced from their intended position during compaction of the concrete and that the concrete surrounding them is fully compacted. The design of the water stop should be practical and take account of the problems often associated with integral water stop construction in difficult placing conditions.

Water stops laid horizontally and located within the concrete mass should be avoided since they attract the greatest risk of local honeycombing.
QC requirements for Handling and erection of precast concrete units

The following items should be specified or agreed:

a) minimum ages of handling and transporting;
b) the position and design of lifting points;
c) the method of lifting;
d) the type of lifting equipment;
e) method of supporting and stacking, both while being stored and transported;
f) method of assembly and erection;
g) the accuracy of assembly and erection: guidance is given in Table 1 of BS 5606:1990;
h) method of providing temporary support;
i) method of providing final structural connections;
j) composition of concrete or mortar used to fill joints;
k) method of protecting the units from damage at all times.

Checks should be made to ensure that:

1) the units bear adequate identity, location and orientation marks;
2) units are not damaged by freezing;
3) temporary supports or connections to newly positioned units are provided as soon as practicable, these being completed before the lifting equipment is removed;
4) final structural connections are completed as soon as practicable;
5) contact surfaces intended to be bonded with in-situ concrete have been properly prepared;
6) reinforcement is accurately located, particularly in the ends of members;
7) structural steel sections in ends of members and additional reinforcement needed to complete the connection, are accurately located;
8) joints are properly packed, particular attention being given to joints packed with concrete or mortar, especially if these are horizontal loaded-bearing joints;
9) all levelling devices, such as nuts and wedges, which have no load-bearing function in the finished structure should be slackened, released or removed as necessary.
QC requirements for reinforcement fixing

Rough handling, shock loading (prior to embedment) and the dropping of reinforcement from a height should be avoided. Reinforcement should be secured against displacement outside the specified limits.

a) the actual concrete cover should be not less than the required nominal cover minus 5 mm;
b) where reinforcement is located in relation to only one face of a member, e.g. a straight bar in a slab, the actual concrete cover should be not more than the required nominal cover plus:
   1) 5 mm on bars up to and including 12 mm size;
   2) 10 mm on bars over 12 mm up to and including 25 mm size;
   3) 15 mm on bars over 25 mm size.

The position of reinforcement should be checked before and during concreting, particular attention being directed to ensuring that the nominal cover is maintained within the limits given, especially in the case of cantilever sections. The importance of cover in relation to durability justifies the regular use of a cover meter to check the position of the reinforcement in the hardened concrete.

Surface condition

Reinforcement should not be surrounded by concrete unless it is free from mud, oil, paint, retarders, loose rust, loose mill scale, snow, ice, grease or any other substance which can be shown to adversely affect the steel or concrete chemically, or reduce the bond. Normal handling prior to embedment in the concrete is usually sufficient for the removal of loose rust and scale from reinforcement.

Laps and joints

Laps and joints should be made only by the methods specified in the contract or design specifications and at the positions shown on the drawings or as agreed by the engineer.
QC requirements for concrete aggregate

1- Fine aggregate (sand)

The most features of a fine aggregate affect its suitability as a concrete aggregate are:

1 Grading

2 Particle shape and surface texture

3 Clay/silt/dust content

The basic concept is to use a smaller amount of a finer sand so as to leave unchanged both the water requirement and the cohesiveness of the mix.

In any particular case, the ideal sand percentage is not solely a matter of its grading. Other factors influencing the ideal percentage include cement content, entrained air content, particle shape and grading of the coarse aggregate, and also the intended use of the concrete.

The original and perhaps most widely known and used grading index is the Fineness Modulus. This is the sum of the cumulative percentages retained on each sieve from
150 micron upwards. This index is used in the ACI mix design system to adjust for sand fineness.
Fine aggregate grading ASTM C 33-03

<table>
<thead>
<tr>
<th>Sieve (Specification E 11)</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5-mm (3/16-in.)</td>
<td>100</td>
</tr>
<tr>
<td>4.75-mm (No. 4)</td>
<td>95 to 100</td>
</tr>
<tr>
<td>2.36-mm (No. 8)</td>
<td>80 to 100</td>
</tr>
<tr>
<td>1.18-mm (No. 16)</td>
<td>50 to 85</td>
</tr>
<tr>
<td>600-μm (No. 30)</td>
<td>25 to 60</td>
</tr>
<tr>
<td>300-μm (No. 50)</td>
<td>5 to 30</td>
</tr>
<tr>
<td>150-μm (No. 100)</td>
<td>0 to 10</td>
</tr>
</tbody>
</table>

**TABLE 1 Limits for Deleterious Substances in Fine Aggregate for Concrete**

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass Percent of Total Sample, max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay lumps and friable particles</td>
<td>3.0</td>
</tr>
<tr>
<td>Material finer than 75-μm (No. 200) sieve:</td>
<td></td>
</tr>
<tr>
<td>Concrete subject to abrasion</td>
<td>3.0&lt;sup&gt;A&lt;/sup&gt;</td>
</tr>
<tr>
<td>All other concrete</td>
<td>5.0&lt;sup&gt;A&lt;/sup&gt;</td>
</tr>
<tr>
<td>Coal and lignite:</td>
<td></td>
</tr>
<tr>
<td>Where surface appearance of concrete is of importance</td>
<td>0.5</td>
</tr>
<tr>
<td>All other concrete</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<sup>A</sup> In the case of manufactured sand, if the material finer than the 75-μm (No. 200) sieve consists of the dust of fracture, essentially free of clay or shale, these limits are permitted to be increased to 5 and 7%, respectively.
Technical reasons for using or not using the crusher fines:

- A coarse grade of crusher fines may be needed to fill the gap between the top of a fine sand grading and the bottom of the coarse aggregate grading. This may be essential to provide pumpability or to avoid segregation where high slump is necessary.

- It should be remembered that a higher water requirement is not purely an economic disadvantage. It also gives increased shrinkage and so may be unacceptable for some purposes even if it is the most economical way of providing the required strength.

- There will normally be a distinct difference in colour between a crusher fines mix and a natural sand mix. One or other may therefore be architecturally either preferred or rejected for exposed architectural concrete.

- There may be a substantial difference one way or the other (depending on actual gradings) in bleeding characteristics which may have a substantial effect on surface appearance (coarse crusher fines being particularly susceptible to heavy bleeding but fine dust inhibiting it).
2- Coarse aggregate

The properties of a coarse aggregate depend on the properties of the basic rock, upon the crushing process (if crushed) and upon the subsequent treatment of the aggregate in terms of separation into fractions, segregation and contamination.

Most rock has an adequate basic strength for use in most grades of concrete.

Even manufactured and naturally occurring lightweight aggregates, which can be readily crushed under a shoe heel, are used to make concrete with an average strength up to 40 MPa (although they do require a higher cement content than dense aggregates).
<table>
<thead>
<tr>
<th>Size Number</th>
<th>Nominal Size (1 in. to No. 4)</th>
<th>Amounts Finer than Each Laboratory Sieve (Square-Openings), Mass Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90 to 37.5 mm (3/8 to 1/4 in.)</td>
<td>100 90 to 100 25 to 60 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>2</td>
<td>63 to 37.5 mm (2/8 to 1/2 in.)</td>
<td>100 90 to 100 35 to 70 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>3</td>
<td>40 to 25.0 mm (2 in. to No. 4)</td>
<td>100 90 to 100 35 to 70 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>387</td>
<td>95 to 40.0 mm (1 in. to No. 4)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>4</td>
<td>37.5 to 19.0 mm (1/2 to 3/4 in.)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>467</td>
<td>31.5 to 15.0 mm (1 1/2 in. to No. 4)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>5</td>
<td>90 to 12.5 mm (1 to 3/8 in.)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>56</td>
<td>25.0 to 9.5 mm (1 to 4 in.)</td>
<td>100 90 to 100 40 to 85 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>57</td>
<td>25.0 to 9.5 mm (1 in. to No. 4)</td>
<td>100 90 to 100 25 to 60 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>6</td>
<td>19.0 to 9.5 mm (1/2 to 3/4 in.)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>67</td>
<td>9.0 to 4.75 mm (1 1/4 in. to No. 4)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>7</td>
<td>12.5 to 4.75 mm (1 3/4 in. to No. 4)</td>
<td>100 90 to 100 40 to 85 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>8</td>
<td>9.5 to 2.36 mm (1 1/4 in. to No. 8)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
<tr>
<td>99</td>
<td>9.5 to 1.18 mm (1/2 in. to No. 16)</td>
<td>100 90 to 100 20 to 55 0 to 15 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5 0 to 5</td>
</tr>
</tbody>
</table>

* Size number 9 aggregate is defined in Terminology C 125 as a fine aggregate. It is included as a coarse aggregate when it is combined with a size number 8 material to create a size number 99, which is a coarse aggregate as defined by Terminology C 125.
QC requirements for Cement

Where regular test data are obtained, it is useful to maintain graphs of the information provided. As with concrete test data, cusum graphs are far more effective at detecting change points.

The main results likely to be provided are:

1- **Setting time.** Initial and final set are both arbitrary stages in smooth curve of strength development. Abnormal results can indicate incorrect proportion of gypsum, excessive temperature in final grinding (which dehydrates gypsum and alters its effectiveness) or deterioration with age.

2- **Fineness.** Finer cement will:

1) React more quickly (faster heat generation)
2) React more completely
3) Improve mix cohesion (or make ‘sticky’)
4) Reduce bleeding
5) Deteriorate more quickly
6) Be more susceptible to cracking
7) Generally require more water (note that this may be less due to any direct effect of fineness than to the reduced range of particle sizes normally resulting from finer grinding).

3- **Soundness** (Pat, Le Chatelier and autoclave tests). Intended to detect excessive free lime (perhaps due to incomplete blending rather than wrong chemical proportions). Some experts disagree that the intention is achieved, but this is
beyond the present scope. Magnesia can also cause unsoundness (if as periclase) but perhaps too slowly for pat or Le Chatelier – needs autoclave or chemical limit.

4- **Normal consistency.** Generally just a starting point for other tests but can show up undesirable grinding characteristics. Where very high strength concrete is involved, large amounts of cement will be required and a very low w/c ratio will be sought. A cement with a high water requirement is at a disadvantage in such circumstances. Interesting uses for this test are as a compatibility check between admixtures and cement or to determine the effect on water requirement of a percentage of fly-ash or silica fume etc.

5- **Loss on ignition.** Mainly a check on deterioration in storage. The test drives off any moisture or carbon dioxide which may have been absorbed. A 3% loss on ignition could mean a 20% strength loss. However up to 5% of limestone (CaCO₃) is permitted to be added to cement and this test would drive off CO₂ from limestone.

6- **Sulphuric anhydride** (SO₃). Check on proportion of gypsum, has considerable significance for setting time, strength development and shrinkage. The test determines the content of SO₃ from all sources (e.g. added gypsum, oxidized sulphur in fuels etc.) and in all states. It therefore may not be an accurate guide to the amount of active (soluble) SO₃ present. It is the amount of active SO₃ which
affects setting time, rate of strength development, tendency to shrinkage and cracking etc.

7- **Insoluble residue**. Check on impurities or non reactive content only, the effect is the same as reducing the cement content by the percentage of the insoluble material. However this test may characterize fly-ash as insoluble residue.

8- **Compressive strength**. This should be directly related to concrete performance but there can be differences with admixture interactions, different water cement ratio etc. Generally higher strength grades are more expensive but less can be used to meet a strength specification.

**Types of cement**

All Portland cement is conveniently regarded as composed of four compounds:

**C\(_{2}\)S** Di-calcium silicate Slow acting, low heat generation, best long term strength and durability.

**C\(_{3}\)S** Tri-calcium silicate Quicker acting, more heat generated, still good strength and durability but not as good as **C\(_{2}\)S**.
**C₃A** Tri-calcium aluminate Very rapid reaction, high heat generation, responsible for early (but not high) strength and setting, easily attacked by chemicals.

**C₄AF** Tetra-calcium Relatively little influence on properties alumino-ferrite of concrete (except colour), present because needed during manufacture.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Abbreviation</th>
<th>Compound</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>C</td>
<td>3CaO·SiO₂</td>
<td>C₃S</td>
</tr>
<tr>
<td>SiO₂</td>
<td>S</td>
<td>2CaO·SiO₂</td>
<td>C₂S</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>A</td>
<td>3CaO·Al₂O₃</td>
<td>C₃A</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>F</td>
<td>4CaO·Al₂O₃·Fe₂O₃</td>
<td>C₄AF</td>
</tr>
<tr>
<td>MgO</td>
<td>M</td>
<td>4CaO·3Al₂O₃·SO₃</td>
<td>C₄A₃S</td>
</tr>
<tr>
<td>SO₃</td>
<td>S</td>
<td>3CaO·2SiO₂·3H₂O</td>
<td>C₃S₂H₃</td>
</tr>
<tr>
<td>H₂O</td>
<td>H</td>
<td>CaSO₄·2H₂O</td>
<td>CSH₂</td>
</tr>
</tbody>
</table>

The relative amounts of these compounds are varied to produce different types of cement to suit different uses:

Type I – also known as Type A, OPC (ordinary Portland cement), GP (general purpose)

Type II – modified low heat cement

Type III – high early strength or rapid hardening

Type IV – sulphate resisting cement

Type V – low heat cement.

A fifth compound, CaSO₄ (gypsum) is interground with the cement clinker to
control setting. It is also thought to have a substantial beneficial influence on shrinkage and to produce improved strength. However an excess can cause slow setting and also unsoundness (destructive expansion). Gypsum can be rendered less effective by excessive heat during grinding.

The Bogue equations for estimating the theoretical or the potential compound composition of portland cement are as follows:

\[
\begin{align*}
\%C_3S &= 4071C - 7.600S - 6.718A - 1.430F - 2.850\overline{S} \\
\%C_2S &= 2867S - 0.7544C_3S \\
\%C_3A &= 2650A - 1.692F \\
\%C_4AF &= 3.043F
\end{align*}
\]

**TABLE 6-5** Principal Compounds of Portland Cement and their Characteristics

<table>
<thead>
<tr>
<th>Approximate composition</th>
<th>$3\text{CaO} \cdot \text{SiO}_2$</th>
<th>$\beta\text{CaO} \cdot \text{SiO}_2$</th>
<th>$3\text{CaO} \cdot \text{Al}_2\text{O}_3$</th>
<th>$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbreviated formula</td>
<td>$C_3S$</td>
<td>$\beta C_3S$</td>
<td>$C_3A$</td>
<td>$C_4AF$</td>
</tr>
<tr>
<td>Common name</td>
<td>Alite</td>
<td>Belite</td>
<td>—</td>
<td>Ferrite phase, $\text{Fss}$</td>
</tr>
<tr>
<td>Principal impurities</td>
<td>$\text{MgO}, \text{Al}_2\text{O}_3, \text{Fe}_2\text{O}_3$</td>
<td>$\text{MgO}, \text{Al}_2\text{O}_3, \text{SiO}_2, \text{MgO}, \text{alkalies}$</td>
<td>$\text{SiO}_2, \text{MgO}$</td>
<td></td>
</tr>
<tr>
<td>Common crystalline form</td>
<td>Monoclinic</td>
<td>Monoclinic</td>
<td>Cubic, orthorhombic</td>
<td>Orthorhombic</td>
</tr>
<tr>
<td>Proportion of compounds present (%):</td>
<td>Range 35–65</td>
<td>10–40</td>
<td>0–15</td>
<td>5–15</td>
</tr>
<tr>
<td>Average in ordinary cement</td>
<td>55</td>
<td>20</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Rate of reaction with water</td>
<td>Fast</td>
<td>Slow</td>
<td>Fast</td>
<td>Moderate</td>
</tr>
<tr>
<td>Contribution to strength:</td>
<td>Early age Good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Ultimate Good</td>
<td>Excellent</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Heat of hydration Medium</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Typical ($\text{cal/g}$) 120</td>
<td>60</td>
<td>320</td>
<td>100</td>
</tr>
</tbody>
</table>
### TABLE 1 Standard Composition Requirements

<table>
<thead>
<tr>
<th>Cement Type(^{A})</th>
<th>Applicable Test Method</th>
<th>I and IA</th>
<th>II and IIIA</th>
<th>III and IIIA</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide (SiO(_2)) min, %</td>
<td>C 114</td>
<td>...</td>
<td>20.0(^{B, C})</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Aluminum oxide (Al(_2)O(_3)) max, %</td>
<td>C 114</td>
<td>...</td>
<td>6.0</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Ferric oxide (Fe(_2)O(_3)) max, %</td>
<td>C 114</td>
<td>...</td>
<td>6.0(^{C})</td>
<td>...</td>
<td>6.5</td>
<td>...</td>
</tr>
<tr>
<td>Magnesium oxide (MgO), max, %</td>
<td>C 114</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Sulfur trioxide (SO(_3)), max, %</td>
<td>C 114</td>
<td>3.0</td>
<td>3.0</td>
<td>3.5</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>When (C(_2)A(_2)) is 8 % or less</td>
<td>...</td>
<td>3.5</td>
<td>4.5</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>When (C(_2)A(_2)) is more than 8 %</td>
<td>...</td>
<td>3.5</td>
<td>4.5</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Loss on ignition, max, %</td>
<td>C 114</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Insoluble residue, max, %</td>
<td>C 114</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Tricalcium silicate (C(_3)S), max, %</td>
<td>See Annex</td>
<td>...</td>
<td>...</td>
<td>35(^{D})</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Dicalcium silicate (C(_2)S), min, %</td>
<td>See Annex</td>
<td>...</td>
<td>...</td>
<td>40(^{D})</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Tricalcium aluminate (C(_3)A(_2)), max, %</td>
<td>See Annex</td>
<td>...</td>
<td>8</td>
<td>15</td>
<td>7(^{E})</td>
<td>5(^{E})</td>
</tr>
<tr>
<td>Tricalcium aluminoferrite plus twice the tricalcium aluminate (C(_3)AF + 2(C(_3)A)), or solid solution (C(_3)AF + C(_3)F), as applicable, max, %</td>
<td>See Annex</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>25(^{F})</td>
<td>...</td>
</tr>
</tbody>
</table>

\(^{A}\) See Note 2.
\(^{B}\) Does not apply when the heat of hydration limit in Table 4 is specified.
\(^{C}\) Does not apply when the sulfate resistance limit in Table 4 is specified.
\(^{D}\) There are cases where optimum SO\(_3\) using Test Method C 593) for a particular cement is close to or in excess of the limit in this specification. In such cases where properties of a cement can be improved by exceeding the SO\(_3\) limits stated in this table, it is permissible to exceed the values in the table, provided it has been demonstrated by Test Method C 1038 that the cement with the increased SO\(_3\) will not develop expansion in water exceeding 0.020 % at 14 days. When the manufacturer supplies cement under this provision, he shall, upon request, supply supporting data to the purchaser.
\(^{E}\) See Annex for calculation.
\(^{F}\) Not applicable.

### TABLE 3 Standard Physical Requirements

<table>
<thead>
<tr>
<th>Cement Type(^{A})</th>
<th>Applicable Test Method</th>
<th>I</th>
<th>IA</th>
<th>II</th>
<th>III</th>
<th>IIA</th>
<th>III</th>
<th>IIA</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air content of mortar, volume %:</td>
<td>C 165</td>
<td>...</td>
<td>12</td>
<td>22</td>
<td>12</td>
<td>22</td>
<td>12</td>
<td>22</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>min</td>
<td>...</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Fineness, specific surface, m(^2)/kg (alternative methods):</td>
<td>C 115</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>...</td>
<td>...</td>
<td>160</td>
<td>160</td>
<td>...</td>
</tr>
<tr>
<td>Turbidity test, min</td>
<td>C 201</td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>280</td>
<td>...</td>
<td>...</td>
<td>280</td>
<td>280</td>
<td>...</td>
</tr>
<tr>
<td>Air permeability test, min</td>
<td>C 151</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Absorptive expansion, max, %</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Strength, not less than the values shown for the ages indicated as follows:</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Compressive strength, MPa (psi):</td>
<td>C 109/109M</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1 day</td>
<td>...</td>
<td>12.0</td>
<td>12.0</td>
<td>(1740)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>3 days</td>
<td>...</td>
<td>14.0</td>
<td>14.0</td>
<td>(1850)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>7 days</td>
<td>...</td>
<td>17.0</td>
<td>17.0</td>
<td>(2240)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>28 days</td>
<td>...</td>
<td>19.0</td>
<td>19.0</td>
<td>(2790)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Time of setting (alternative methods):</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Gillmore test:</td>
<td>C 266</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Initial set, min, not less than</td>
<td>...</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Final set, min, not more than</td>
<td>...</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Vicat test:</td>
<td>C 191</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Time of setting, min, not less than</td>
<td>...</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
</tr>
<tr>
<td>Time of setting, min, not more than</td>
<td>...</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
<td>375</td>
</tr>
</tbody>
</table>

\(^{A}\) See Note 2.
\(^{B}\) Compliance with the requirements of this specification does not necessarily ensure that the desired air content will be obtained in concrete.
\(^{C}\) The testing laboratory shall select the fineness method to be used. However, when the sample fails to meet the requirements of the air-permeability test, the turbidity test shall be used, and the requirements in this table for the turbidity metric method shall govern.
\(^{D}\) The strength at any specified test age shall be not less than the attained at any previous specified test age.
\(^{E}\) When the optional heat of hydration or the chemical limit on the sum of the tricalcium silicate and tricalcium aluminate is specified.
\(^{F}\) The time-of-setting test required shall be specified by the purchaser. In case he does not so specify, the requirements of the Vicat test only shall govern.
\(^{G}\) The time of setting is that described as initial setting time in Test Method C 101.
Storage (EN 197-1):

To protect cement from premature hydration after delivery, bulk silos should be waterproof and internal condensation should be minimized.

Paper bags should be stored clear of the ground, not more than eight bags high and protected by a waterproof structure. As significant strength losses begin after 4 weeks to 6 weeks of storage in bags in normal conditions, and considerably sooner under adverse weather conditions or high humidity, deliveries should be controlled and used in order of receipt. Manufacturers are able to provide a system of marking a high proportion of the bags in each delivery to indicate when they were filled.

Rejection

1 The cement shall be rejected if it fails to meet any of the requirements of the specification.

2 At the option of the purchaser, retest, before using, cement remaining in bulk storage for more than 6 months or cement in bags in local storage in the custody of a vendor for more than 3 months after completion of tests and reject the cement if it fails to conform to any of the requirements of this specification.
Cement so rejected shall be the responsibility of the owner of record at the time of resampling for retest.

3 Packages shall identify the mass contained as net weight. At the option of the purchaser, packages more than 2 % below the mass marked thereon shall be rejected and if the average mass of packages in any shipment, as shown by determining the mass of 50 packages selected at random, is less than that marked on the packages, the entire shipment shall be rejected.

**Packaging and Package Marking**

When the cement is delivered in packages,

1- the words “Portland Cement,” the type of cement,

2- the name and brand of the manufacturer, and

3- the mass of the cement contained therein

shall be plainly marked on each package. When the cement is an air-entraining type, the words “air-entraining” shall be plainly marked on each package. Similar information shall be provided in the shipping documents accompanying the shipment of packaged or bulk cement. All packages shall be in good condition at the time of inspection.