QUALITY CONTROL OF CONCRETE

G. Frigione
Universita degli Studi della Calabria. Facolta di Ingegneria
Dipartimento di Chimica. Arcavacata (CS), Italy

F. Zenone
Cementir, Cementerie del Tirreno, Napoli, Italy

1. INTRODUCTION

No production process is so perfect that each of its products is completely alike. There is always a small variation caused by many small uncontrollable factors and must, therefore, be regarded as a change variation. It is important to make sure that the products have the required values. For this purpose, one tests the hypothesis that the products have the required property (say, $\mu = \mu_O$ where μ_O is a required value). If this is done after an entire lot has been produced, the test will tell us how good or how bad the products are, but it is too late to alter the undesirable results. It is much better to test at regular intervals of time during the production run. This is called quality control.

Generally, the quality level is defined by the quality/cost relation as seen by both the manufacturer and the consumer. This means that continuing effort should be made to find an optimum compromise between the manufacturer's operating costs and the consumer's quality requirements and price expectations, in consideration of the final product which, in our case, is concrete.

To elaborate a detailed programe for control, it is necessary to know:

- what should be examined and the methods of testing;
- which information is required for the control of mean value, variation;
- when must the information be available, at the latest, to enable effective control (retention time, dead time);
- how often has the test to be performed (frequency of sampling and testing); and
- an unbiased interpretation of test results, independent of the analyst's or operator's opinion. This is possible only if clearly defined procedures for data processing and evaluation are established.

On the basis of the company's quality objectives and targets, alarm and control lmits have to be established as valid decision criteria to ensure that the product is continually under control.

Each particular programme must periodically be brought up to date on the basis of information feedback and technological advancements. Furthermore, a quality control programme should have the flexibility to cope with changing conditions, be it on the consumer's side or the manufacturer's side.

The aim of this paper is to state the basic concepts, principles and criteria which are relevant for the design of a concrete quality control programme with special reference to durability.

From the engineering point of view, quality of concrete is gauged by its mechanical strength, workability and durability.

Workability can be defined as the ease with which a given set of materials can be mixed into concrete and subsequently mixed, transported, placed in the framework and compacted with minimum loss of homogeneity. If workability with regard to the methods and the means available for the compaction of the concrete cast remains below a certain limit, the compactness, and therefore the other required qualities (in particular, mechanical strength), cannot be obtained on hardened concrete. Thus, correct and suitable workability is a fundamental requirement for the successful manufacture of concrete.

Mechanical strength is a feature of concrete which, to date, has been considered most important. The reason is twofold: first and foremost, the strength of the material plays a fundamental role in structural calculations and secondly, determining this property is relatively simple and rapid.

Durability is the capability of the concrete to perform the functions for which it has been designed without deterioration over a period of years. Deterioration may be caused either by the environment to which the concrete is exposed or by internal causes within the concrete itself. The external causes can be physical, mechanical or chemical; they may be due to the adverse effect of freezing and thawing—a temperature cycle frequently met with in nature—to abrasion and erosion, to attack by the sulphate present in soil, ground water and industrial liquids, to attack by soft water and of marine environments, to steel reinforcement corrosion due to carbonation and/or penetration of chlorides, etc. The internal causes are corrosion of the steel reinforcement by the chloride present in the mix components, in alkali—aggregate reaction and unsoundness of the aggregates.

Durability is a function of(1).

- the choice of cement and its dosage;
- the choice of the aggregates (form, cleanness, stability, etc.);
- the water (quality, content and cement-water ratio);
- the use of appropriate admixtures;
- the batching and casting methods; and
- the curing of concrete.

An implicit assumption seems to have developed that if the compressive strength is satisfactory, then durability follows. This is now known not be the case in that some qualities of concrete may worsen with an increase in mechanical strength, and concrete with a satisfactory mechanical strength is not always satisfactory as regards its other properties. According to Bentur and Jaegermann(2), specifications and quality control methods based on strength may not be adequate for ensuring the quality of the concrete skin, especially in a hot-dry environment. Therefore, other parameters or tests must be developed when the specifications are needed for durability performance, in particular the corrosion of steel in concrete. The coefficient of absorption test might be considered for this purpose since it provides better correlation with the performance of the skin than the strength values.

As already mentioned, the only value capable of being measured with reasonable ease and speed is the compressive strength. Thus, concrete is commercially classified according to its compressive strength.

Systematic studies(3),(4),(5) on the products of numerous establishments have confirmed that the strength of concrete samples responds to a normal distribution. According to Mirza Sher et al.(6) the compressive strength can be modelled by a normal or lognormal distribution function, depending upon the degree of quality control. In cases of excellent quality control, the distribution of compressive strength results is better modelled by a normal distribution; in cases of poor control, it is better modelled by a lognormal distribution. In other words, excellent quality control, which generally results in a low coefficient of variation, yields a unimodal distribution of compressive strength values which is symmetrical about the mean. Poor quality control, generally characterized by a higher coefficient of variation, yields a unimodal distribution of test results, which is positively skewed(7). It follows that if one assumes compressive strength as the index of concrete quality control, there is an aleatory variable, then the quality of the concrete also becomes an aleatory variable and thus quality control, to be of significance, must be based on statistical laws.

Statistical quality control normally includes(8)

— systematic acquisition of test data;
— computation of statistics;
— graphical plot of data in the form of control charts; and
— checking of data against acceptance criteria (i.e. rules for compliance with specifications or building code).

2. TECHNIQUES OF QUALITY CONTROL

2.1 Concept of Control: Principles

In quality control, we find two autonomous, yet connected, parts—production control and conformity control.

2.1.1 Production control or "Self-control"

This is a set of actions and decisions taken during production to regulate output and obtain a reasonable assurance that the specifications will be met.

Two phases can be identified in production control—initial test and the controls made during production. The initial test, made before production begins, aims to verify whether the concrete required can be realized with the materials available(9). The quality and compatibility of the materials and components of concrete are verified on the basis of both past experience and appropriate tests. The tests refer mainly to the consistency to the strength of hardened concrete, impermeability to water, resistance to freezing and to abrasion, etc.

In the production phase, the manufacturer himself organizes his own quality control of homogeneous concrete supplies without any supervision or intervention on the part of the buyer. On the basis of a large number of results, the manufacturer determines the average and the dispersion values of the consistency, compressive strength, cement, water content, air content, etc. Thus, he will know the theoretic dispersion curve for each of these values and to what it is associated as, for example, in the case of compressive strength, a well-determined value of characteristic strength. In this case, the manufacturer establishes a criterion which allows an agreement between the characteristic strength required and that of the concrete supplied to be verified. The manufacturer, in the control phase, verifies that the concrete obtained posseses the prescribed quality in all its characteristics, modifying, if need be, the initial conditions if the level is not achieved.

In all this, training of personnel and the provision of equipment control is involved. The personnel involved in the production and control of concrete shall have appropriate knowledge, training and experience for its task. At the production place, there shall be a person with appropriate knowledge and experience who shall be responsible for production, and in the case of ready-mixed concrete, also for delivery. He or his appropriately trained representative shall be present while production is running(10).

Equipment control is particularly important from the viewpoint of production constancy and serves mainly the producer's interest. It concerns planning and maintenance of the weighing plant, mixing and transport of concrete. The quality control personnel must ensure their reliability.

2.1.2 Conformity control or 'Out-control''

Acceptance control is effective at the moment of use and is carried out at the moment of casting to establish whether or not the concrete conforms to the requirements of the project and can be accepted or not.

Conformity criteria which define the acceptance control so far as compressive strength is concerned, are not intended to determine the characteristic strength or the theoretic distribution curve to which a certain supply of concrete belongs but to establish, through a limited number of tests, whether a particular batch of concrete can be accepted since it conforms to the characteristic strength required, or refused if it does not do so. Practical and economic reasons make it necessary to base the acceptance of the concrete on conformity cirteria involving a limited number of tests. This means that one cannot completely ensure that the supply responds to the characteristic strength required. A certain risk will remain in that a good quality product may be judged unsuitable on the basis of valid, pessimistic but necessarily few test results (manufacturer's risk) or, conversely, an unacceptable quality product may be judged acceptable on the basis of over-optimistic but valid results (buyer's risk). Such a risk must not be too high since the security of the construction may be dangerously compromised by the acceptance of poor quality concrete.

In accepting a prescribed composition concrete, control must normally be made on the composition of the mix. Usually, acceptance tests refer to the maximum size of the aggregate, the cement content and the proportion of the components, particularly of water and admixtures, and the extent of air content, when required. However, given the importance of the compressive strength of concrete on the stability of the construction, and the indirectness of the composition's verification, starting from strength tests, the compressive strength values can equally be used.

2.2 Mechanics of Control

Testing involves a series of activities such as sampling, sample handling and preparation, the actual measuring itself and finally, data processing. The reliability of such a chain of procedures depends on the weakest link as the overall random error of testing is estimated from the sum of variances of each individual step.

$$S_{(total)}{}^2 = S_1{}^2 + S_2{}^2 + S_n{}^2$$

where S_1 = random errors in sampling
S_2 = random errors in sample preparation
S_n = random errors in data processing

From this law of error propagation, the following important conclusions can be derived:

- an error which has been committed in the testing procedure cannot be compensated by increased precision in the subsequent testing steps;
- the individual errors of the sequence should be of similar size; there is no point in increasing the precision of one step as long as others are decisive for the overall error. Therefore, it is necesary to determine the precision of the individual steps in each control.

2.2.1 Sampling

It is impossible to over-emphasize the importance of proper sampling. Under these aspects it is evident that sampling must be considered a crucial step in testing. No amount of care and accuracy in subsequent testing will provide correct information if the samples are carelessly taken and do not represent the material sampled. Procedures should be set up for gathering samples in such a manner as to provide the maximum possible information on the average characteristics and the nature and extent of variability of materials.

A sample or samples shall be taken in such a way that the resulting sample is representative for the batch to be inspected. Generally, test portions should be taken from a laboratory sample using a sample divider or by quartering. To assess repeatability, duplicate test portions are needed. Repeatability is defined in terms of the range between two test portions which have been obtained by separate sample reductions. With these procedures, any variability which may be introduced by the sample reduction operations will be apparent in test results and so it can be checked by comparing the between-test-portion range with a quoted value of repeatability.

The frequent occurrence of all sorts of large errors — systematic as well as random—call for an adequate planning of sampling (procedures and techniques) on the basis of fundamental principles:

- for economic and technical reasons, it is necessary to rely on a limited number of small samples to assess and control the basic material quantity;
- the frequency of sampling has to be determined according to the variability of the basic quantity whereby the correlation between subsequent samples has to be considered; if the individual samples are not correlated, the sampling error of a resulting composite sample is reduced by $\sqrt{n}$;
- each subsequent step of reduction in sample size by crushing, grinding and splitting represents a further step of sampling with its own inherent error; and
- in the course of further sample treatment, any alteration of the sample, e.g. by the loss of fines as dust or by contamination, has to be carefully avoided (systematic errors).

Consequently, for the design of an acceptable sampling procedure, the following criteria have to be established:

- determination of the basic material quantity (e.g. mixing bed, silo volume, etc.);
- estimation of the minimum size for each individual sample (guideline: approx, for coarse material 30-40 times the weight of the largest grain, but at least 5 kg);
- variability of material to be sampled (estimation of standard deviation by experiment) and from this the sampling interval; and
- definition of the desired overall sampling accuracy.

With respect to sampling place and technique a differentiation must be made between sampling stationary material (static sampling) and sampling a material stream (dynamic sampling).

It must be stated that static sampling should be avoided whenever possible, as this generally makes it much more difficult to establish representative samples. Special procedures are required to establish representative samples from trucks, piles, etc. Dynamic sampling is always recommended. For all of these, the use of automatic samplers where the frequency and/or accurancy of sampling must reach a high level, is strongly recommended. The timing of drawing samples out of the continuous production process is determined by random numbers. One can obtain a random sample also by taking samples out of the continuous production process at equal intervals(12). There are numerous types of automatic sampling systems but many of them are subject to considerable systematic errors. Therefore, a thorough selection of suitable equipment is required, wherein the following factors have to be taken into consideration:

- material characteristics (grain size distribution, consistency, humidity, stickiness, etc.);
- sampling site (to avoid systematic errors due to segregation, sampling of partial material etc.; particularly suitable are transfer points in the material transport system);
- sampling conditions (size of material flow, material humidity, simplicity of control);
- sampling frequency (type and size of material variability, purpose of sampling); and
- reliability and simplicity of sampler.

2.2.2 Testing

Regardless of the method of analysis and the physical testing procedures applied in quality control, each testing laboratory must be aware of:

- the size of random errors for the individual testing procedures; they are determined by systematic experiments; and
- the type and size of systematic errors between different operators within the laboratory (to be evaluated by within-lab-experiments) and of the laboratory in comparison to other testing organizations (by experiment between laboratories.

These are prerequisits for the optimization of testing procedures and for establishing reasonable control limits for quality control.

In addition to the basic test methods for routine control, a large variety of sophisticated methods and procedures are applied for material technological investigations in connection with special manufacturing and application problems and in research and development.

Test procedures for the control of concrete characteristics are specified to the last detail by the standards. Generally, the standards make it very difficult or impossible to compare results obtained by different testing procedures. Also, repeatability and reproducibility of testing vary from one standard to another. Attempts to establish international standrds (e.g. ISO) show only very slow progress(13).

2.3 Quality Control Charts

Quality control charts have been used by manufacturing industries for many years as an aid in reducing variability in production.

Control charts are special time-plots to show a possible change of the characteristics in a production process. For example, in concrete production, compressive strength, consistency and water-cement ratio can be controlled. Special control limits can be calculated and drawn in the chart. Values outside the control limits indicate the process to be out of control. A control chart is an effective means to show the variation of test results. Plotting of the individual test results in sequence is suitable for detecting non-sustained changes, such as occasional 'wild' results departing from the general pattern. Plotting of the running mean of a number of consecutive test results (say five), as advocated by ACI 214-77(13), is an alternative which shows the trend more clearly by evening out the very short-term irregularities(8).

An illustration and example of a control chart is given in Figure 1. At predetermined intervals, n samples are taken and the characteristics under examination determined. Average is made and the result plotted on the control chart. If the point is sited in zone A, there is no reason to suppose that there is a shift in the production process. If the point is in zones B or C, there are 2.5 chances in 100 that a shift exists; changes are not made to the production process but the control is repeated immediately. If the representative point of A average falls in zones D or E, the process of production is 'out of control', that is, there has been a shift in the process level. Action is called for whenever a point exceeds the limits. In the same way, one controls dispersion increase(14).

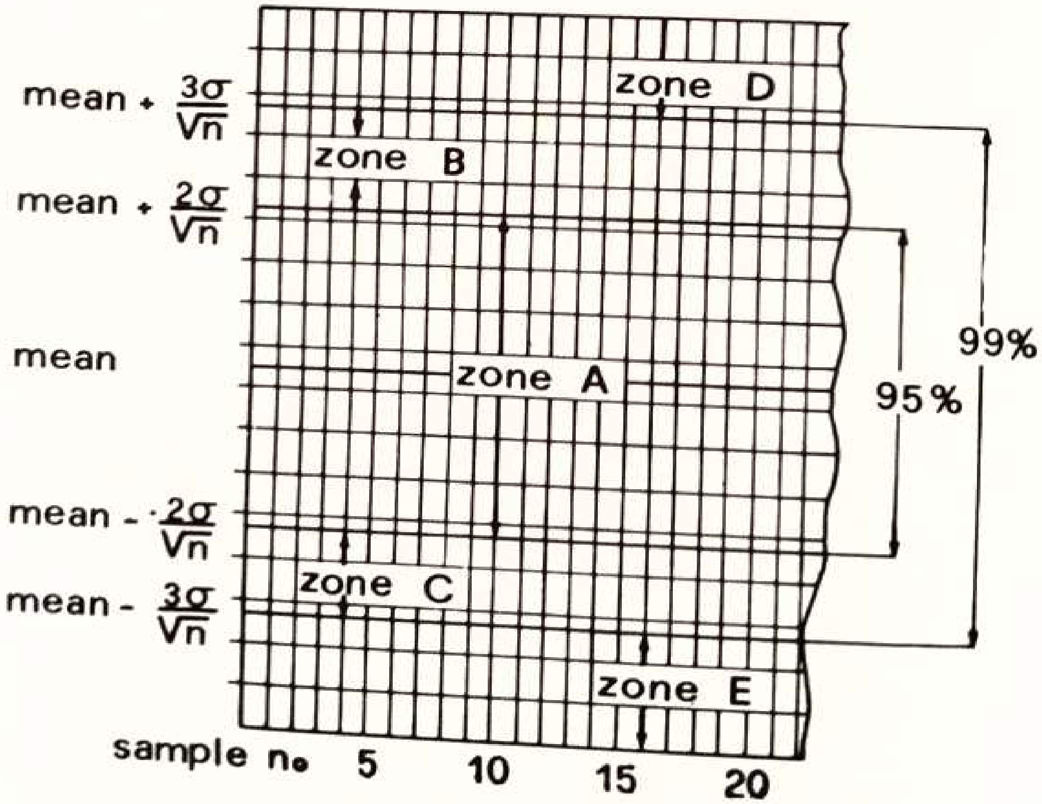

Figure 1. Control chart for the mean (n = number of the samples).

What usually happens in practice when quality control charts are introduced is that after establishing control limits on the basis of 20 or more samples, and after searching for and eliminating the causes of process trouble, every time a point falls outside the control limits, it is soon found that the variability from mean to mean becomes smaller than it was for the initial set of samples.

A new set of samples can then be taken and new upper and lower control limits established. These control limits, in practice, will usually be closer together than the original ones. After a few stages of this kind, we arrive at a stage of statistical control involving control charts. These are mainly used to detect assignable causes of out of control readings to determine whether concrete meets the specifications and can be accepted with or without minor adjustments, and to determine whether the process is capable of manufacturing concrete with the required properties as described in the ASTM Manual on Presentation of Data and Control Chart Analysis(15).

One should not be satisfied merely with the observation that 'all points are in control'. For example, a control chart may indicate a trend (an increase or decrease of the means) or a periodic fluctuation of the values and if this is repeated, one may examine the production process and try to eliminate the cause of that behaviour.

3. RAW MATERIALS CONTROL

Concrete, being a hardened mass of heterogeneous material, is subject to the influence of numerous variables. Characteristics of each of the ingredients of concrete, depending on their variability, may cause variations in the behaviour of concrete. Variations may also be introduced by practices used in proportioning, mixing, transporting, placing and curing. In addition to the variations which exist in concrete itself, variations will also be introduced by the fabrication, treatment and testing of test specimens. Variations in the properties of concrete must be accepted but concrete of adequate quality can be produced with confidence if proper control is maintained, test results are properly interpreted and their limitations are considered.

Proper control is achieved by the use of satisfactory materials, correct batching and mixing of these materials and good practices in transporting, placing, curing and testing. Although the complex nature of concrete precludes complete homogeneity, excessive variation of concrete properties signifies inadequate concrete control.

Strength is not necessarily the most critical factor in proportioning concrete mixes, since other factors, such as durability, may impose lower water-cement ratios than are required to meet strength requirements. Nevertheless, strength tests are valuable in such circumstances since, with established mix proportions, variations in strength are indicative of variations in other properties.

The water-cement ratio, to a large extent, governs the quality of the hardened portland cement binder. Strength, impermeability and most other properties of concrete are improved by lowering the water-cement ratio. A comparison of strength values given in Figure 2(16) shows considerable variation from a uniform relationship between the water-cement ratio and strength. The useful life of concrete is ordinarily limited by its permeability. Concrete has a tendency to be porous due to the presence of voids formed during or after placing. First, it is usually necessary, in order to obtain workable mixes, to use far more water than is actually necessary for chemical

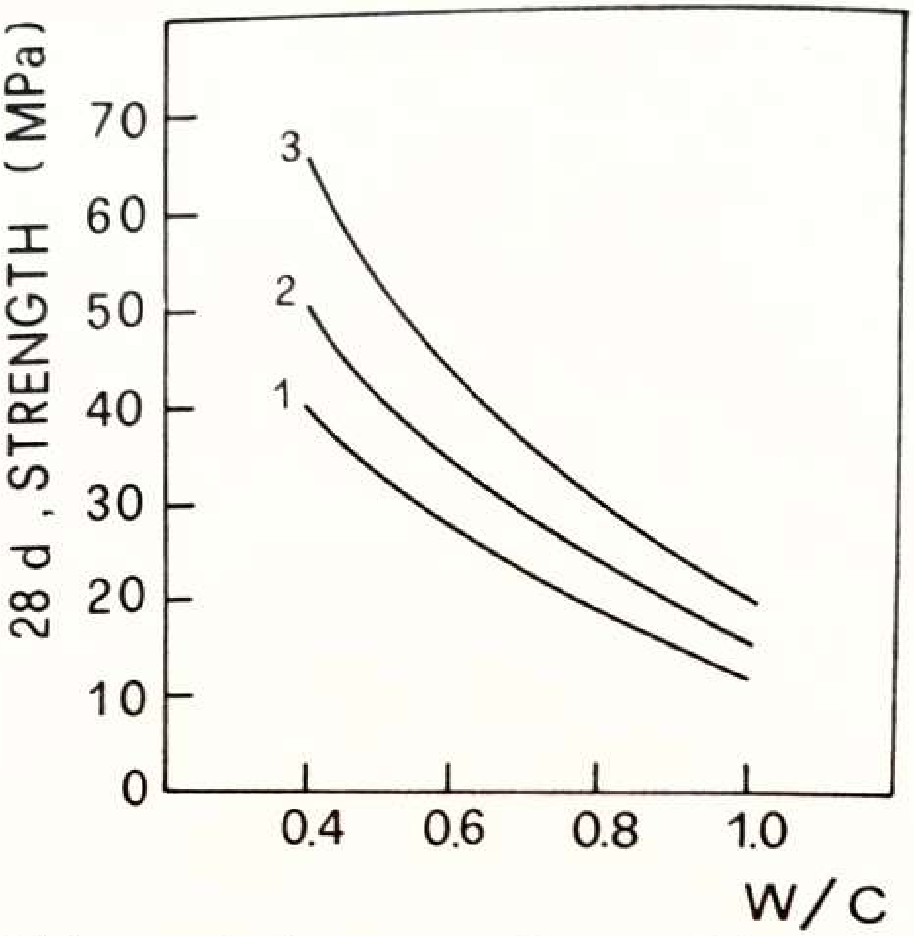

Figure 2. Water-cement ratio vs compressive strength for various strength class cements.

1. Portland cement, Class 35
2. Portland cement, Class 45
3. Portland cement, Class 55

combination with the cement. This water occupies space and when it dries out later, it leaves behind air voids. In addition to these initially water-occupied voids, there is always a small percentage of entrained air voids. Secondly, there is a decrease in the absolute volume of the cement paste which, when dry, occupies less volume than the fresh paste, whatever the water-cement ratio.

If proper care is taken, cement can be made sufficiently impermeable for most purposes without the addition of any special materials. From the above analysis of the cause of voids, it is clear that for the most dense and least permeable concrete, the water-cement ratio should be reduced to a minimum, consistent with adequate workability for thorough compaction without segregation. A compromise is, therefore, required between a low water-cement ratio and adequate workability, and the best conditions will depend on the type of structure and the method of compaction(17).

Factors totally or partially independent of the water-cement ratio, which affect the quality of the hardened concrete, are:
— the type and brand of cement;

- the amount and type of hydraulic additions;
- the surface texture and shape of the aggregate;
- the quality of the aggregate (strength, soundness and porosity);
- the aggregate grading;
- the type of admixture;
- the compacting process; and
- curing.

To find out the causes for inferiority or changes in quality, in a first retrospective analysis of available data, parallel changes of parameters and quality are studied. This is done by performing a regression analysis. The disadvantage of retrospective studies is the difficulty to detect casual relationships. The effect of several variables are mixed and cannot be separated due to their casual origin. On the other hand, an observed correlation indicates a possible casual effect. The decision about what cause is really responsible must be made by an experienced specialist and not by a statistical test. Often a decision is not possible because dependences are too complex. In this case, a special experiment has to be planned and performed with a controlled variation of suspected variables and careful elimination of interfering effects (prospective analysis). In contrast to the retrospective analysis, an adequately designed experiment makes it possible to evaluate and judge casual effects with statistical methods.

Discrepancies in sampling, fabrication, curing and testing of specimens may cause indications of variations which do not exist in the concrete in the structure. Good testing methods will reduce these variations and therefore standard testing procedures should be followed.

The selection of materials is not easy since many variables will affect the quality of the concrete produced, and both quality and economy must be considered.

3.1 Cement

3.1.1 *Cement type*

Portland and blended cements of the same strength class do not harden at the same rate, but at ages of 28 days, the variation in compressive strength is small compared with that at early ages. However, blended cements are more sensitive to curing temperature(18).

With the development of modern building technology the consumer is not only interested in the level of strength but also in the uniformity of the cement characteristics. Cement should be selected according to the type of work—massive concrete or thin structures—the final performance required and the environment conditions.

Portland and blended cements, when used in properly proportioned concrete, will provide similar compressive strength and abrasion resistance while a cement, from a rheological point of view, can behave more favourably than others. On the other hand, protection against chemical attack is obtained by using a proper cement type. Recommendations for the type of cement for normal concrete which will be exposed to sulphates or groundwater and mountain water containing large amounts of dissolved carbon dioxide, are given in Tables 1(19) and 2(20).

Table 1. Composition requirements of special sulphate-resistant cements

Cement	Chemical resistance		
	Moderate	High	Very high
Portland	$C_3A \leqslant 8\ \%$	$C_3A \leqslant 5\ \%$ $2C_3A + C_4AF \leqslant 25\ \%$ or $C_4AF + C_2F \leqslant 25\%$	$C_3A = 0$ $C_4AF \leqslant 20\ \%$ or $C_4AF + C_2F \leqslant 20\ \%$
Pozzolanic	no particular prescription	$C_3A \leqslant 6\ \%$	$C_3A \leqslant 3.5\%$
Blast furnace slag	slag $\geqslant 36\ \%$	slag $\geqslant 70\ \%$	slag $\geqslant 70\ \%$ and $C_3A < 2\ \%$ in clinker

Table 2. Composition requirements of special leaching resistant cements

Cement	Leaching resistance		
	Moderate	High	Very High
Portland	$C_3S \leqslant 40\ \%$	—	—
Pozzolanic	no particular prescription	no particular prescription	pozzolanic test positive at 8 d
Blast furnace slag	slag $\geqslant 36\ \%$	slag $\geqslant 50\ \%$	slag $\geqslant 70\ \%$

A portland cement with low C_3A content, while being favourable with regard to the sulphate attack, is unfavourable from the viewpoint of chloride penetration(21).

The problem of chloride penetration is directly linked to the velocity of transport of chloride ions through the hardened cement paste. The effect of the type of cement upon the rate of chloride ion diffusion through hardened cement paste and mortar has been studied by various investigators. Recently, Rio and Turriziani(22) have shown that this rate of diffusion through hardened cement paste is greatly reduced by using blended cements.

The use of a type of cement—low alkali portland cement or slag cement (cement with a minimum blast-furnace slag content of between 65 and 70%)—which prevents harmful reactions between alkalis and aggregates is to be recommended strongly when aggregates which have the potential to expand are present. The different portland and blended cements, when manufactured in air-entrained concrete, will provide similar resistance to cyclic freezing.

3.1.2 *Cement Content*

Concrete of reasonable strength, properly placed, is durable under ordinary conditions but when high strength is not necessary and the conditions of exposure are such that high durability is vital, it is the durability requirement that will determine the water-cement ratio to be used(23). It is generally known that the strength and impermeability of concrete increases with the cement content. If the water-cement ratio is maintained constant, an increase in the cement content improves the workability of the mix without affecting the strength.

Generally, national standards give minimum cement contents required in concrete to ensure durabilty under specified conditions of exposure. For example, the values required from the British Code of Practice for the Structural Uses of Concrete CP 110:1972 are reported in Table 3 for reinforced, pre-stressed and plain portland cement concrete for maximum aggregate sizes of 20 mm.

Table 3. Minimum cement content of concretes under different conditions of exposure (maximum aggregate size: 20 mm)

Exposed to	Minimum cement content (kg/m³)		
	Plain concrete	Reinforced concrete	Prestressed concrete
Non-corrosive conditions	220	250	300
Rain and freezing	250	290	300
Sea water or wetting and drying	310	360	360
De-icing salt	280	290	300

For better resistance to freezing and better resistance to external agents in general, it is essential to use a relatively high cement content which affords increases in impermeability and compressive strengths of concrete(24).

The main causes of non-structural cracking in concrete are drying, shrinkage and cracking due to temperature, connected to the fact that temperature alterations cause volume change(25). Thermal deformation may occur in consequence of heat due to the hydration of the cement in concrete(26). The higher the initial temperature of the fresh concrete, the more rapidly will the heat of hydration be released. It produces a temperature gradient in the young concrete. This effect is intensified by the very large differences between day and night temperatures. The maximum temperature attained in hardening concrete can be controlled by lowering the initial temperature of the fresh concrete and by an appropriate choice of cement type and cement content in the mix(21).

3.2 Hydraulic Additions

Finely divided inorganic, pozzolanic or latent hydraulic material may be added to concrete either to reduce the cost or to modify the properties of the concrete, e.g. by reducing the rate of heat-evolution in thick sections. Obviously, additions must be made to the mix in such quantities that they do not impair the durability of the concrete and do not cause corrosion of the reinforcement.

3.2.1 Ground Granulated Blast-Furnace Slag

The early 1960s saw the commencement of the manufacture of separate ground granulated blast-furnace slag (GGBFS) which could be blended with ordinary portland cement in the concrete mixer as a partial replacement for portland cement to produce portland blast-furnace cement concrete.

It is important that the molten slag emerging from the blast-furnace has been well quenched and rapidly cooled; slag which has cooled slowly and crystallized will not exhibit good cementitious properties. To check this, a glass count is carried out. This differentiates between glassy particles and crystalline particles. The test is carried out by reflected light microscopy. The ground slag is mounted in resin, cut, polished and etched before being viewed at 600 × magnification. One thousand individual particles greater than 5 microns are examined and categorized as either 'pure glass', 'glassy' (containing glass with crystalline intrusions) or 'other types'. According to Higgins(27), the slag must contain a minimum of 40% 'pure glass' or 85% 'glassy' particles.

According to Yuan Runzhang et al.(28), the more the content of vitreous substances, the higher is the hydraulic activity of slag when the chemical composition is roughly kept the same.

There are also limits on the chemical composition. The chemical modulus:

$$(CaO + MgO + Al_2O_3)/SiO_2$$

has to be greater than 1.0 to ensure that the slag is chemically reactive(27). The hydraulic behaviour of the slag is influenced by the actual soluble alkalis in the concrete(29).

Concretes made with high blast furnace slag content (> 65% of cement content) show resistance detrimental to alkali-aggregate reaction, compared to concretes made with ordinary portland cement(30)(31). Blends of 70% or more slag with portland cement can be used in sulphate environment(32)(33).

Considerable benefit has been obtained in massive constructions by significantly reducing the early temperature rise of concrete, by using ground granulated blast-furnace slag without detriment to later strength development(32).

Compressive strength concrete can be improved (60–80 MPa) by the use of very finely ground granulated blast-furnace slag (715m^2/kg) as a partial replacement for portland cement. It was found that high compressive strength could be obtained together with improvement of permeability and resistance to chloride penetration even if very fine ground slag was substituted for cement at a replacement level of 70%(34).

3.2.2 *Pozzolans*

A pozzolan is defined as a material which in itself possessess no cementitious value but will, in finely divided form in the presence of water, chemically react at ordinary temperatures with calcium hydroxide liberated during the hydration of portland cement to form a stable strength producing cementitious compound. Pozzolans added separately to the mixer, in amount approximately 15 to 25 per cent of the portland cement, increase the life expectancy of concrete in sulfate exposures considerably since compounds produced by the reaction between pozzolans, hydrated lime and water confer impermeability on concrete, reducing the concrete's tendency to destruct.

Pozzolanic activity defines the series of phenomena transforming mixes of lime, pozzolan and water into a compact, hard material having a stony appearance and characteristics. The activity of a pozzolan depends on many factors:

- chemical composition;
- mineralogical composition;
- specific surface; and
- thermodynamic instability.

They are often interdependent but not always correlatable. However, they are not sufficient to determine the activity of a material.

The evaluation of pozzolanic activity was the object of many studies. All the proposed methods substantially aimed at evaluating the mechanical properties of mixes of pozzolan with lime or portland cement by chemical, physical or mechanical determinations.

The chemical ones are based on the measurement of the amount of lime fixed by the material as a function of time or the amount of $SiO_2 + Al_2O_3$ present in the pozzolan that becomes soluble after the reaction with lime or sodium hydroxide(35).

As for the physical methods, the heat evolved during dissolution of the natural pozzolan in a $HNO_3 + HF$ mix or the increase in the specific surface of the hydrated pastes of lime and pozzolan, as a function of time or the content in vitreous phase as determined by X-ray diffraction, were used as an index of reactivity of these materials.

Mechanical methods are based on the measurement of the mechanical strengths of lime-pozzolan and cement-pozzolan mortars(36).

It is well-known that reactive pozzolans can be used to control the expansion associated with the alkali-aggregate reaction.

Caution must be exercised in the selection and use of pozzolans as their properties vary widely and some may introduce adverse properties into the concrete, such as excessive drying shrinkage and reduced early strength. Before accepting a pozzolan for a specific job, it is advisable to test it in combination with the cement and aggregate to be used so as to determine the advantages or disadvantages of the pozzolan accurately with respect to the quality and economy of the concrete.

Under the term 'pozzolan', natural and artificial products of different origin are grouped together.

3.2.2.1 Natural Pozzolans: Natural pozzolanic materials occur in large deposits in the form of pumicite, volcanic ashes, tuffs, clays, shales and diatomaceous earth. These natural pozzolans usually require grinding. However, some of the volcanic materials are of suitable fineness in their natural state.

3.2.2.2 Fly Ash: According to ASTM C 618(37), fly ash is classified in Class F or Class C. The former is produced by burning anthracite or bituminous coal and has pozzolanic properties but few or no cementitious properties. Class C ash results from the burning of lignite or sub-bituminous coal and has some pozzolanic properties as well as autogenous cementitious properties. The general principle of combining fly ash with the minimum cement content and taking it into account in determining the water-cement ratio presupposes that a sufficient high contribution to the strength and especially also to the durability of the concrete will always be ensured. Therefore, regular checking of the activity of the ash in the context of quality assurance is essential.

The effect of fly ash in improving the quality of concrete is attributable to several causes. In this context, a fundamental distinction is to be made between a chemical and a physical effect. Because of the pozzolanic reaction, especially that of the amorphous silica in the ash, together with the calcium hydrates and the resulting denser matrix containing less capillary pore space, fly ash can make a contribution to strength and durability. Since the pozzolanic reaction proceeds at a relatively slow rate, the favourable effect of fly ash manifests itself more particularly at a fairly advanced age of the concrete. Furthermore, by complementing the grading of the other components of the concrete mix (Fuller's effect), fly ash has a strength and density enhancing effect. Finally, the rheological behaviour is due to various causes such as the spherical particle shape and smooth particle surface of the fly ash ('ball-bearing action')(38).

Since the various factors that exercise an influence on the activity of the ash can be determined only by means of tests on mortar or concrete, testing methods based on this approach have been developed in many countries. As a rule, the ratio of the compressive strengths of mortars made with and without fly ash is adopted as the criterion of assessment. This characteristic value is called the pozzolanic activity index. In the United States, a minimum value of 75% is required for this index (ASTM C 618(37)), in Britain a value of 85% (BS 3892(39)) but the test mortars used in the respective countries differ in composition and in conditions of curing(38).

The major disadvantage of mortar testing methods is that the results become available only after a relatively long time so that rapid assessment of the properties of fly ash is made difficult. Yet such assessment is necessary, for example, in deciding what control measures to take for optimizing the quality of ash in the operation of a power station. A number of relationships between fly ash characteristics and properties of mortar and concrete made with fly ash are known which can be used fundamentally for the assessment of fly ash(38).

Only the amorphous predominantly glassy constituents of the ash particularly amorphous silica, participate in the pozzolanic reaction. Accordingly, in the future European Cement Standard EN 197(40) for fly ash used in cement manufacture, the content of reactive silica is specified at not less than 25%. The prescribed method of determination is by dissolution with potassium hydroxide in accordance with EN 196 Part 2(41).

While using fly ash, it should also be noted that apart from its pozzolanic contribution to the properties of concrete, fly ash also influences certain other properties of fresh and hardened concrete, the water requirement in particular (positively or negatively), the bleeding (reduction), the setting time (a certain prolongation)(42), and the early age strength. Mix proportioning by the simple replacement of cement by fly ash, either by volume or by weight, does not result in a concrete of equal or higher strength as that of the control concrete even after 90 days of curing. However, the optimum level of the replacement of cement by fly ash depends on the actual amount of cement in the mix(43).

The fineness, expressed as the mass proportion of the ash retained when wet sieved on a 45 μm mesh sieve, is one of the main variables affecting their rheological behaviour(39),(44),(45). This is contradicted by the experimental results obtained by Cabrera and Hopkins(46) that, by a comparative study of several different fly ashes in a variety of ash-cement-water combinations suggest that it is predominantly the physical properties of fly ash that influence the rheology of the system. A requisite of uniformity in terms of fly ash fineness is common to Australian(47), Japanese(48) and American(37) standards.

The use of superfine fly ash will be an effective way for extensive utilization of fly ash (specific surface area about 400-600 m^2/kg(49) or residue very low on 45 μm sieve(50).

The effect of fly ash on the consistency depends on the cement in any particular case. The fineness of the cement would appear to be the main factor in this respect. With decreasing specific surface area, the plasticizing effect is more pronounced, especially with Portland cement. With Portland blast-furnace slag cement, the effect of fineness was less clearly manifest(51) (52).

It is sufficiently well-known that more particularly the fineness and loss on ignition of fly ash significantly affect the water requirement of concrete(53) (54). Gu Zhangzhao et al.(55), experimenting with Chinese fly ashes, did not find a correlation between LOI (loss of ignition), which identify the carbon content, and strength contribution. The absence of correlation cannot mean that it denies the harmful effect of carbon. The critical point is that the presence of carbon affects the ash properties not only in relation to its content but also to its physical properties(56).

3.2.2.3 Silica Fume: Condensed silica fume (CSF) is a by-product of the smelting process used to produce silicon and ferro-silicon alloys. Other names that can be found in the literature for CSF are: micro-silica, ferro-silicon dust, arc furnace silica, silica flue dust, amorphous silica and volatized silica. CSF share the following main characteristics:

— SiO_2 contents from 85 to 98%;
— mean particle size in the range 0.1–0.2 microns;
— spherical shape; and
— the particles are amorphous.

Regarding the pricing of the CSF, it is impossible to give exact figures. Generally, the cost ratio of silica fume to cement is around 2(57). For special products, the price may be as high as fifteen times the cement price.

CSF for concrete use is either in a 'natural' state, densified or in slurry form, mixed with 50% water by weight. General field experience, as well as laboratory tests, have shown remarkably little difference in the properties of hardened concrete containing CSF with different characteristics or in different forms. The type and form of CSF may significantly influence fresh concrete properties, however, and in particular, the rheological properties. It is at present not possible to relate such differences to specific CSF-CSF is used in two principally different ways:

(i) As a cement replacement, in order to obtain reduction in the cement content, usually for economic reasons. For normal low-grade structural concrete, the required strength can be obtained with an extremely low level of cement content when CSF is used.
(ii) As an addition to improve concrete properties, both in fresh and in hardened state(58).

Pozzolanic activity measured by the Fratini test(59) is quite high. This result is also confirmed by applying ASTM 311(60) and ASTM C 618(37) standards for natural pozzolans and fly ash, although the water demand is too high to satisfy the limits of ASTM C 618. This fact is justified if we consider the high specific surface of silica fume, which causes an immediate reaction silica with calcium hydroxide, producing strong particle coagulation. This may be eliminated by using the appropriate dispersing agents(61)

The pozzolanic reaction of silica fume is considered to occur from a relatively early age, after the age of 3 days, because the compressive strength of concrete having 20% silica fume replacement ratio of cement became larger than that of the reference concrete at the age of 7 days(62).

CSF is both high reactive pozzolan(63), (64), (65) and a very effective filler exclusively due to the extreme fineness of its particles, about 50 times greater than that of cement. It is believed to distribute the hydration products in a more homogeneous fashion in the available space. These two factors have the combined effect of refining the pore structure when CSF is added to cement based mixes. The refinement of the pore structure leads to reduced permeability and is considered to be the main factor responsible for the influence CSF has on mechanical and durability properties of concrete. In concrete, with a cement content of more than 250 kg/m^3, the water demand will increase by adding CSF when no water reducing agents are used(66). However, water reducing agents have a much stronger effect in CSF concrete.

The main contribution of CSF to concrete strength development at 20°C takes place from about 3 to 28 days. For a CSF and a control concrete of equal 28-day strength, the strength of the CSF concrete will be lower over the entire time period with 20°C curing. Curing at elevated temperatures has a greater accelerating effect on CSF concrete than on control concrete(66).

The properties of cement based binders changes dramatically when ultrafine particles are homogeneously placed in the spaces between densely packed cement grains. The increased density and refinement of the pore structure of such binders result in considerable increases in properties such as compressive strength, impermeability and adherence to aggregates(67).

The available data indicate that CSF in concrete, for equal compressive strength levels, reduces the permeability(66), (68), (69). Sulphate resistance is improved when 10-15% of the cement is replaced by CSF(70), (71).

The chemical composition of the pore fluid of the concrete is affected by the presence of blending agents in the cement system. Those blending agents that most rapidly lower the CaO-SiO$_2$ ratio of the C-S-H phase are most effective in lowering the alkali content of the pore fluid, thus making it unavailable for reaction with reactive silica in the aggregates; silica fume is a good example(72).

The use of a silica fume not only permitted one to obtain a concrete with a higher 28-day compressive strength with less cement but also a concrete having a better resistance to freezing and thawing than the normal concrete. The concrete with silica fume has a dense microstructure and does did not become as critically saturated as the concrete without silica fume(73).

When silica fume is used with a super water reducing agent, it makes it possible to get high strength concrete, with compressive strength of about 80 MPa at one day by steam curing at normal pressure, and about 45 MPa if curing at room temperature, and over 100 MPA at 28 days. Moreover, the elastic portion and the ultimate strain of the concrete tend to increase(74).

Finally, Holland(75) showed that high strength concrete made with a selected aggregate and with 30% of the portland cement replaced with silica fume, can reduce the abrasion loss by a factor of 3.

3.3 Aggregates

Aggregate is a mixture of particles some or all of which may be crushed or uncrushed and which are composed of natural and/or artificial substances. Since aggregates occupy three-quarters of the volume of concrete, it is to be expected that properties of the aggregate have a major effect on the properties of concrete. For design purposes such as cover to steel and reinforcement spacing etc., the important criteria are that aggregates should be defined by the highest sieve size in its designation of aggregates, it may be convenient to describe them by defining the theoretical sieve sizes at which 10%, 50% and 90% are calculated to pass and determined graphically by interpolation. Whilst useful for laboratory comparisons, it is not intended that aggregates should be specified in this manner(76). Sieve sizes shall allow for a progressive sizing of the aggregates into fractions and normally be based on a logarithmic or geometric progression (e.g. $\sqrt{2}$). Intermediate sizes may also be selected and included where required(76). The aggregate should be durable under normal environmental conditions and should not excessively soften, disintegrate or change volume. Sieve analysis, specific gravity, absorption and moisture content of both fine and coarse aggregate and dry-rodded unit weight of coarse aggregate are physical properties required for mixture computations. Other tests which are essential include petrographic examination and tests for chemical reactivity, tests for soundness and resistance to abrasion.

Samples for test representing the various aggregate sizes batched should be obtained as closely as possible to the point of their introduction into the concrete. The difficulty in obtaining representative samples increases with the size of the aggregate. The method of taking samples will have an important influence on the accuracy of the results, and reference should be made to national standard, for example BS 812: Part 1(77) for the correct procedure. Important points to note are(17);

- under favourable conditions, at least ten portions (increments) should be drawn from different parts of the bulk. All the increments should be combined to form the main sample to be sent to the laboratory,
- the minimum size of each individual sample is mainly dependent on the grain size distribution of the material, particularly with respect to its maximum grain size. The German specification(78) states that the minimum weight of each individual sample for coarse material must be at least 10 × the weight of the largest grain.
- in difficult circumstances, a greater number of increments will be required so that the main sample may be larger and therefore more truly representative of the bulk. It is difficult to sample accurately from stockpiles where there may be segregation of the coarser material towards the base and sides. Similarly, 'sandwich loaded' vehicles into

which different sizes of aggregate have been loaded one after another cannot be sampled satisfactorily and a proper sample can only be taken after the load is mixed.

- sampling is best carried out when the aggregate is being loaded into or unloaded from vehicles, or when it is being discharged from a conveyor belt.
- when sampling rock direct from a natural outcrop or from a pit or quarry face, special care should be taken to ensure that samples are truly representative of the range of variations over the whole of the quarry face, vein or bed, later to become the source of the aggregate, at the laboratory, the main sample should be reduced to the quantity required for testing, using a sample divider which extracts representative parts of the whole or by quartering. When reduction is made by quartering, fine and all-in aggregates are most accurately mixed and quartered when a damp condition, if necessary, is achieved by sprinkling with clean water before mixing.

3.3.1 Grading Curves

Grading of the fine and course aggregates and the proportions used have a definite effect on the water requirement of concrete made from a given aggregate and thereby has an effect on all the properties of concrete related to water requirement. It also has an important effect on the workability and finishing characteristics of fresh concrete. Sieve analysis is probably the most frequently made of all aggregate tests. Particle size distribution is determined directly by passing samples of the aggregate through a nest of sieves of successively smaller openings and weighing the material retained on each sieve. This procedure also esablishes the maximum size of particles present in the sample.

Numerous aggregate grading curves have been proposed but a universally accepted standard has not been developed. The well known Fuller curve is widely accepted as a good grading curve. In mathematical terms, it can be described as:

$$P = (d/D)^n \times 100$$

where d = sieve opening
D = maximum size of aggregate
P = cumulative percent passing sieve size d
n = factor related to the particle shape and texture of the coarse aggregate.

The exponent n is usually in the range of 0.4 to 0.5 with rounded aggregate assigned the higher number. However, the theoretical methods are only devices for obtaining an initial approximate coarse aggregate grading.

For a high-quality visual concrete, the grading limits for coarase aggregate in British Standard BS 882(79) permit a high proportion of 10–5 mm material in the 20–5 mm range. For this reason, coarse aggregate should be obtained in two separate sizes, 20–10 mm and 10–5 mm. They may then be combined in the proportions required for the concrete mix(80).

3.3.2 Particle Size

The maximum aggregate size has to be chosen so that the concrete can be placed and compacted around the reinforcement in a satisfactory way without being segregated. However, the nominal maximum size of the aggregate shall not exceed(10)

- — one quarter of the smallest dimension of the structural member,
- — the distance between the reinforcing bars less 5 mm,
- — 1.3 times the thickness of the concrete cover,

Theoretically, the larger the maximum aggregate size, the lesser the cement required in a given volume of concrete to achieve the desired quality. However, it has been demonstrated that to achieve the greatest cement efficiency, there is an optimum maximum size for each compressive strength level to be obtained with a given aggregate and cement.

3.3.3 Particle Shape and Texture

A primary consideration in concrete aggregate selection and use is particle shape. Ideally, we would like to have a well-graded aggregate composed entirely of spherically shaped particles. The workability, finishability and low water-cement ratio which could be realized with such material would be excellent . However, in the natural sands and gravels deposited for our use, nature is almost never that cooperative. Furthermore, nature makes the manufacture of a reasonably acceptable, well-shaped aggregate from crushed quarry rock even more challenging(81).

The flat shape is the least favourable since it is difficult for the elements to lie side by side. Instead they tend to form a felt with voids, causing difficulties in concrete working, for example, during pumping. For like volumes, these aggregates present a greater surface and require a larger volume of cement paste, with higher cost, to obtain a determined concrete workability.

The aggregate shape is characterised by the ratios of the dimensions of the smallest rectangular prism into which the nominal size aggregate particle can be fitted. Particles are classified as flasky when they have a thickness (smallest dimensions) significantly less than their nominal size, this size being taken as the mean of limiting apertures used for determining the size fraction in which the particle occurs(76). Aggregates are classified as elongated when they have their lengths (largest dimension) significantly greater than their nominal size, this size being taken as the mean of the limiting sieve apertures used for determining the size fraction in which the particle occurs. The elongation index of an aggregate sample is determined by separating the elongated particles and expressing their mass as a percentage of the mass of the sample tested(76).

Angularity or roundness is a distinct feature of the shape and refers to the state of abrasion at the edges of the stone elements. The angularity, as shape, can affect the workability of the fresh concrete and the mechanical strength of the hardened one. Rounded aggregates act like dosages of cement and water and render the concretes more workable. This means that at an equal level of workability, it is possible to obtain more resistant and durable concretes for a lower water-cement ratio. The effect of sharpness on the workability, and thus indirectly on all the properties of the hardened concrete, is anything but negligible.

A testing method was developed for determining voids in individual sand size fractions as an indirect measure of particle shape. The results of the tests reveal the following:

- the more angular the sand, the greater will be the water requirement to produce a given consistency,
- the higher the percentage of voids in a given sand, the lower will be the compressive strength,
- the detrimental effects of freezing and thawing are greatly reduced when the stone sand is processed to have less voids and thereby requires less water.

In the United States, the National Crushed Stone Association suggests limiting the void content to not more than 53% as determined by their particle shape test(81).

Acceptance testing provisions for quality control during construction specify that at least one particle shape test on both fine and coarse aggregate would be made each week for a minimum of 3 months during the initial placement of concrete. Additional tests would be made as needed should workability, pumpability or some other unusual observation of concrete mixtures warrant further testing. If the records of tests indicate consistent results within the specification requirements for the 3-month initial period, then, thereafter, the aggregate need only be visually examined each day and the test performed once a month(81).

The surface texture of the aggregates is a feature regarding the arrangement of the crystalline grains and pores of the aggregate surface. Qualitatively, it is distinguished by a glassy, smooth, granular, rough, crystalline and porous texture. Quantitatively the surface texture can be assessed by a number of methods all of which are based on the rather sophisticated and laborious techniques of optic and electronic microscopy, projecting the image of a small section on to a screen, and examination of the surface under diffused light(82),(83) etc. Orchard(83) distinguishes two aspects when defining the texture—undulation and roughness of the aggregate—both of which may affect the workability and the aggregate-paste adherence(84). A smooth aggregate, without undulation increases the workability of the fresh concrete but lessens the aggregate-paste adherence so that, like the water-cement ratio, the tensile strength of concrete is lower than that of a concrete containing wavy aggregate.

3.3.4 *Strength*

Strength of the concrete depends largely on the strength of the cement paste, and on the bond between the paste and the aggregate. The strength of the aggregate also affects the strength of the concrete but for many aggregates, the differences are relatively small as compared to those resulting from the differences in the strength of the cement pastes in which they are used. The bond between the paste and the aggregate is influenced by the surface texture and cleanness of the aggregate.

The strength of the aggregate may need to be considered if very weak aggregates are used or if very high strength or wear-resisting concrete is required.

Generally more resistant rocks are those characterized by a high specific weight, fine grain and uniform structure. Also, the mineralogical composition may influence the mechanical strength of the aggregate. In general, silicates are more resistant than carbonates, while the presence of clay materials may seriously compromise the mechanical properties of the aggregate.

Rather than the compressive strength of the rock samples, which is higher than that of the cement mortar, it is important to know the resistance of the aggregate to abrasion. The abrasion resistance of coarse and fine aggregate is an important element controlling the abrasion resistance of concrete. The service life of some concretes may be greatly lengthened by the use of especially hard and tough aggregates. The effect of differences in hardness between aggregates is more pronounced in lower strength concretes; it becomes less in high strenth concrete and toppings.

The resistance of the aggregate to crushing, abrasion or impact is determined by the use of the Los Angeles machine according to ASTM C 131(85) and ASTM C 535(86). The test evaluates abrasion resistance from the increase in fineness produced by tumbling the aggregate with steel balls inside a steel vessel. By determining the percentage of wear on a single sample after two different periods of exposure, the Los Angeles rattler can be used to detect the presence in the sample of constituents that are markedly non-resistant to abrasion. A uniform material yields a percentage of wear at a uniform rate whereas a sample containing a component that is markedly non-resistant to abrasion yields a percentage of wear rapidly at first but with a diminishing rate as the test progresses(13).

3.3.5 Resistance to Freezing and Thawing

Concrete containing a good aggregate will not be resistant to freezing and thawing if the paste is inadequate; nor will a concrete containing a frost-resistant paste, if it contains unsound aggregate particles which are critically saturated. A particle is considered to be critically saturated when there is insufficient unfilled pore space to accommodate the expansion of water which accompanies freezing. The ability of an aggregate to resist large or permanent changes of volume when subjected to freezing and thawing, heating and cooling, or wetting and drying, is related to the porosity, absorption and pore structure of the aggregate. Rocks that can absorb water so as to become critically saturated are potentially vulnerable to freezing.

When the aggregate contains only a few particles of unfavourable pore characteristics, freezing frequently produces, instead of general disintegration, the phenomenon known as pop-outs in which coarse aggregate particles near the surface push off the surface layer of mortar when they expand, leaving holes in the surface.

The measurement of the freezing of the aggregates can be based on the fragmenting of the grains, and thus on the increase of finer materials, following a certain number of freezing-thawing cycles. This method, first adopted by ASTM in 1938 (C 137)(87), was later substituted with a faster method (C 88). This widely used test consists of alternately immersing an aggregate sample in a solution of sodium or magnesium sulphate and drying it in an oven. The enlargement of salt crystals in the aggregate by rehydration during immersion after oven drying is presumed to simulate the increase in the volume of water on freezing in the aggregate pores or cracks. Poor performance is indicated if, after the test, a large part of the coarse aggregate sample will pass a sieve with openings 5/6th of those on which it was originally retained and if, after the test, a large part of the sand sample will pass sieves on which it was originally retained. The sulfate soundness test has not been successful in evaluating the resistance of aggregate to freezing and thawing in concrete. Its failure is apparently due not to the lack of similarity between sulfate crystal growth and ice formation but to the fact that in the sulfate test, the aggregate is tested in the unconfined state. Unconfined freezing tests of aggregate particles have been no more successful than the sulfate test. Aggregate in concrete is surrounded by the fine-grained cement paste of extremely low permeability which greatly alters the exposure conditions(13).

Freezing and thawing tests of aggregate in concrete (RILEM/CDC 1(89), RILEM/CDC 2(90), probably provide the best measure of the soundness of aggregates. These methods permit the comparison of aggregates by subjecting air-entrained concrete containing samples of the aggregates to alternate cycles of freezing and thawing. Deterioration, if any, is measured by the progressive reduction in the dynamic modulus of elasticity. It may also be determined by periodic measurements of weight loss or length. All the methods require the use of moist-cured specimens and they specify thawing in water. The use of accelerated freezing and thawing test has been limited largely to within-laboratory comparison of aggregates.

Laboratory tests on concrete include rapid freezing and thawing tests (ASTM C 666(91)) where its durability is measured by the reduction in the dynamic modulus of elasticity. These tests have been criticized because they are accelerated tests and do not realistically duplicate the actual moisture condition of the aggregates in field concretes. The rapid methods have also been criticized because they require cooling rates greater than those encountered in the field. Also, the small test specimens used are unable to accommodate large aggregate sizes which may be more vulnerable to deterioration than smaller sizes. Because of these objections to ASTM C 666, a dilation test was proposed. ASTM C 671(92) requires that air-entrained concrete specimens be initially brought to the moisture condition expected for the concrete at the start of the winter season, this moisture content preferably having been determined by field tests. The specimens are then immersed in water and periodically frozen at the rate and frequency to be expected in the field. The increase in the length of the specimen during the freezing portion of the cycle is accurately measured. An excessive length change in this test is an indication that the aggregate has become critically saturated and vulnerable to damage. If the time to reach critical saturation is less than the duration of the freezing season at the job site, the aggregate is judged unsuitable for use in that exposure. If it is more, it is judged that the concrete will not be vulnerable to cyclic freezing(13).

3.3.6 Moisture Content

It is well established that concrete properties are governed, to a large extent, by the water-cement ratio. The first criterion for producing concrete of constant characterisitcs, therefore, is a constant water-cement ratio. Since the quantity of cement and added water can be measured accurately, the problem of maintaining a constant water-cement ratio is primarily one of correcting for the variable quantity of free moisture in aggregates(93). Water carried into the mixer on the aggregate must be subtracted from the weight of added water while the scale settings for the aggregate must be increased by an equal amount. Surface moisture is commonly determined in the field by oven drying a sample and subtracting the absorption from the total water content. A knowledge of absorption is essential to field control when surface moisture is determined by drying. Absorption is determined directly from the weights of a sample in the saturated surface-dry and oven-dry conditions (ASTM C 127)(94).

There is a standard test for the direct measurement of surface moisture of fine aggregate, ASTM C 70(95).

Lightweight aggregates, due to their cellular structure, are capable of absorbing more water than normal weight aggregates. Based on a 24-hour absorption test(96), lightweight aggregates generally absorb from 5 to 20% by weight of dry aggregate. By contrast, normal weight aggregates usually absorb less than 2% of moisture. However, the important difference is that the moisture content in lightweight aggregates is largely absorbed into the interior of the particles whereas in normal weight aggregates it is largely surface moisture. These differences become important in mix proportioning, batching and control.

Efforts must be made to ensure a uniform and stable moisture content in the aggregate as batched. The use of the aggregate having varying amounts of free water is one of the most frequent causes for loss in control of concrete consistency.

3.3.7 Wetting and Drying

The influence of aggregate on the durability of concrete subjected to wetting and drying is also controlled by the pore structure of the aggregate. The differential swelling accompanying moisture gain of a material with a large amount of capillary absorption may be sufficient to cause failure of the surrounding paste. The amount of stress developed is proportional to the modulus of elasticity of the aggregate.

3.3.8 Clay, Silt and Dust

The presence of clay, rock dust or other adherent coatings in large quantities causes a serious reduction in strength and unsoundness due to their retarding action on the hydration of the cement. They are most dangerous when they form a coating on the particles of the aggregate and thus prevent the adherence of the cement paste. Clay is also deleterious in concrete owing to its swelling and shrinkage which results from alternate wetting and drying. When clays occur as constituents of some rocks such as limestone, this absorptive character greatly increases the rock's susceptibility to disruption by weathering.

Stone dust is commonly present in crushed aggregates; nearly all coarse aggregate is coated with rock dust and other fine materials. If the fines are loose and do not exceed 2% of the coarse aggregate, no harm is done. Finely divided and uniformly distributed clay or silt in the sand is not harmful in reasonable amount. However, silt and dust should not be present in excessive quantities. Owing to their fineness and therefore large surface area, silt and fine dust increase the amount of water necessary to wet all the particles in the mix(97). In view of this, it is necessary to control the clay, silt and fine dust content of the aggregate.

The requirement of BS 882: Part 2(98) is that the content of all three materials together shall not exceed the following:

— Crushed stone sand	15% in weight
— Natural or crushed gravel sand	3% in weight
— Coarse aggregate	1% in weight

ASTM C 33(99) limits the amount of material passing a 75 μ (No. 200 sieve) to 3% of the weight of sand for concrete, subject to abrasion and 5% for all other concrete. The corresponding value for coarse aggregate is laid down as one per cent.

The clay content is specified separately as 3% in fine and in the range 3.0–10.0% in coarse aggregate in function of type and location of concrete construction.

A method for the determination of material finer than 75 μm sieve, that is, clay and silt, is described in BS 812(77). It consists of washing the silt and clay through a 75 μm test sieve and finding the difference in weight between the original sample and that retained on the sieve. Analogous methods—ASTM C 117(100) and ASTM C 142(101)—permit the determination of the amount of material finer than 75 μm and the approximate determination of clay lumps and friable particles in aggregate, respectively.

Another method is the sand equivalent test. A sample of sand is agitated in a weak calcium chloride solution and the relative volumes of sand and flocculated clay determined. The test provides information on both the amount and the activity of the clay(102).

3.3.9 *Organic Substances*

Natural aggregates may contain organic impurities such as particles of coal or vegetable matter and humus or organic acids which inhibit the hydration of the cement, thereby delaying setting and reducing strength. Not all organic matter is harmful and it is best to check its effects by making actual test specimens. Generally, however, it saves time to ascertain first whether the amount of organic matter is sufficient to warrant further tests. This is done by the calorimeteric test of ASTM C 40(103). The organic content can be judged by the colour of the NaOH solution in which the sample is placed. The greater the organic content, the darker the colour. If the colour of the liquid above the test sample is not darker than the standard yellow colour defined by the standard, the sample can be assumed to contain only a harmless amount of organic impurities. If the observed colour is darker than the standard, the aggregate has a rather high organic content, but this does not necessarily mean that the aggregate is not fit for use in concrete. The organic matter present may not be harmful to concrete. For this reason, further tests are necessary. Concrete specimens are made using the suspected aggregate and their strength is compared with concrete of the same mix proportions but made with an aggregate of known quality(23).

3.3.10 Salt Contamination

Aggregates shall not contain materials in proportions which are harmful to the durability and appearance of the concrete in which they are incorporated. Chloride is a major cause for the depassivation of the reinforcing steel bars, resulting in the corrosion of steel in concrete. Chlorides may be present in aggregates usually as sodium and potassium salts; the quantity presnt being largely dependent on the source of the aggregates. Such salts contribute to the overall chloride and alkali load of the concrete.

The chloride ion content of the aggregates for concrete shall be such that they permit compliance with national standards. For example, the requirements of ENV 206(10) are usually achieved when the chloride ion content of the coarse and fine aggregate, combined in the proportions intended for a particular concrete, does not exceed the values given in Table 4(76).

Table 4. Maximum chloride content of aggregate for concrete

Type or use of concrete	Maximum total chloride content expressed as percentage of chloride ion content by mass of combined aggregate
Plain concrete	0.15
Reinforced concrete	0.06
Prestressed concrete	0.03

Sulphates in aggregates may give rise to the expansive disruption o the concrete. Under certain circumstances, other sulphur compounds present in the aggregates may oxidize in the concrete to produce sulphates (76)).

3.3.11 Resistance to Alkali-Silica Reaction and Soundness

Although aggregate is commonly considered to be an inert filler in concrete, such is not always the case. Certain aggregates may react with alkalis present in the pore fluids of concrete. Under adverse conditions and in the presence of moisture, this may lead to expansion and subsequent cracking of the concrete. Cracks produced by alkali-silica reaction pose a potential durability risk for the structure by permitting the ingress of carbon doixide which may cause carbonation of the concrete along the crack line and where the crack and reinforcement intersect, so reducing the alkaline protection normally given to the steel. Observation has shown that the most severe cracking caused by the alkali-silica reaction is often found only in the cover zone. Unfortunately, this is where it poses the greatest threat to durability(104). The most common form of reaction occurs between alkalis and certain forms of silica (alkali-silica reaction). Other much less common forms of reaction are the alkali-silicate and the alkali-carbonate reactions. In the absence of previous long-term experience of a lack of disruptive reactivity of a particular combination of cement and aggregate, it may be necessary to take one or more of the precautions to minimise the risk of damage from the alkali-aggregate reaction. If not, the combination of aggregates and cement shall be assessed using the procedures described in the national standards and regulations valid in the place of use(76).

Laboratory tests should be made on aggregates from new sources and when service records indicate that reactivity may be possible. The most useful are:

— *Petrographic examination:* Recommendations are available which show the amounts of reactive minerals, as determined petrographically, which can be tolerated (ASTM C 295(105)).

— *Mortar bar test for potential reactivity (ASTM C 227)*(106): This method is generally relied on to indicate potential alkali reactivity. Acceptance criteria are given by ASTM C 33(99) for evaluating these test results. The procedure is useful not only for the evaluation of aggregates but also for the evaluation of specific aggregate-cement combinations.

— *Chemical test for potential reactivity (ASTM C 289)*(86): This method is used primarily for a quick evaluation of natural aggregates, the results being obtainable in a few days as compared with 3 to 6 months with the mortar bar test. Acceptance criteria for this test are given in ASTM C 33(99) and elsewhere. Care must be exercised in interpreting the results of this test.

In case where aggregates are shown by service records or laboratory examination to be potentially reactive, the following precautions should be taken:

— limit the total alkali content of the concrete mix;

— use a cement with a low effective alkali content;

— change the aggregates;

— limit the degree of saturation of the concrete e.g. by impermeable membranes; and

— the use of pozzolanic material (natural pozzolan or fly ash) as a separate cementing material to be added at the mixer, in the ratio of one part pozzolan to two or three parts of portland cement. The amount of expansion reduction has been found to vary with the character and fineness of the pozzolan and the amount employed; for some pozzolanic materials, the reduction may exceed 90%.

Some constituents of metallurgical slags may also adversely affect their volume stability when used as aggregates for concrete. Free lime present in slag resulting from steel production is an example of such a constituent. Blast-furnace slag, when used as aggregate for concrete, should be free from iron unsoundness(76). Laboratory methods of testing for soundness are given in BS 1047: Part 2(107). There is a chemical analysis test for stability and a water absorption test.

Some constituents of aggregates may adversely affect the surface finish of concrete, causing staining, discolouration or pop-outs if present close to the surface of the concrete. Lignite and iron pyrites are two examples of materials which may affect concrete in this way.

3.3.12 ***Recycled Concrete Aggregates***

Recycled concrete aggregates produced by the crushing of structure concrete can be fine or coarse aggregates Demolished concrete may be mixed with soil or other building materials, or it may be contaminated by impurities. However, by observng a few simple precautions during the demolition process, the potential for recycling of the demolished concrete can be improved and the value of the debris increased.

Records of composition, quality and history of the original concrete are valuable documents in determining the recycling potential of any concrete structure.

It may be concluded that fine recycle aggregates as they come from the crusher are somewhat coarser and more angular than desirable for production of good concrete mixes. As fine recycled aggregates also consist of angular particles, it is not surprising that concretes which are produced exclusively with coarse and fine recycled aggregates tend to be harsh and unworkable. However, by adding a certain amount of a finer natural blending sand, it is possible to bring fine recycled aggregates within the grading limits of ASTM C 33(99). At the same time, concrete workability is greatly improved.

When old concrete is crushed, a certain amount of mortar from the original concrete remains attached to stone particles in the recycled aggregates. The amount of cement paste attached to sand or stone particles increases with decreasing particle size of the aggregate. Approximately 20% of the cement paste is attached to 20-30 mm aggregate, while the 0-0.3 mm filler fraction of recycled fine aggregates contains 45-65% of old cement paste. In many cases, old cement paste and mortar unfavourably affect the quality of recycled concretes. The most marked difference in the physical properties of recycled concrete aggregates when compared with conventional aggregates is that the water absorption of coarse recycled aggregates is much higher than the water absorption of original aggregates. This is due to the higher water absorption of old mortar attached to the original aggregate particles.

The compressive strength of recycled aggregate concrete is somewhat lower (in some cases up to 20% lower, but usually less) compared with the strength of control mixes of conventional concrete(108). However, the compressive strength of recycled concrete depends on the strength of the original concrete, and it is largely controlled by a combination of the water-cement ratio of the original concrete and the water-cement ratio of the recycled concrete when other factors are essentially identical. If the water-cement ratio of the original concrete is the same as or lower than that of the recycled aggregate concrete, then the new strengths can be as goods as the strength of the original concrete(109).

There will be no significant difference between the water absorption (and thus presumably the permeability) of recycled aggregate concretes and corresponding control concretes made with conventional aggregate when such concretes are produced with water-cement ratios higher (and therefore compressive strengths lower) than that of the original concrete from which the recycled aggregate is derived. However, the situation is different when recycled aggregate concretes and corresponding control concretes are produced with water-cement ratios lower (and therefore compressive strengths higher) than that of the original concrete from which the recycled aggregate is derived. In such cases, water absorption (and thus presumably permeability) of recycled aggregate concretes may be up to three times that of the corresponding conventional concretes. This is not surprising considering that such recycled aggregate concretes contain a large volume fraction of more porous coarse recycled aggregate which is distributed in a relatively dense matrix, while control concretes contain original coarse and comparatively dense natural aggregate in a similar and relatively dense matrix. It is found that the freeze-thaw resistance of air entrained concretes, made with recycled concrete aggregate is always inferior to that of control concretes made with natural sand and gravel(108).

3.4 Mixing Water

Water, as an ingredient of concrete, greatly influences many of its significant properties, both in the plastic and hardened state.

3.4.1 Quality

Water used for mixing concrete should be free of materials which significantly affect the hydration reactions of portland cement or which otherwise interfere with the phenomena that are intended to occur during the mixing, placing and curing of concrete. Water that is fit to drink may generally be regarded as acceptable for use in mixing concrete(110). When one must determine whether the water to be used contains materials that significantly affect the strength development of cement, tests should be made comparing the compressive strength mortars made with water from the proposed source with that of mortars made with distilled water. If the average of the results of these tests on specimens containing the water being evaluated is less than 90% of that obtained with specimens containing distilled water, the water represented by the sample should not be used for mixing concrete. If a potential water source lacking a service record is so unusual as to contain amounts of impurities as large as 5000 to 10,000 ppm (parts per million) or more then, to insure durable concrete, tests for volume stability (length change) as well as for strength may be advisable.

Water containing up to several thousand ppm of normally found mineral acids such as hydrochloric acid or sulphuric acid can be tolerated so far as strength development is concerned. Waters containing even very small amounts of various sugars or sugar derivatives should not be used as the set may be retarded unacceptably. The hazards of using such waters may be revealed in the comparative strength tests(13).

3.4.2 *Amount of Water (water-cement ratio)*

The required water-cement ratio is determined not only by strength requirements but also by factors such as durability and finishing properties. An acceptable degree of protection against chemical attack is obtained by using a dense, high quality concrete with a low water-cement ratio. This concrete will have lower absorption and lower permeability(111). Since different aggregates and cements generally produce different strengths at the same water-cement ratio, it is highly desirable to have or develop the relationship between strength and the water-cement ratio for the materials which are actually to be used.

Uniformity in the measurement of total mixing water involves, in addition to the accurate weighing of added water, control of such additional sources as mixer wash water, ice and free moisture brought into a mix with aggregates. One specified tolerance (ASTM C 94)(112) for accuracy in the measurement of total mixing water from all sources is ± 3%. Another is that variation in the design water-cement ratio shall not exceed ± 02. After the water content is determined, a control chart can be printed for the water-cement value(113).

The minimum water demand for most concretes is where the 'powder' content or cement represents a water-cement ratio of about 0.55. Above and below this, the water demand increases, particularly as the water-cement ratio increases or there is less cement present, which usually results in water gain and bleeding. This is understandable because voids in the aggregate grading are not being filled by the cement and sedimentation can occur as there are fewer fines to hold the water. Conversely, as the cement content approaches and extends below about 0.37, the water-cement ratio (about 550 kg/m^3), there will be a proportional increase in water of about 10 literes for every 30 kg/m^3 increase in the cement content(110). This is the main reason why BS 8110(114) apply limits to the maximum cement content to prestressed concrete to reduce excessive long-term movements such as shrinkage and creep.

The net water-cement ratio of most lightweight concrete mixes cannot be established with sufficient accuracy to use as a basis for mix proportioning. This is due to the difficulty in determining how much of the total water is absorbed in the aggregate and therefore not available for reaction with the cement while the concrete is in its plastic state. As with normal weight concrete, the amount of water which should be added to a lightweight concrete mix is the minimum amount which will permit the concrete to be properly placed, consolidated and finished.

High water temperatures cause higher concrete temperatures, and as the concrete temperature increases, the water demand increases and strength decreases for the concrete of the same consistency. Mixing water has the greater effect per unit of weight of any of the ingredients on the temperature of concrete since it has a specific heat between four and five times that of cement or aggregate. The temperature of water is easier to control than other components and even though water is used in smaller quantities than the other ingredients, the use of cold mixing water will effect a moderate reduction in concrete placing temperatures.

3.5 Admixtures

The chemical admixtures for concrete are used for improving various properties of concrete by effect of its surface activity(115). According to their main function, admixtures can be classified as accelerating, retarding, water reducing, air-entraining agents, etc. The total amount of admixtures, if any, shall not exceed 50 g/kg cement and should not be less than 2 g/kg cement in the mix. Smaller quantities of admixtures are allowed only if they are dispersed in part of the mixing water. Liquid admixtures in quantities exceeding 3 $1/m^3$ of concrete shall be taken into account when calculating the water-cement ratio.

Admixtures are tested for one or more of the following reasons:

- to determine compliance with a purchase specification;
- to evaluate the effect on the properties of the concrete to be made with job materials;
- to determine within-lot uniformity of product; and
- to provide data showing that any lot is the same as those previously supplied.

Uniformity of the results is usually as important as, or more important than, the average result with respect to each significant property of the admixture or the concrete.

The specific effect of admixtures varies with the composition of cement, the water-cement ratio, temperature of the concrete, ambient temperature, the type of admixture, the amount of admixture used and other factors or job conditions. Different sources and types of cement or different lots of cement from the same source, because of variations in chemical composition or fineness or both, may require different amounts of the admixtures to give the desired results.

3.5.1 Accelerating

An accelerating admixture is a material added to the concrete for the purpose of shortening the setting time and/ or accelerating early strength development of concrete. They may modify the rate of setting or hardening of the concrete or both.

The effects on some of the properties of concrete are:

- the setting time, initial and final, is reduced. The amount of reduction varies with the amount of accelerator used, the temperature of the concrete and the ambient temperature. Excessive amounts of the accelerator may cause rapid setting.
- compressive strength is increased substantially at early ages but may decrease at later ages. The resistance to sulphate attack is decreased.

By far the best known and most widely used accelerator is calcium chloride, though it should not be used when steel reinforcement is employed.

3.5.2 Retarding

Retarding admixtures slow down the setting of cement, extend workability and therefore allow the concrete to be handled over long distances, especially when the temperature is very high. In the construction of large dams where the temperature of the concrete should be kept low to prevent cracking, significant heat reductions can be obtained by using retarders.

Obviously the retardation of the hydration of cement, necessary to extend setting times, slows down strength at early ages. However, as in the case of retardation caused by low temperature, the inital retarding action is followed by increased strength at later ages with respect to concrete not containing the admixtues(116).

Change in the cement content, the water-cement ratio, temperature and sequence of addition influence the initial and final setting times. Setting times generally decrease as the temperature increases. Hence, for the same type of set retarder, larger additions would be required at higher temperatures. The efficiency of the retarder also depends on the type of cement used to make the concrete. Cements with low C_3A and alkali contents are retarded better than those containing larger amounts of these constituents. In view of the variation in the chemical composition of different brands of cement, the addition of even a recommended dosage may produce varying results(117).

3.5.3 Water Reducing

Water-reducing admixtures are water soluble materials which reduce the water requirement of concrete for a given consistency. These admixture may be in retarding or accelerating form. The effects on the properties of concrete may vary considerably depending on the type and on the materials. These admixtures increase the slump of the concrete if the water content of the mixture is held constant.

Benefits from the use of water-reducing admixtures used to date are principally in the areas of reduced water for a given slump. In many instances, the reduction in water permits a reduction in the cement content that would otherwise be required to produce concrete of the required strength. This, in turn, lowers the total heat of hydration developed by the cement and hence reduces the temperature rise in the mass concrete.

When high water-reducing admixtures have to be added at the site on account of the short duration of their effects, the concrete should be uniformly mixed before the admixture in question is added. After making the addition, the concrete shall be remixed until the admixture has been completely dispersed throughout the batch and has become fully effective. These admixtures can increase drying shrinkage. This depends on the admixture nature and dosage(118). The admixtures, variously known as superplasticizers, superfluidizers and super water reducers are distinguished from normal water reducers only from the quantitative viewpoint. The reduction in the water-cement ratio, which is an average of 5-10% for a fluidifier, becomes 15-25% for a superfluidifier(119).

On the other hand, a superfluidifier can transform the 'dry' concrete with a 1-2 cm slump into a 'fluid' concrete with a slump of more than 20 cm at equal water-cement ratio. In the former case, it is even possible to obtain the so-called 'flowing concretes' which are pumpable and self-levelling and demand a little work for compaction(120).

Studies on concrete containing superplasticizers reveal that they are as durable as the control concrete made at the same water-cement ratio(121), (122), (123),(124),(125). According to Costa and Massazza(126), in the presence of superplasticizers salified with sodium, the expansive phenomena related to the alkali-pyrex glass reaction become more marked. On the other hand, it was found that calcium naphthalene sulphonate reduces expansion.

Superplasticizer admixtures in themselves have no significant deleterious effect on the surface durability of concrete exposed to freeze-thaw environments and de-icing agents. Behaviour in these environments is similar to 'control' concretes prepared without superplasticizer admixtures(127).

Monosi and Collepardi(128), using a high dosage of superplasticizer, have reduced the mixing water by about 40% and have manufactured flowing concrete with a water-cement ratio of 0.32. Because of the low capillary porosity, such a concrete is able to resist sulphate attack, chloride penetration and freezing-thawing cycles even after only 3 days' curing time.

3.5.4 Air-entraining Agents

The primary purpose of air entrainment in concrete is to provide a high degree of resistance to the disruptive action of freezing and thawing and of de-icing chemicals.

Not only is the total volume of air of importance but even more, the size and distribution of the air voids must be such as to provide efficient protection to the cement paste. The air-void system must be characterized by a large number of small voids uniformly distributed throughout the cement paste. Too little entrained air will not protect cement paste against cyclic freezing. Too much air will unduly penalize the strength.

The resulting air content of air-entrained concrete, produced through the use of an air-entraining admixture (added at the concrete mixer) or an air-entraining cement depends on many factors, eg. on the particle shape and grading of the aggregates used. Concrete using crushed fine aggregate may require up to twice as much admixture as is needed when rounded natural sand is used. Organic impurities in the aggregate may either increase or decrease the air-entraining admixture requirements depending on the nature of the impurity. An increase in the hardness of water will generally decrease the air-entraining admixture requirements depending on the nature of the impurity. An increase in the hardness of water will generally decrease the effectiveness of the air-entraining admixture. Increasing the amount of finely divided materials in concrete by the use of fly ash or other pozzolans usually determination of the air content of the concrete should be made.

Fly ashes having a high carbon content will require a larger amount of air-entraining admixture to develop the required amount of entrained air.

The type and degree of consolidation used in placing concrete can reduce the air content. Generally, the air loss as a result of these manipulations consists of the larger bubbles of entrapped air which contribute little, if anything, toward the beneficial influences of entrained air. Frequent determination of the air content of the concrete should be made.

For regular weight concrete, the following test methods may be used: the volumetric method (ASTM C 173)(129) and the pressure method (ASTM C 231)(130) or the unit weight test (ASTM C 138)(131). For lightweight concrete, the volumetric method is recommended.

Air entrainment, while improving both workability and durability, may reduce strength. Within the range of air contents normally used, the decrease in strength is usually proportional to the amount of air entrained.

For many structures, it has been a problem to meet the combined requirements of high compressive strength and high air content in the concrete based on local aggregates available. For these structures it has been crucial to keep the total air-void content in the concrete not higher than strictly necessary in order to provide adequate frost resistance. It is primarily the amount of smaller air voids, i.e. below 300 μm, which is related to the frost resistance. Since the larger voids only reduce the general level of concrete strength, efforts should be made to keep the amount of these voids at a minimum(132).

4. PRODUCT CONTROL

4.1 Fresh Concrete

The compactness degree of hardened concrete has a considerable influence on its fundamental properties, such as strength and durability. To obtain sufficient compactness and an appropriate surface finish of hardened concrete, a certain amount of work needs to be applied to the corresponding fresh mix.

The purpose of the fresh concrete compaction in the formwork is to minimize the amount of entrapped air or the voids between the elements forming the mix. The work necessary to do this has to overcome the internal friction between the mix components and the internal friction occurring between the concrete and the surfaces bounding it—those of the formwork and the reinforcement. Moreover, in order to fill the formwork perfectly, the fresh mix must be able to take a shape which is different from the one its mass had before casting without, however, losing its homogeneity.

The characteristics and rheological properties of the fresh mix are merged into the general term of 'Workability'.

If workability with regard to the methods and the means available for the compaction of the concrete cast remains below a certain limit, the compactness and therefore the other required qualities (in particular, mechanical strength and durability) cannot be obtained on hardened concrete. Thus, a correct and suitable workability is a fundamental requirement for the successful manufacture of concrete.

The concrete workability is determined by a certain number of properties of the fresh mix, such as internal friction, cohesion, viscosity, possibility of plastic deformation, tendency to bleeding, etc. In addition, there are properties which cannot be expressed in fundamental units of measurement (mass, length and time) but can play a role in workability, for instance, a tendency to segregation and aptitude to surface finish.

This complex dependence explains why workability cannot be completely defined and quantitatively expressed. There is no test known at this time which will measure this property in quantitative terms. Depending on the cases, these tests measure consistency, penetrability, shear flow, compactability, stability, pumpability, etc.

Another fact to consider is that the workability of a given fresh mix can be sufficient for mass concrete castings but quite unsuitable for thin castings having dense reinforcement. Depending on the cases, different combinations of the different fresh mix properties are necessary to obtain an appropriate workability.

Actually, one cannot expect to measure workability, which is an intrinsic property of the mix, by performing a consistency measurement whose value is related *a priori* to the type of equipment used(133).

The different methods used to measure consistency have a practical meaning and give information on workability. Nevertheless, it is obvious that these methods afford only a rough measurement of workability.

It must be noticed that even slight changes in the concrete composition, especially in the water content, can have considerable influence on the concrete properties and, above all, on its consistency. Therefore, the consistency of the concrete composition can also be verified easily by performing a consistency test at regular intervals by means of the most suitable method.

4.1.1 Sampling of Concrete

The sampling of concrete for testing should be done with care to ensure that the test results are representative. Concrete may not be homogeneous for a number of reasons, such as errors in proportioning, non-uniform mixing, segregation during handling and placing, loss of moisture from the surface or from absorption by contact with an absorbent material. Samples should be taken either at the mixer or as close as possible to the point of final deposit, in which case they should be taken immediately after the concrete is deposited and before it is compacted.

The procedure to be used for obtaining samples of fresh concrete is described in national standards to which reference should be made. Whenever possible, the sampling should be performed as the concrete is delivered from the mixer to the conveying vehicle used to transport the concrete to the forms. However, specifications may require other points of sampling, such as the discharge of a concrete pump. BS 1881(134) requires not less than four increments (samples) when sampling from a moving stream and not less than six increments when sampling from a lorry or heap. These increments are to be taken using 5 kg and 3.5 kg scoops, respectively. The increments are taken at equally spaced intervals and the scoop moved about in the concrete stream to obtain as representative a sample as possible. The increments are mixed to provide one composite sample which is then devided as may be necessary to give the quantity required for any specific test. Samples should not be taken at the beginning or end of a priod of concreting(135).

4.1.2 Workability and Consistency Measurements

The standard method for determining the workability of fresh concrete is by using empirical tests, namely slump(136), VeBe(137) and compaction or Walz index(138). For very high workability or flowing concretes, it is common practice to use the Flow table test(139).

— *Slump measurement:* The slump is always zero in dry concretes (water content = 165-180 1/m^3). When the water passes to 195-210 1/m^3, the slump becomes extremely sensitive to both the cement content and the water-cement ratio. When a mix is rather dry, a slight change in the water content does not cause large slump variation. On the contrary, when a mix is wet, the same water increase causes a large slump variation. The slump test is a good measurement for consistency changes when the aggregates and the cement content remain nearly constant. If the materials are proportioned accurately, a slump variation indicates a change in either the aggregate grading, the water content or the entrapped air content of the mix.

— *VeBe measurments:* This method is always sensitive to the variation in the water content. The changes in the cement content are observed with the lowest water content (165-180 1/m^3).

— *Compaction factor measurements:* This method is very sensitive to the water content and the lower the content, the more sensitive it becomes towards the cement dosage. It does not show any area of marked sensitivity but efficaciously points out the consistency variations for the whole range of cement contents tested here.

A comparison among the respective applicability fields of the methods is proposed in Table 5(133).

It is interesting to point out the existence of a significant correlation among the consistency measurments performed by the three methods on a great number (about 150) of concretes having varying composition and made with different cements and aggregates, with and without admixtures.

By considering the methods two by two, it was possible to establish first-degree and higher degree relationships. In order to allow the use of these

Table 5. Applicability ranges of the methods for workability measurement

Methods	Actual measurement range of the method	Consistency of concrete				
		Wet soil	Dry	Plastic	Flowing	Superflowing
Slump	1-15 cm	–	+	+ +	+	–
VeBe time	1-30 sec	+	+	+ +	+	–
Walz index	1.03 – 1.45	+	+ +	+ +	+	–

(–) not valid; (+) valid; (+ +) very valid

relationships in the usual practice, it was interesting to replace the found curvilinear correlations with linear correlations. The classification of the latter, according to the correlation coefficients, is as follows:

— Slump — VeBe $r = 0.53$ $n = 155$
— Slump — Walz $r = 0.78$ $n = 118$
— Walz — VeBe $r = 0.79$ $n = 112$

where r = correlation coefficient
n = number of samples.

The equations of significant correlation are:

$$\text{VeBe} = 20.69\ \text{Walz} - 18.947$$
$$\text{Slump} = -1.261\ \text{VeBe} + 10.22$$
$$\text{Slump} = -37.037\ \text{Walz} + 47.037$$
$$\text{Walz} = -0.027\ \text{Slump} + 1.27$$

The purpose of the search for correlations among the different methods for workability measurement is not to compare methods which are not generally comparable or to replace one method with another but to establish evolution diagrams of the fresh concrete rheological properties as a function of either the time elapsed after mixing or the variations in the water content of a mix, other conditions being unchanged. In fact, if the question is to follow a normally flowing concrete from its mixing till the beginning of hardening, or if the aim is to establish the gradual and progressive water demand of a mix so that it can take a flowing consistency from a consistency of wet soil, there is not a single method which is simultaneously reliable and reproducible. Therefore, it is necessary to use different measurement methods, each of which having a determined application area, in its turn reliable and reproducible in a different degree.

The application areas of the measurement methods include common zones, that is, fresh concretes show, in certain moments and for different consistency values, rheological properties where two (or more) methods can be applied. It is precisely in these zones of common application that the correlation needs to be found in order to perform without difficulty, the measurements by passing from one method to another and to plot the diagrams giving the rheological evolution of the mixes as continuously as possible(133).

4.1.3 Factors affecting workability

The rheological properties of concrete are affected by numerous parameters with regard to both the composition of the mix and the mixing conditions, temperature and the time of mixing. Table 6 schematically shows the influence of these parameters on the workability of concrete(116).

Table 6. Factors affecting concrete workability

Concerning mix	Not concerning mix
Water-cement ratio	Mixing conditions
Type of cement:	Temperature
- C_3A content	Time (workability loss)
- fineness	
- gypsum content	
- alkali content	
Type of aggregate:	
- maximum size	
- grading	
- content very fine particles	
Cement-aggregate ratio	
Mineral additions	
Admixtures	
- water reducing	
- air-entraining agents	

The effect of water content on the workability of the concrete is expressed by Lyse's rule(140) which says that for a given type of aggregate, mix workability depends on the water content of the concrete, irrespective of the water-cement ratio.

As regards the particle size distribution of the aggregate, it is to be remembered that the greater the aggregate surface greater is the amount of water and cement paste necessary to cover the aggregate. Thus, in general, the finer the aggregate, the lesser the workability of the concrete at lime water and cement paste content. However, it has been verified experimentally that the aggregate fraction of less than 0.3 mm fineness, and also the cement, does not negatively affect the workability as one might expect from the high surface area to be covered by water. Indeed, a certain fraction of this fine material, excluding undesirable lime, clay and very fine aggregates, is indispensable in obtaining a workable fresh concrete since it acts as a lubricant for the coarse aggregates. For concrete with a high cement content, in particular, those with aggregate-cement ratios equal to or less than 2, the effect of the type of aggregate on workability, as regards both angualrity and specific surface area, becomes virtually negligible.

The temperature of fresh concrete influences the amount of water needed to achieve the proper consistency. As the temperature of concrete, as placed, is allowed to increase, the water content will increase for a given slump. The increased water content will cause a proportionate decrease in strength and durability and increase in drying shirnkage.

4.1.4 Loss of Workability

The construction of durable concrete structures requires, among other things, the use of concrete which can, under the given conditions, be reliably placed and compacted with the normal amount of cost and effort, i.e., its workability must be suited to the demands of the job. As time goes by, the consistency of fresh concrete changes, it becomes stiffer, i.e. its slump becomes less. This stiffening behaviour is referred to as 'slump loss'. The change in consistency is ultimately always brought about by the chemico-mineralogical reactions of the cement with the mix water which also produce the desired hardening and strength development.

If concrete is not made on the construction site itself and has to be brought from elsewhere, there may be a fairly long interval of time between making and placing it. In such cases, its slump loss must be taken into account by a suitable allowance in the consistency of the fresh mix, so that the worakbility at the time of placing the concrete complies with the requirements.

The slump loss of fresh concrete can be influenced by chemical and/or physical processes. These are substantially governed by:

- the initial materials used for making the concrete;
- the composition of the concrete;
- the procedure for making the concrete; and
- the temperature of the fresh concrete.

Information on the order of magnitude and time-related development of setting and slump loss is obtained by determining the rheological changes that the concrete undergoes. In principle, the slump loss of fresh concrete can be assessed by means of any consistency testing method capable of giving useful information in the consistency range concerned.

There is, at present, no standardized method for testing the slump loss of concrete. In order to comprise as many as possible of the influencing factors occurring in practice, the repeated determination of the consistency by means of slump or flow table test has proved satisfactory for assessing the slump loss of concrete with plastic or highly plastic consistency. The result of the determination of the slump loss of fresh concrete is strongly dependent on the treatment of the concrete prior to the consistency test. The time at which the first consistency determination (after the mixing of the concrete) is carried out is important. In practice, for reasons of reproducibility, it has been found advantageous to perform the first consistency determination 10 minutes after the addition of water to the concrete mix because the early chemical reactions of hydration have substantially ended by this time.

The slump loss of concrete ultimately depends on the processes that take place in the cement paste. However, for different cements, there may occur differences in the time-dependent behaviour of the change in the consistency of the concretes made with them. Moreover, the factors affecting the slump loss of the concrete may have different effects with different cements(14).

No evidence of any direct influence of the aggregate on the slump loss of fresh concrete over a period from 10 to 90 minutes after mixing has as yet been detected. Through its water demand, the aggregate influences the initial consistency of the fresh concrete to an important degree. The water demand depends particularly on the nature, preparation and grading of the aggregate(142). Dry porous aggregate can absorb water during and after concrete mixing so that the effective water content—which determines the consistency of the fresh concrete, is reduced. With natural aggregates, this water absorption process generally proceeds rapidly and has been completed by the time the initial consistency is measured. With absorbent lightweight aggregates, however, subsequent water absorption may occur.

The intensity and the duration of mixing may have an influence on the slump loss of the concrete. For mixing times and mixing plant as normally used in concrete construction practice, these influences are of minor importance. However, in assessing the results of laboratory tests, it must be borne in mind that laboratory pan mixers mostly have a distinctly more intensive mixing action than big mixers and that differences in slump loss between concrete in preliminary tests and in practice may occur in consequence of this. Greater mixing intensity may reduce the slump loss but it may increase it under certain conditions(141).

If the concrete has become so stiff that proper placing and compaction are no longer possible, it must not be used in this condition. It is not permissible to add water to it in order to restore the desired consistency. If the concrete is still in the mixer (truck mixer), it may in appropriate cases be possible to restore the concrete to a proper consistency by adding a suitable superplasticizer.

Slump loss of concrete may occur to a certain extent during transport as a result of evaporation of some of the mix water. This slump loss due to loss of water, however, is generally much less pronounced than the slump loss due to chemical reaction. In actual field applications in hot climates, it may be necessary to retemper the concrete to maintain the required workability. According to Ramakrishnan et al.(143),(144),(145), at higher ambient temperatures, if concrete is retempered with 'optimum' quantity of water (the amount of water added is just sufficient to restore the initial slump), there are no detrimental effects on fresh as well as hardened concrete properties even under the unfavourable high ambient temperature of 60°C.

Loss in workability during warm weather can be minimized by expediting delivery and placement and by controlling the mix temperature. It may also be desirable to use a retarder to prolong the time the concrete will respond to vibration after it is placed.

Tests show that the slump loss of concrete containing water-reducing admixtures is usually slightly greater than that for comparable concrete without admixtures. However, with equal water content, the higher slump obtained by the use of these admixtures may allow a longer period between mixing and placing.

For cement of low (<5%) C_3A content, the overall rate of slump loss when superplasticizers are employed is somewhat lower. When an undersulphated, low C_3A cement was used, slump loss was dramatically reduced. The use of low C_3A cement, however, is no guarantee that slump loss will be reduced(146). If the cement has a tendency to false set, slump loss is likely to be aggravated, particularly in hot weather.

Even the composition of the concrete can influence the workability loss, which becomes faster with cement rich mixes and with lower water-cement ratio. Probably the high slump loss found in the presence of superfluidity admixtures is to be related to the lower initial water-cement ratio.

4.1.5 Mixing: Mixer, Uniformity, Time

The way of mixing the fresh concrete components, the workability and the segregation as well as the system of compaction can affect the characteristics of the hardened concrete, and above the dispersion in the results obtained. Mixing of the constituent materials shall be carried out in a mechanical mixer and continued until a uniform mixture is obtained. Obviously, the mixing time depends on the type of mixer and the workability of the concrete.

Blending the materials during batching makes it possible to reduce the mixing period. Some of the mixing water and aggregate should lead other materials into the mixer to prevent sticking and clogging. Mixing times may be lengthened or shortened depending on the results of mixer performance tests.

The performance of mixers is usually determined by a series of uniformity tests made on samples taken from two to three locations within the concrete batch being mixed for a given time period. Mixer performance requirements are based on allowable differences in test results between any two locations or in differences between individual locations and the average of all locations.

Another important aspect of mixer performance is batch-to-batch uniformity of the concrete which is also largely affected by the uniformity of materials and their measurement, as well as by the efficiency of the mixer. The mixing time required should be based upon the ability of the mixer to produce uniform concrete throughout the batch and from batch to batch. The mixing time should be measured from the time all ingredients are in the mixer.

4.1.6 Pumped Concrete

Pumped concrete may be defined as the concrete conveyed by pressures through either a rigid pipe or a flexible hose and discharged directly into the desired area.

Although the ingredients of the mixer placed by the pump are the same as those placed by other methods, dependable controls are essential for successfully pumped concrete.

The maximum size of angular coarse aggregate should be limited to one-third of the minimum inside diameter of the hose or pipe and the maximum size of rounded aggregates should be limited to 40% of the inside diameter. The properties of the fine normal weight aggregates (sand) play a more prominent role in the proportioning of pumpable mixes than the properties of coarse aggregates. Together with cement and water, sand provides the mortar which conveys the solids or coarse aggregates in suspension, thus making the mix pumpable. Experience has shown that particular attention should be given to sand portions passing the finer screen sizes. Another important gradation indicator of sand suitability for pumping is its fineness modulus, that is, the sum of the cumulative percentages retained on a series of standard sieves. Sands having a fineness modulus between 2.40 and 3.00 are generally satisfactory(13).

Because of the usual higher ranges required in slump and in the ratios of fine to coarse aggregates, pump mixes will usually require an increase in the amount of cement above those used in conventionally placed concrete.

4.1.7 Compacting Process: Vibration, Autolevelling

A mass of freshly mixed concrete as deposited in a form or mold is usually honeycombed with entrapped air. If allowed to harden in this condition, the concrete will be non-uniform, weak, porous and poorly bonded to the reinforcement. It will also have a poor appearance. The mixture must be densified if it is to have the properties normally desired and expected of concrete. Consolidation, also called compaction, is the process of removing entrapped air from fresh concrete in the form. Several methods and techniques are available, the choice depending mainly on the workability of the mix, placing conditions and the degree of deaeration desired.

Equipment and methods are now available for fast and efficient consolidation of concrete over a wide range of placing conditions. Concrete with a relatively low water content can be readily molded into an unlimited variety of shapes, making it a highly versatile and economical construction material. When good consolidation practices are combined with good formwork, concrete surfaces have a highly pleasing appearance.

Proper finishing procedures and timing are essential if the quality of concrete near the surface of a slab is to be as good as that for the underlying section. Delaying the floating and trowelling operations increases resistance to abrasion.

Results of Stark's study(147) support previous findings(148) that internal vibration can significantly alter the entrained air-void system in concrete. However, the manner in which vibration is carried out determines whether it will adversely affect the final characteristics of the air-void system and the consequent durability of concrete in freeze-thaw exposures.

The most serious imperfections resulting from ineffective vibration are honeycomb, excessive entrapped air void, sand streaks and 'pour' lines.

Honeycomb: This occurs when the mortar does not fill the space between the coarse aggregate particles. The presence of honeycomb indicates that the first stage of consolidation has not been completed at these locations. Where it shows on the surface, it is necessary to chip out the area and make a repair. Such repairs should be kept to a minimum, mainly because they mar the appearance of the structure. Honeycomb is generally caused by using improper or faulty vibrators or by poor vibration procedures. Unsystematic insertions at haphazard angles are likely to cause an accumulation of mortar at the top surface while the lower portion of the layer may be undervibrated. Sometimes, there are other factors contributing to honeycomb such as insufficient paste to fill the voids between the aggregate, improper ratio of sand to total aggregate, poor aggregate grading, improper ratio of sand to total aggregate, improper workability for the placing conditions or insufficient clearance between the reinforcing steel. In setting steel spacing, both the designer and the builder should keep in mind that the concrete must be consolidated.

Excessive entrapped air voids: Concrete which is free of honeycomb still contains entrapped air voids because complete removal of entrapped air is rarely feasible. The amount of entrapped air remaining in the concrete after vibration is largely a function of the vibratory equipment and procedure but it is also affected by the properties of the concrete mix, location in the placement and other factors. Where proper equipment or procedures are not used, or there are other unfavourable conditions, the entrapped air content will be high and surface voids are likely to be excessive. To reduce air voids in concrete surface, the distance between internal vibrator insertions should be reduced and the time at each insertion increased.

Sand streaking: This is caused by heavy bleeding along the form, resulting from the character and proportions of the materials and the method of depositing the concrete. Harsh, wet mixes deficient in cement and containing poorly graded aggregates may cause sand streaking. Dropping concrete through reinforcing steel and depositing it in thick lifts without adequate vibration may also cause streaking. Another cause is form vibrators attached to leaky forms which have a pumping action with a resulting loss of fines or an indrawing of air at the joints.

"Pour" lines: These are dark lines showing on the formed surface, demarking the boundary between adjacent batches of concrete. Generally, they indicate that when vibrating a layer, the vibrator was not lowered far enough to penetrate the layer below(13).

4.1.8 Segregation

Segregation is another rheological property of freshly mixed concrete. Segregation is the ability of the mix to separate various constituents owing to the size and specific weight differences of the particles. Popovics(140) distinguishes two types of segregation—internal and external. Internal segregation occurs within the framework or mold. External segregation is that which occurs during transport after an improper handling of the concrete. Segregation causes notable defects in concrete structures. Firstly, all the properties of the material which depend on its composition, from strength to durability, change by passing from the lower to the upper zones of a structure, owing to the macroscopic heterogeneity of the concrete.

There are no methods for assessing segregation which allow it to be measured quantitatively. The methods so far available are usually very laborious and furnish only qualitative or at most semi-quantitative indications. The tendency to segregate internally can be assessed, according to Shima et al.(149), by taking samples from the upper and the lower parts of the concrete specimen. Mortar is separated from the concrete sample by wet screening (5 mm sieve) and dried rapidly. The dry mortar is separated by a 74 μm sieve into fine aggregate and cement. The coarse aggregate retained on a 5 mm sieve is washed, dried, classified and weighed. Differences between the content of various constituents in the upper and lower parts are an index of segregation. Tattersall(140) suggests assessment of the tendency to segregate by measuring the absorption of gamma rays through the concrete. Walz(140) has proposed the measuring of the tendency to segregate externally by letting the concrete slide on an inclined sieve and measuring the increase in the large aggregate content due to the loss of mortar through the sieve. According to Popovics(140), to reduce the tendency of a concrete to segregate, it is necessary to avoid the following conditions: the maximum aggregate size above 25 mm; increase of coarse aggregate fraction and the use of aggregates with a discontinuous grading curve; the use of coarse aggregate with a specific weight greater than that of the fine aggregate; the use of flat or elongated aggregates; decrease in the cement content; too high or too low water-cement ratio. In the case of concretes having a slump of 20 cm (max. size of aggregate of 25 mm), the amount of particles finer than 200 μm is required to be more than 430 kg/m^3 to prevent the external segregation and 500 kg/m^3 to minimize the internal segregation. The obtaining of a cohesive and non-segregable fresh concrete is favoured by the addition of fly ash or pozzolans(121) beside by the removal of the mentioned possible causes.

4.1.9 Bleeding

Bleeding is a particular aspect of segregation, although between the two characteristics, there is no constant and rigid correlation. Unlike segregation, bleeding in concrete can be easily measured (ASTM C 232(150)). Bleeding capacity is higher as the workability of the concrete is greater and generally the higher the water-cement ratio, the lower the cement content. The use of finely divided mineral additions, particularly material passing the No 200 ASTM seive, can reduce bleeding.

Water-reducing admixtures containing lignosulphonates reduce bleeding, while those based on hydroxycarboxylic acids increase the bleeding rate. Limited data suggest that accelerating water-reducing agents do not enhance the bleeding rate.

Bleeding can be beneficial, especially during hot and windy weather conditions. If the rate of evaporation exceeds the bleeding rate, plastic cracks may develop. Under other situations, when a hydroxycarboxylic acid-based water reducer is used, the bleed water should be removed continuously, otherwise the surface strength will decrease(117). In addition, mixes with silica fume present markedly reduced bleeding which, though it is a positive factor for various reasons, results in greater risk of cracking cured by protecting it immediately after pouring, wherever possible, with curing agents or with other adequate means(151).

Excessive bleeding will impair both the strength and the durability of concrete. This impairment may appear in the form of non-uniformity of strength, increased transverse permeability, plastic settlement cracking and poor bonding between the cement matrix and the undersurface of coarse aggregates and reinforcing bars(152).

4.2 Hardened Concrete

The most important properties of hardened concrete are directly affected by the characteristic of the various existing pore systems in the cement paste. Strength depends principally on the total volume of the pores, and the resistance to chemical attack, through permeability, in relation to the pore sizes and their degree of continuity, besides the volume; shrinkage, at least the reversible part, is influenced by the total surface area of the pores.

The pores present in a hardened paste are associated with the structure of the cement hydration products (gel pores) or derive from the excess of water used to ensure a certain workability to the concrete mix or come from the air entrapped during the preparation and casting of the mix.

4.2.1 Curing

Curing is the process of maintaining a satisfactory moisture content in a favourable temperature in concrete during the hydration of the cementitious materials so that the desired properties of the concrete are developed. Curing is essential in the production of quality concrete. The potential strength and durability of concrete will be fully developed only if it is properly cured for an adequate period prior to being placed in service.

Much of the concrete deterioration that takes place each year should be blamed on inadequate curing. Generally it is not blamed on curing, because we have no good test to confirm that the near-surface curing was inadequate(153).

It is especially important to prevent an undesirable reduction in the moisture content of the paste as soon as the concrete is placed. Such a reduction tends to reduce hydration. Loss of moisture at this stage results in drying, shrinkage and the development of cracks in the paste.

An indication that the paste is losing water is the appearance of plastic shrinkage cracks in the surface of the concrete about two hours after placing and finishing the concrete, and may be seen soon after or sometimes before the water sheet disappears from the surface of the concrete. They are often not noticed until the day after construction. The principal cause of their occurrence is an excessively rapid evaporation of water from the concrete surface. When the rate of evaporation exceeds the rate at which bleeding water would naturally rise to the surface, plastic shrinkage cracks are likely to occur. The ambient temperature, the relative humidity, the wind speed and the bleeding characteristics of the concrete are all factors influencing the formation of these cracks. Appearance of plastic shrinkage cracks indicates the need for immediate corrective measures to prevent their further development.

Plastic shrinkage cracks on horizontal surface may be identified and distinguished from other types of cracks by the following features(17):

- they are roughly straight and often more or less parallel:
- they are often, but not always, at an angle of about 45°;
- they may vary in length from a few centimetres to several decimetres and seldom extend across the full width of the unit under construction; and
- they can occur in both unreinforced and reinforced horizontal slabs, either on the ground or suspended.

The rate of reaction between the cement and water varies with temperature, proceeding slowly at low temperatures down to $-12°C$ and more rapidly at high temperatures somewhat below the boiling point of water. Concrete temperatures below 10°C are unfavourable for the development of early strength. Below 5°C the development of early strength is greatly retarded and at freezing temperatures, little strength develops. There is some evidence, in spite of increased rate of reaction at elevated temperatures, that curing at temperatures in excess of 70°C is not as beneficial as prolonged curing at lower temperatures. Autoclaving at temperatures above 160°C greatly accelerates hydration and may produce strengths in a few hours equal to those obtained at 28 days of curing at 20°C.

Tests indicate that when concrete is maintained at higher temperatures during setting and early hardening, strengths at later ages are lower than for similar concretes cured at lower temperatures during this early period. Avoiding high concrete temperatures during curing will not only help to reduce the amount of random cracking on cooling but also result in greater strength at later ages.

According to Owens(154), there are indications that elevated temperatures produced during cement hydration may lead to an increase in the permeability of portland cement concrete whilst producing a reduction in the permeability of concrete incorporating fly ash.

The temperature of the concrete, as placed, is affected by the surrounding air, by the absorption of solar heat, by the heat of hydration of the cement, and by the initial temperature of the materials. Evaporation of mixing or curing water at the surface of the concrete can produce a significant cooling effect which is beneficial as long as evaporation is less than that necessary to cause cracking.

In order to obtain the potential properties to be expected from the concrete, especially in the surface zone, thorough curing and protection for an adequate period is necessary. Curing and protection should start as soon as possible after the compaction of the concrete.

There are two general systems of maintaining the presence of the required water for hydration which is initially furnished by the mixing water in the concrete:

(i) a moist environment from the continuous or frequent application of water through ponding, sprays, steam or saturated cover materials such as burlap or cotton mats, rugs, earth, sand, sawdust;

(ii) the prevention of loss of mixing water from the concrete by means of sealing materials such as waterproof sheets of paper or plastic or by the application of a membrane forming curing compound to the freshly placed concrete. Care should be taken to ensure that saturated cover materials do not dry out and absorb water from the concrete.

The required curing time depends on the rate at which a certain impermeability of the surface zone (cover to the reinforcement) of concrete is reached. Therefore, curing times shall be determined from the maturity based on the degree of hydration of the concrete mix and ambient conditions.

The time required for concrete to attain the strength required for safe removal of shores is influenced by many factors. Most important among them are those which affect the rate and level of strength development, such as the initial temperature of the concrete when placed, the temperature at which the concrete is maintained after placing, the type of cement, the type and amount of accelerating admixture or other admixtures used, and the conditions of protection and curing.

Before being exposed to extended freezing in a severe exposure, it is desirable that air-entrained concrete attains a specified compressive strength of about 25 MPa. A period of drying following curing is advisable. For moderate exposure conditions, a specified strength of about 20 MPa should be attained(13).

In hot weather, there is need for continuous curing, preferably by water. The need is greatest during the first few hours. Throughout the first day after the concrete is placed, all surfaces should be protected from drying, even intermittently, as this contributes to the development of pattern cracking.

For water containment structures, absorptive wood forms remaining in place should not be considered as a satisfactory means of curing in hot, dry weather. Forms should be covered and kept moist. The forms should be loosened as soon as this can be done without damage to the concrete and provisions made for the curing water to run down inside them. During form removal, care should be taken to provide wet cover to newly exposed surfaces to avoid exposure to hot sun and wind. At the end of the prescribed curing period (7 days should be minimum; 10 days is better), the covering should be left in place without wetting for several days so that the concrete surface will dry slowly and be less subject to surface shrinkage cracking(13). Control quality personnel should keep a record of the date, hour, outside air temperature, temperature of concrete as placed and weather conditions(155).

4.2.2 Compressive Strength

The purpose of strength tests of concrete is to determine compliance with a strength specification and to measure the variability of concrete. Test specimens indicate the potential rather than the actual strength of the concrete in a structure.

Statistical procedures provide tools of considerable value in evaluating results of strength tests and information derived from such procedures is also of value in defining design criteria and specifications. For these statistical procedures to be valid, the data must be derived from samples obtained by means of a random sampling plan designed to reduce the possibility that choice will be exercised by the sampler. 'Random sampling' means that each possible sample has an equal chance of being selected. To insure this condition, the choice must be made by some objective mechanism such as a table of random numbers.

Variations in results of strength tests can be traced to two different sources:

(a) variations in testing methods, and

(b) properties of the concrete mixture and ingredients.

It is possible by analysis of variance to compute the variations attributable to each source(13).

Within-test variation: The variation in the strength of concrete within a single test is found by computing the variation of a group of specimens fabricated from a sample of concrete taken from a given batch. It is reasonable to assume that a test sample of concrete is homogeneous and any variation between companion specimens fabricated from a given sample is caused by fabricating, curing and testing variations.

Batch-to-batch variations: These variations reflect differences in strength which can be attributed to variations in:

- Characteristics and properties of the ingredients;
- Batching, mixing and sampling; and
- Testing that has not been detected from companion specimens since these tend to be treated more alike than specimens tested at different times.

The batch-to-batch and within-test sources of variation are related to the overall variation by the following expression:

$$\sigma^2 = \sigma_1^2 + \sigma_2^2$$

where σ = overall standard deviation
σ_1 = within-test standard deviation
σ_2 = batch-to-batch standard deviation

Different variability can be expected for compressive strength tests subject to different degrees of control. These values range between 3 and 5 MPa for the standard deviation of overall variation and below 3.0 and above 6.0 for the coefficient of variation of within-test variation, for excellent control and poor control, respectively.

The decision as to whether the standard deviation or the coefficient of variation is the appropriate measure of dispersion to use in any given situation depends on which of the two measures is more nearly constant over the range of strength characteristics of the particular situation. Present information indicates that the standard deviation remains more nearly constant, particularly at strengths over 20 MPa. For within-test variations, the coefficient of variation is considered to be more applicable(13).

The strength of control specimens is generally the only tangible evidence of the quality of concrete used in constructing a structure. To satisfy strength performance requirements, the average strength of concrete must be in excess of the design strength. The amount of excess strength depends on the expected variability of test results as expressed by a coefficient of variation or standard deviation.

Strength data for determining the standard deviation or coefficient of variation should represent a group of at least 30 consecutive tests made on concrete produced under conditions similar to those to be expected on the project. The requirement for 30 consecutive strength tests will be considered to have been complied with if the tests represent either a group of 30 consecutive batches of the same class of concrete or the statistical average for two groups totalling 30 or more batches. In general, changes in materials and procedures will have a larger effect on the average strength level than on the standard deviation or coefficient of variation.

If previous information exists for concrete from the same plant meeting the similarity requirements described above, that information may be used in deciding on a trial value of σ to be used in determining the target strength. For small jobs that are just getting started where no prior information is available, the concrete should be designed to produce an average strength at least 10 MPa greater than the design strength. As the job progresses and more strength tests become available, all the strength tests can be analyzed together to give a more reliable estimate of the standard deviation(13).

To analyze variations in the strength of concrete, Quality Control Report plots the X charts for both individual and the moving average of three-five consecutive tests(113).

The compressive strength of concrete is expressed in terms of the characteristic strength defined as that value of strength below which 5% of the population of all possible strength measurements of the specified concrete are expected to fall. The strength shall be determined in accordance with national standards on molded specimens—generally 150 mm cubes or 150/300 mm cylinders—aged 28 days. Normally, concrete is classified according to these compressive strengths.

The compressive strength of concrete which has been allowed to dry is lower than the strength of a similar specimen in a saturated condition. This difference is due to the tensile stresses induced by restrained and non-uniform shrinkage prior to the application of the load. If, however, the test specimen is small and drying takes place very slowly so that internal stresses can be redistributed and alleviated by creep, an increase in strength is observed(23).

According to ASTM C 39(156), moist cured specimens should be tested immediatedly on removal from moist storage.

In the range of speeds at which a load can be applied to a specimen, the rate of application has considerable effect on the apparent strength of concrete; the lower the rate at which stress increases, the loer the recorded strength(23).

The potential strength and variability of concrete can be established by standard specimens made and cured under standard conditions. Strength specimens of concrete made or cured under other than standard conditions provide additional information but should be analyzed and reported separately(13).

4.2.3 *Prediction of Final Strength*

Efforts are often made to control the quality of the final product at the earliest possible stage of the process and to apply accelerated test methods. This applies especially to the strength development characteristics. Many attempts have been made to correlate early strength with late strength after 28 days. Acceleration by increased temperature shall provide information on late strength after only a few hours(157). Although results may be used to predict the potential compressive strength of concrete at some later age, the most important use of accelerated strength test is for control of concrete production so that rapid adjustments of batching and mixing can be made(158). The 28-day strength can be predicted using the results of strength tests obtained at early ages by performing a linear regression analysis on the strength and maturity data obtained in accordance with ASTM C 918(159). Compressive strength at later ages is predicted using the equation

$$S = S_m + b\,(\log M - \log m)$$

where S = predicted strength at specified maturity M
S_m = strength at maturity m
b = slope of the prediction line
M = specified maturity under standard conditions
m = early age concrete maturity

To predict the value of strength at 28 days, we may correlate the 28-day strengths with strengths at 1 day or 3 days. For this purpose, a regression line is fitted to the data. It is possible to fix the confidence interval that may be later limited to give a more reliable estimate of 28-day strength, using the strength values obtained at 7 days(160). The regression equation may be developed from laboratory or field test data. The regression analysis should use a minimum of 30 sets of test data which have a broad strength range. If project materials change during the course of construction, a new linear regression analysis must be performed using compressive strength data representing concrete made from the new materials. The prediction equation is valid only in the observed range of observations. Extrapolations may give misleading results because we have no information that linearity holds outside of the present observations.

4.2.4 *Quality Concrete Surfaces*

Good exposed concrete meets three kinds of requirement or performance:

(i) uniform colour and structure;

(ii) a closed, compact surface; and

(iii) a surface as free as possible of blow-holes, cracks and efflorescences.

The surface aspect must be greatly affected by the choice and uniformity of the aggregates, of the fines in particular. The major obstacle in obtaining a uniform structure is the segregation the concrete undergoes during placing and compacting. Closed and compact surface means one displaying no segregation of gravel or one that is not 'poorly closed' (owing to a stiff mix or to insufficient mortar). There must, in the first place, be enough mortar; it must also be abundant. While obtaining a 'closed and compact surface' depends on the fresh concrete and on its composition and placing, blow-holes, cracks and efflorescences are phenomena which are more difficult to control and whose root causes are hard to find.

The blow-holes (on the surface, their size generally being less than 10-12 mm) result from air bubbles trapped between the pour and the formwork because they are unable to climb up the form wall and vent in the atmosphere. Cracking is almost always due to too much cement, to forms that are too smooth and impermeable, having no or slight absorbency, or to unprotected curing. Efflorescences are caused by the drift of calcium hydroxide freed during the cement hydration and brought in solution to the concrete surface where it carbonates and evaporates. Efflorescences are formed every time, and at the points where the concrete stays in contact with slowly percolating or dead water(161).

Concrete incorporating fly ash may be darker than similar concrete made with OPC and whilst slag may introduce a tinge of green or blue to newly-placed concrete, this tends to fade to a somewhat lighter grey than OPC(80). The colour of the fine aggregate has an important influence on the colour of the concrete. It is, therefore, vital that the supply does not vary during the course of work(80). Generally, when coloured pigments in powder form are used as admixtures in concrete for the purpose of producing integrally coloured concrete, fresh concrete properties are virtually unaffected by the presence of the pigment. Some of the extra water requirement may be counteracted by a slight increase in workability caused by the presence of metallic soap(162).

According to Monaco(163), the water-cement variation influences the brightness of the hardened cement paste surface.

4.2.5 *Permeability*

One of the most important parameters influencing the durability of concrete is its permeability. It dictates the extent to which concrete can be affected by external agents. The permeability of concrete determines the ease with which liquids, gases and dissolved deleterious substances such as sulphate or chloride ions or carbon dioxide can penetrate the concrete(23),(165),(166),(167).

The permeability is determined by the pore structure of the hydrated cement paste matrix in the surface zones of the concrete. The pore structure itself is influenced by the type of cement, water-cement ratio, duration of curing and carbonation of the concrete.

Whatever the absorption characteristics of a given aggregate, its rate of absorption in concrete is limited by the rate at which water can pass through its envelope of hardened paste. Because the coefficient of permeability of the hardened paste is lower, its cement content is higher and it is wet-cured longer—the rate of absorption of any kind of aggregate can be lowered by reducing the water-cement ratio of the paste and by good curing.

The permeability of the concrete mainly depends on the following factors:

- the total porosity and characteristics of the pore system (distribution by dimension, average dimension, degree of continuity);
- the development of the hydration process which, in a specific manner, lowers the continuity of the pore system; and
- the aggregate porosity and grading.

The value of the total porosity is less important than dimensional distribution, average dimension and continuity of the pores. The permeability will be lower as the uniformity of distribution is greater, the average dimension smaller and the continuity more limited. Since the quantity of water which exceeds that removed by the hydration reactions has a marked influence on these features, the permeability of the hardened concrete will depend mainly on the water-cement ratio used and on the hydration degree of the cement. It is equally necessary to adopt every precaution to avoid cracking and to extend the period of curing as long as is practical, especially when building in hot climates(168). The difference in permeability between a high water-cement ratio concrete badly cured and a lower water-cement ratio fully hydrated concrete is enormous, up to six orders of magnitude(169).

Permeability to aggressive agents appears to mainly depend on pores that have diameters exceeding 0.1 μm but the real shape of the pores and their interconnection play a leading role. The pastes of pozzolanic cement and slag cement (high slag content) have a lower permeability and therefore greater durability, although they present greater porosity, probably because their pore microstructure is different from that of portland cement(170). When compared with the same level, the diffusion coefficient of each ion through hardened paste becomes smaller in the order of OPC and fly ash cement with high calcium fly ash, blast furnace slag cement, fly ash cement with ordinary fly ash and silica cement with silica fume(171).

Certain pozzolans are more effective than others in reducing the permeability of concrete at early ages. However, under most conditions of service, the permeability of concrete containing any pozzolan is markedly reduced at later ages.

The lower resistance to carbonation attributed to blended cements compared with that of portland cements, disappears if the concretes are well cured before being submitted to the action of aggressive agents(172).

Concrete permeability diminishes rapidly with the increase in the cement content but beyond certain limits, variations of permeability become negligible. Moreover, permeability depends notably on the effectiveness of compaction.

4.2.6 *Steel Cover*

Hydrated portland cement is subject to chemical reaction with the carbon dioxide of the atmosphere. Such carbonation reduces the alkalinty of concrete and thus reduces its effectiveness as a protecting medium for reinforcing steel against corrosion. In concrete containing chlorides, however, the protective film that is normally formed cannot be maintained with the same efficiency. The simultaneous presence of chlorides and carbonation has an additive effect on the corrosion rate of steel reinforcement in concrete and results in higher values than when they act separtely(173). The corrosion product expands up to four times its original volume, creating internal pressures which ultimately severely damage the concrete. Typical effects include cracks, stains, potholes and spalling. When spalling is accelerated and eventually the steel deteriorates enough to cause section loss and serious reduction in structural strength(174).

Protection against penetration of salts to reinforcing steel and other embedded items is affected considerably by the thickness of concrete cover over the steel. It is generally recognized that at or near the waterline or in other locations exposed to a combination of seawater, including spray, and atmospheric oxygen in marine construction and other severe environments, more cover is required than is normally used.

A linear relationship has been found between the water-cement ratio and the depth of carbonation. Depth of carbonation and chloride penetration has appeared to be enhanced considerably by insufficient curing(175) and probably connected to the kind of cement(176).

Lin Xianxiong et al.(177) showed that rates of carbonation of various kinds of steam cured slag cement concrete and ordinary portland cement concrete with fly ash additive are larger than that of plain concrete—the higher the fly ash content, the faster the rate of carbonation.

Cracking of concrete cover signifies an important step in corrosion development as crack formation brings a significant increase in oxygen supply(178).

4.2.7 *Cracks Control*

A serious matter in preventing the penetration of water and gases into concrete is cracking. Apart from those due to structural movement, cracks are due to drying shrinkage and thermal expansion-contraction. Although highly impermeable concrete can be made with a low water-cement ratio and a mix rich in cement, this produces excessive shrinkage and an increase in the temperature of the concrete, with consequent thermal expansion-contraction and results in a number of shrinkage and/or thermal cracks. In consequence, the penetration of water and gases is greater than would occur in a structure constructed with concrete of higher permeability.

The shrinkage of concrete which occurs in drying can be reduced by efficient curing while the increase of the temperature of concrete can be controlled using a suitable cement.

4.2.8 Frost Attack and De-icing Salts

Protection to harmful action of frost is obtained by adding the so-called air-entraining admixtures to mixes but another means of preventing frost damage that should be considered is the use of concrete mixes with the water-cement ratios sufficiently low for the paste to have only small capillaries and only little freezable water.

4.2.9 Abrasion

Tests and field experience have generally shown that compressive strength is the most important single factor controlling the abrasion resistance of concrete, the abrasion resistance increasing with the increase in compressive strength. According to Gjorv et al., by increasing the concrete strength from 50 to 100 MPa, the abrasion of the concrete was reduced by roughly 50%. At 150 MPa, the abrasion of the concrete was reduced to the same low level as that of high quality massive granite(179). Compressive strength and abrasion resistance vary inversely with the ratio of voids (water plus air) to cement. For rich mixes, limiting the maximum size of the aggregate will improve compressive strengths and result in maximum abrasion resistance of concrete surfaces.

Tests confirmed that abrasion resistance of structural lightweight concrete varies with compressive strength in a manner similar to normal weight concrete.

5. TEST

5.1 Microscopic Analysis

The microscopic structural analysis of hardened concrete allows the assessment of(180):

- the basic components of concrete viz aggregates, cement, filler, slag, fly ash, their shape, quality and composition;
- the proportion of components in the concrete viz. granulometry, finest fraction, entrained air content, etc.;
- concrete pouring quality and errors viz. mixing efficiency, degree of compaction, aggregate segregation, subsequent addition of water, curing etc.;
- concrete resistance against environment agencies e.g. gases such as CO_2, SO_3, frost and de-icing salts, abrasion, etc.; and
- damaging attacks and how these affect concrete (causes of distress) such as caused by freeze, freeze-de-icing salts, acids, carbonation, water containing sulphate, mechanical influences, etc.

The sample of examination will normally be prepared by sawing the core longitudinally with thé plane of the cut perpendicular to the layers in which the concrete was compacted. The slice is polished by using successively finer grades of abrasive. The lubricant used is normally non-aqueous media to avoid the dissolution of water-soluble compounds in the concrete. Examination of the polished surface is carried out with a stereoscopic microscope at magnifications typically of x10 up to x100. Features of importance may be recorded by photomicrography.

According to Wilk and Dobrolubov(181), the microscopic control of concrete is carried out on thin sections made from a concrete core specimen impregnated with a special fluorescent dye and examined under microscope in transmitted ultraviolet light. This new method permits a clear distinction of the three concrete texture components, viz. aggregates, hardened cement paste and voids. Linear measurements of crack widths are normally made with a calibrated eye-piece graticule.

The volumetric proportions of selected constituents in the concrete slice can be quantified by one of the three methods:

1. *Point count analysis:* This is the most widely used method as it is the least laborious of the manual options. The polished slice is examined under stereoscopic microscope whilst being traversed along a series of regularly spaced parallel lines. At regular points along each traverse line, the constituent falling on that point (coarse aggregate, fine aggregate, cement paste or air void) is recorded on tally counter. From the data collected, the volume percentage of each constituent can be calculated. The aggregate would normally be sub-divided on the basis of the composition and possibly the presence of reaction features.

The area of an individual surface to be counted will be governed by the size of core available and any special objectives of the analysis. Where the data is intended to indicate the composition of the concrete at a particular sample location, the area of the surface or combined surfaces analysed should take into account the maximum aggregate size and any inhomogeneity of the concrete. As a general guide, the larger the area the better but the minimum dimension should be 5 × the maximum aggregate size. The reliability of the analysis will be controlled by the number of points counted and the relative proportion of the component. The maximum theoretical standard deviation for a given component may be calculated by:

$$s = \sqrt{x}(100 - x) / S_t$$

where x = volume percentage of component
S_t = total number of points counted

2. *Linear traverse method:* In this method, the volumetric composition of the concrete is determined by integrating the distance traversed across each component along regularly spaced parallel lines. The equipment required consists of a motor-driven stage permitting the sample to be moved in two directions at right angles and possessing a means of recording the distance traversed over each component. The slice is examined with a stereoscopic microscope. The method is extremely laborious for multi-component analysis.

3. *Computer aided image analysis:* Automatic image analyzing systems have been used for determining the air void and aggregate contents in concrete samples. These require additional sample preparation to provide sufficient colour contrast between components. At present, distinction of aggregate types is not feasible. This technique is not readily available commercially.

From the volume percentages of coarse aggregate, fine aggregate, cement paste and air voids, it is possible to calculate the original concrete mix proportions by mass, if additional data on the concrete density, aggregate densities and water absorption and specific gravity of the cement can be determined(104).

Distress that has occurred in the aggregate and surrounding matrix, such as micro- and macro-cracking, may be observed. Also, reaction rims may be observed in certain aggregate particles and may be identified as negative or positive by acid etching.

5.2 Checking of Freshly Mixed Concrete Composition

There have been a number of methods proposed for determining the various constituents of fresh concrete. Among them are the nuclear, flocculation, flotation, chemical, microwave absorption, thermoconductivity, capacitance and electrical resistance. However, three methods have emerged as either the most used systems or ones with the best potential for being used. These are chemical, flotation and flocculation methods. The devices employing these methods are commonly known as the Concrete Quality Monitor (CQM)(182), flotation process(183) and the Rapid Analysis Machine (RAM)(184) respectively. According to Williamson(185) all three systems are equally accurate in obtaining the cement content of fresh concrete. CQM, which is the only system that directly determines the water content, is accurate in this determination, as are the cement content measurements. Both RAM and CQM have been used extensively in the field and have proven to be acceptably accurate under field conditions.

Recently, Ohgishi et al(186) have developed a field apparatus by which all the constituents of fresh concrete can be separated and measured. The testing apparatus developed consists of two portions, sample washing-separation unit and weighing unit. According to them, the errors on the measurement values against the values of mixed ingredient are within the ranges of ± 2.0, ± 1.7% and ± 1.6%, respectively. The error on the water-cement ratio was 1%. With this apparatus, the whole process of work can be completed within 30 minutes.

5.3 Determination of Cement Content in Hardened Concrete

The test procedure for the determination of the cement content of a concrete, for example BS 1881: Part 6(134), can give erroneous results. The sample is crushed to obtain a representative sub-sample passing the 150 μm test sieve. This sample is then subjected to successive extraction with cold dilute acid and hot dilute alkali solution to dissolve the cement component (although a proportion of the aggregate may also dissolve). The extract is then analyzed for both silica and calcium oxide content (the two major components of a cement), If the cement source is known, figures will be available for the calcium oxide and silica contents of the cement and the cement content can be determined for each component by simple proportion.

It is normal to analyze a control sample of the aggregate alongside the sample under test and to apply appropriate corrections to the results obtained from the sample before calculating the cement content. If control samples of the aggregate are not available then the cement content determined will be too high. When the concrete being analyzed is many years old, it is usually difficult to be certain that the control samples truly represent the aggregate which was used in the concrete. If the appropriate corrections for the aggregate have been made, the calculated cement content derived from silica and that derived from calcium oxide should be within 1% of each other. It is then normal to take the mean value. If they are not within 1% of each other, it is likely that the control aggregate does not represent that used in the concrete. If either or both of the cement and aggregate compositions are unknown, then reasonable assumption as to their composition must be made, recognizing that this will lead to some loss in accuracy. It is normally possible for a competent analyst to provide results for the cement content within ± 15% of the true value(104).

5.4 Test for Durability

The accelerated method proposed by Mehta(187),(188),(189) was used to evaluate the resistance of cements to sulphate attack. According to this test, cylindrical paste specimens are immersed in a 4% Na_2SO_4 solution, whose pH is kept constant by the addition of H_2SO_4. After 28 days, the specimens are removed from the solution and the compressive strength tested. A cement which, after the sulfate attack, shows a strength loss equal to or higher than 25% is considered not resistant to sulphates.

This test, like the analogous accelerated ones, also has the disadvantage of not reproducing (as regards quality and sizes of the specimens, composition and concentration of the attack solution) the concrete performances and, therefore, it is unable to give an absolute scale of the strength values of cements. Nevertheless, it has the advantage of operative simplicity and allows a discrimination, even if not sharp, between the cements more or less resistant to sulphates, belonging to the same family(166).

Expansion test: The prime function of expansion testing is to determine whether the concrete as represented by one or more core samples has the potential to expand or continue to expand as a result of the alkali-silica reaction. The results of these tests will be used to determine the potential for expansion in those parts of the structure so far unaffected by the alkali-silica reaction, and further expansion in parts already affected. Under the standard test temperature of 38°C, all cores exhibit an initial thermal expansion, up to one day, of up to 300 microstrain. A continuing slight expansion due to moisture uptake normally occurs for up to two or three weeks. The magnitude and rate of this moisture uptake and the resulting expansion, depends on the permeability of the concrete, the nature of the aggregates, the mix proportions and the initial moisture content. They will also be influenced by the quantity of alkali-silica gel present in the concrete.

Concrete in which the alkali-silica reaction is in an advanced state and which may contain much gel, sometimes exhibits a large, rapid expansion at early ages in the test. Where there is a potential for further reaction, continued expansion will be observed at greater ages. The distinction between early and longer-term expansion is not clear and is likely to vary for different concretes.

Asymmetric expansion of cores may occur and considerable differences between individual measurements of expansion along the length of a single core are not uncommon.

The shape of the expansion-time curve for each core must be considered, both in relation to the early age expansion and the longer-term expansion. At present, the precision of the test methods and the lack of information on the correlation between the results of core expansion testing the expansion in the structure, do not permit firm guidance to be given on the interpretation of expansion test results(104).

Chloride in concrete may be in the water soluble from or may be chemically combined with other ingredients(190), (191). Soluble chlorides induce corrosion, while combined chloride is believed to have little effect. Tests for soluble chloride, however, are time-consuming and difficult to control. Factors such as sample size, boiling and soaking time, temperature and quantity of distilled water used, all affect the results. Therefore, the test must be performed in a standardized manner(192),(193),(194),(195). Conversely, the test for total chloride which involves nitric acid extraction, is not significantly affected by the above factors. Most interested parties, therefore, measure total (soluble plus combined) chloride. If the total chloride is less than the allowable limit, obviously soluble chloride need not be measured. Should the total chloride content exceed this limit, additional information on the risk involved in using the material may be obtained by performing a soluble chloride test. When this value is found to be above the limit, corrosion is likely if moisture and oxygen are readily available. If it is below the limit, the risk of corrosion is low(13).

To minimize the risk of corrosion of embedded steel, it is usual to limit the amount of chlorides in concrete contributed from all sources.

ACI Committee 222(13) suggests the following limits for chloride ion in concrete prior to service exposure, expressed as a per cent by weight of cement:

1.	Prestressed concrete	0.06%
2.	Conventionally reinforced concrete in a moist environment and exposed to chloride	0.10%
3.	Conventionally reinforced concrete in a moist environment but not exposed to chloride	0.15%
4.	Above ground building construction where the concrete will stay dry	No limit for corrosion

For steam cured products, it is worth considering, as regards the chloride content, that the reaction rate of aggressive ions eventually present in the concrete mix is much enhanced and so undesirable effects may be produced with greater rapidity and intensity(196).

Corbonation of concrete: The determination of the carbonated layer mainly around the steel reinforcements is usually measured by the phenolphthalein test on recent fracture surfaces perpendicular to the surface exposed to carbonation(197),(198).

The coefficient of exygen gas permeability is an indirect measure of the penetration of gases like CO_2 which penetrate by diffusion and react with components for the hydration products. The measuring equipment(199),(200),(201) provides the investgation of concrete disks cut from drilled cores. Permeability is very difficult to measure accurately and tests are not often made outside the reasearch laboratory.

A permeability cell for measuring the permeability of mortar and concrete to gas is described by Cabrera and Lynsdale(202). The cell is designed to test mortar samples but can also be used for concrete specimens. Measurements using these cells are highly repeatable and reproducible. The cell is very sensitive to evaluate the influence of the water-cement ratio, age, replacement of cement by pulverized fuel ash and the influence of different curing conditions or curing compounds.

The most widely used test of the resistance of concrete to freezing is ASTM C 666(92). This test consists of two procedures. In Procedure A, both freezing and thawing occur with the specimens surrounded by water and in Procedure B, the specimens are frozen in air and thawed in water. In these tests, the deterioration of the specimens is evaluated by the resonance frequency method. These tests tend to give variable results both within and between laboratories, but the variability is less for very good or very poor concrete than for concretes of intermediate durability. Procedure A is somewhat more reproducible than Procedure B(117).

Quality air-entrained hardened concrete with the correct volumetric content of correctly spaced air void, its uniform distribution in cement paste and crackfree aggregates may be determined microscopically (ASTM C 457 82a(203). In order to calculate certain air-void parameters, an accurate value for paste content of the specimen under examination is necessary(204). The determination of paste content via linear traverse is quite tedious, as it involves obtaining lengths of lines traversed across every aggregate particle, thus significantly increasing the time needed to complete a linear traverse. To make the examinations more efficient, the specimens are subjected to point count analyses across 90 linear in. of surface, prior to running full linear traverse. Point count allows a rapid and accurate determination of the paste content to be made. The values for paste content determined via point count are then used in the linear traverse computations(127).

ASTM C 672(205) is often used to assess the resistance of concrete to de-icer scaling.

In order to evaluate abrasion resistance properly, the 'Standard Method of Test for Abrasion Resistance of Horizontal Concrete Surface' ASTM C 779(206) can be adopted. It includes three optional procedures:

(i) The revolving-disc adaptation of the Schuman and Tucker machine;
(ii) the dressing-wheel machine; and
(iii) the ball-bearing machine.

Recently, a versatile apparatus with three different types of abrasion head

(a) revolving pads,
(b) rolling wheels, and
(c) dressing wheels

has been developed for assessing the abrasion resistance of concrete slabs in the industrial enviornment. The abrasion resistance is expressed in terms of the depth of the groove produced by 15 min. of abrasion. This has the additional advantages of simulating service conditions, of being repeatable and easy to follow(207).

5.5 Non-destructive Tests

The purpose of non-destructive testing is to determine the various properties of the concrete such as strength, modulus of elasticity, homogeneity and integrity without damaging the structure.

Non-destructive testing can be applied to both new and existing structures. Its principal applications are(164):

— quality control of precast or *in-situ* construction;
— assessment of uniformity or homogeneity of concrete;
— back-up for compliance of materials and workmanship with specifications;
— assessing whether forms can be safely removed, curing discontinued, prestresses applied, loads imposed, etc.
— location and assessment of the extent of cracks, voids, honeycombs, etc; and
— monitoring progressive changes in the condition of the concrete.

Because most methods for assessing *in-situ* concrete strength suffer from certain limitations, a combination of methods is recommended.

5.6 Precision of Test Methods

Many different factors (apart from sampling error) may contribute to the variability of a test procedure, such as(208):

— the operator;
— the instruments and equipment used;
— the calibrations of the equipment; and
— the environment (temperature, humidity, etc.)

Variability will be larger when the tests to be compared have been performed by different operators and/or with different instruments than when they have been carried out by a single operator using the same instruments. Hence, many different measures of variability are conceivable according to the circumstances under which the tests have been performed:

Two extreme measures of variability, termed repeatability and reproducibility, have been found sufficient to deal with most practical cases. Repeatability refers to tests performed at short intervals in one laboratory by one operator using the same equipment while reproducibility refers to tests performed in different laboratories which implies different operators and different equipment.

5.7 Laboratory Affidability

Laboratory has the responsibility of making accurate tests. Concrete will be penalized unnecessarily if tests show greater variations or lower average strength levels than actually exist. Since the range between companion specimens from the same sample can be assumed to be the responsibility of the laboratory, a control chart for ranges should be maintained by the laboratory as a check on the uniformity of its operations. It should be noted that these ranges will not reveal day to day differences in testing, curing and capping procedures or testing procedures which affect strength levels over long periods(13)

5.8 Calibration of Testing Apparatus

The importance of using accurate testing machines needs no emphasis since test results can be no more accurate than the equipment and procedures used. Laboratory equipment and pocedures should be calibrated and checked periodically.

6. EQUIPMENT

Generally, the accuracy of the measuring equipment shall comply with the relevant national requirements or regulations valid in the place of production of the concrete. According to ENV 206(10), in the absence of such requirements, the minimum values reported in Table 7 should be applied:

Table 7. Accuracy of measuring equipment

Position on the scale or range of a digital indicator	Accuracy during operation
0 to 1/4 full scale or range	1.0 % or 1/4 range value
1/4 to full scale or range	1.0 % of the actual reading

For batching of the constituent materials, the accuracies (of equipment and its operation) have been given in Table 8.

7. CONCLUSIONS

In Tables 9, 10 and 11 are summarized, according to ENV 206(10), the tests and minimum frequencies for, respectively:

Table 8. Accuracies for batching of constituent materials

Material	Accuracy
Cement	± 3 % of required quantity
Water	± 3% of required quantity
Total aggregates	± 3 % of required quantity
Additions	± 3 % of required quantity
Admixtures	± 5 % of required quantity

Table 9. Materials control

Material	Test	Minimum frequency
Cement		Samples are taken and stored once per week for testing in case of doubt
Aggregate	Sieve analysis	- First delivery from new source - Periodically depending on local or delivery conditions - in case of doubt
	For impurities	- First delivery from new source - Periodically depending on local or delivery conditions - In case of doubt
Light or heavy aggregates	Bulk density according to ISO 6782[209]	- First delivery from new source - Periodically depending on local or delivery conditions - In case of doubt
Admixtures	Density for comparison with nominal density	Samples are taken and stored each delivery for testing in case of doubt
Additions		Samples are taken and stored once per week for testing in case of doubt
Water	Chemical analysis (to ascertain that the water is free from harmful constituents) and concrete or mortar specimens (to compare setting and strength with control specimens)	When a new source is used for the first time and water is not taken from public supply and in case of doubt

Table 10. Equipment control

Equipment	Inspection/Test	Minimum frequency
Stockpiles, bins	Visual inspection	Once per week
Weighing equipment	Visual inspection Test of accuracy	Daily Periodically depending on national regulations
Admixture dispenser	Visual inspection Test of accuracy	Daily Monthly or in case of doubt
Equipment for continuous measurement of water content of fine aggregates	Comparison of the actual amount with the reading on the meter	Monthly or in case of doubt
Batching system	Visual inspection Comparison of the actual mass of the constituents in the batch with the intended mass	Daily Monthly or in case of doubt
Testing apparatus	Tests according to standards or other regulations	Regularly depending on apparatus—however, at least every 2 years
Mixers	Visual inspection	Montly

Table 11. Control of production procedure and of concrete properties

Characteristics	Inspection/Test	Frequency
Mix proportions	Initial test to ensure that properties are met	Before using a new mix
Chloride content	Chemical analysis	Initial test and a case of change of constituents
Water content of coarse and fine aggregate	Continuous measuring system or drying test	If not continuous, daily

(Table 11 Contd.)

Characteristics	Inspection/Test	Frequency
Consistence of concrete	Visual inspection	Each batch
	Consistence test according to: ISO 4109[(136)] ISO 4110[(137)] ISO 4111[(138)] ISO 9812[(139)]	- When making specimens for testing hardened concrete - When testing air content - In case of doubt following visual inspections
Density of fresh concrete	Density test according to ISO 6276[(210)]	As frequently as for compressive strength test
Compressive strength test moulded concrete specimen	Test according to: ISO 4012[(211)]	As frequently as needed to conformity control
Apparent density of hardened light or heavyweight concrete	Test according to: ISO 4012[(211)]	As frequently as compressive strength tests
Added water content, cement content, additions of fresh concrete	Record of the quantities	Every batch
Air content of fresh concrete (mixes with specified air content)	Test according to: ISO 4848[(212)]	- First batch at least daily - More frequently depending on the conditions of production
Uniformity	Test by comparing the properties of samples taken from different parts of a batch	In case of doubt
Water penetration	Test according to: ISO 7031[(213)]	Initial testing. Subsequent frequency to be agreed upon

(i) control of raw materials;
(ii) control of equipments; and
(iii) control of production procedures and of concrete properties

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