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The Variation of Works Concrete Test Cubes

La variabilité des essais sur cubes de béton effectués au chantier

Die Veränderlichkeit von Baustellen-Betonwürfelproben

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Introduction

In the past, it has often been customary to specify nominal mix proportions and usually also the minimum strengths of preliminary and works test specimens. Under favourable circumstances, these requirements were easily met, but, where poor conditions were encountered, the attainment of the required strengths presented considerable difficulty; neither circumstance is desirable since the first is uneconomical and the second unsatisfactory. More recently there has been a trend towards specifying the quality of concrete by the minimum strength of works test specimens leaving the design of the mix to the contractor. However, suitable mix proportions can only be estimated on the basis of the *mean* strength so that a knowledge of the relationship between the mean and minimum values is required.

The margin by which the mean strength must exceed the specified minimum is, of course, related to the standard of control to be exercised but conflicting opinions have been expressed as to whether, for any particular standard of control, there was a constant difference between the mean and minimum strengths, so that the standard deviation is independent of the mean, or whether there was a constant ratio between these strengths so that the standard deviation was proportional to the mean and the coefficient of variation was constant. It has also been suggested that the relationship is probably intermediate between the two, i. e. that "in the absence of better information... the variation in cube strength is assumed to be proportional to the average strength up to 3,000 lb/in^2 (about 200 kg/cm^2) and constant above this figure".

In order to investigate thoroughly the relationship between the mean and minimum strengths, cube results and details of the control methods have recently been collected from about 300 British construction sites and have been analysed in detail. Wherever possible the degree of control being exercised was carefully noted by personal observation in order to achieve maximum accuracy in the findings and to study the effects of various particular factors on the variability for any standard of control.

Standards of Control

For the purposes of this investigation it was, of course, necessary to define a range of Standards of Control. Since the results obtained appeared to suggest that the control on sites where feeding of the materials to the weighing hopper was effected pneumatically, either directly, by means of air valves, or by electric solenoids, was significantly better than where the weigh-batching equipment was operated manually, these Standards have been kept separate. Continuous mixers are not now normally used, but some data became available for this investigation. However, although all the materials, including the cement, are proportioned by volume, continuous mixing differs fundamentally from those cases where batch mixers are used; the Standard for batch mixers is therefore referred to as Da and that for continuous mixers as Db.

In addition, further results were available from laboratory work. The highest possible standard of control, using dried aggregates and a carefully prepared uniform quantity of cement, all the materials being accurately weighed, has been denoted by La and gives an indication of the testing error between nominally identical cubes from different batches made under the most strictly controlled laboratory conditions. Other laboratory tests (Standards of Control Lb and Lc) on concrete made with dried aggregates and various consignments of cement, give an estimate of the variation caused by the varying rates of hardening of cement from a single works and from a wide variety of sources respectively.

The following nine standards were therefore considered:

Standard of Control	Control measures on	
	Cement	Aggregates
La	Uniform, by weight	Dried, by weight
Lb	By weight (single works)	Dried, by weight
Lc	By weight (various works)	Dried, by weight
Aa	Bulk, by weight (servo-operation)	By weight (servo-operation)
Ab	Bulk, by weight	By weight
B	By full bags	By weight
C	By full bags or weight	By volume
Da	By volume	By volume
Db	By volume (continuous mixer)	By volume (continuous mixer)

Analysis of Results

Definition of "Minimum" Value

When investigating the relationship between the mean and minimum values of the results of works test cubes some consideration must be given to the interpretation of the "minimum" strength. It was thought inadvisable to consider the minimum as the value of the lowest cube strength actually obtained, since this would give undue emphasis to this one result and ignore much of the information contained in the data. Further, it can be shown that two otherwise similar groups of results, containing different numbers of cubes, are likely to have different minimum values. For example, if the mean strength of both groups is 5,000 lb/in^2 (about 350 kg/cm^2) the minimum values for a particular degree of variability might be expected to be about 3,850 and 3,100 lb/in^2 (about 270 and 220 kg/cm^2) for 10 and 100 cubes per group respectively. Since the number of results per group included in the investigation ranged from about 10 to nearly 4,000 it was obviously preferable to adopt the use of an "estimated" minimum value which would overcome these difficulties.

Since it is not possible to evaluate an absolute minimum below which no values will ever fall, it is usual to allow a small fixed proportion of results to lie below the "minimum". A proportion of 1% has often been suggested but it is frequently found that only about 25 sets of test cubes are made for any one particular condition. The minimum value, x_0, which has been adopted in this paper, corresponds to 4% of the results falling below x_0 and is given by the formula

$$x_0 = \bar{x} - 1.75\,s$$

where $\bar{x}$ = mean value

s = standard deviation.

(This formula is dependent on the assumption of a "normal distribution" of the results, which will be discussed in greater detail later.)

Evaluation of Standard Deviation

The variation in the results of the works test cubes depends to a considerable extent on the degree of control being exercised in the production of the concrete and results from a number of factors. For convenience these may be considered in three groups arising respectively from

(I) fluctuations in the water/cement ratio;
(II) varying rates of hardening of different consignments of cement;
(III) variations inherent in the methods of sampling and of making, curing and testing cubes.

Group (I) includes all the variations caused by the method of batching, since variations in the proportions of the cement and the aggregates, or in the grading and particle characteristics of the aggregates, would probably result in an adjustment of the quantity of water added at the mixer in attempting to maintain a constant degree of workability. The variations due to Groups (II) and (III) are in general much smaller; nevertheless, where a high degree of control is being exercised on the job they may become relatively more significant. The testing error is usually negligible, especially where tests are carried out according to the appropriate Standard Specification and can be eliminated almost entirely by testing a large number of cubes out of each batch of concrete (although this technique is obviously uneconomical). Moreover, where cubes are made in sets of two or more it can be evaluated separately. However, in many cases, only one cube was in fact tested for each condition so that the standard deviation evaluated contains both sources of variation. In order to achieve consistency, therefore, it was decided to express *all* values of standard deviation as the value that would have been obtained had only one cube been tested in each condition. This refinement, although adopted for the purposes of this investigation, is often of little importance in practice, but the appropriate adjustment can be made if desired. The testing error was also evaluated where possible. It may be noted that if the standard deviation is required to be known at an early stage a more reliable value would be obtained if the cubes are made singly out of separate batches rather than in pairs or threes out of a smaller number of batches. Where statistical methods are in use, the advantage of making cubes in sets for any particular age is reduced to the possibility of evaluating the "testing error" which is generally relatively unimportant and can be determined at a later stage if required.

Form of Distribution

The above-mentioned statistical definition of an estimated minimum below which only a known proportion of results is likely to fall is dependent on the assumption that the distribution of the results is "normal" or "Gaussian". This can most conveniently be confirmed by plotting them in the form known as a "histogram", shown in fig. 1 for one of the groups of results examined; the horizontal scale is divided into a number of equal ranges of compressive strength referred to as "group intervals", and the height of the vertical columns represents the number of cubes in each of these ranges.

In a "normal" distribution most of the results lie symmetrically relatively close to the mean but there are a few scattered wide on each side. If the group intervals are made smaller, and at the same time the number of observations is increased, the histogram will approach more and more closely to a smooth bell-shaped curve. Although many authors assume that concrete test results give a symmetrical curve resembling this "normal" sufficiently closely for practical purposes, doubts have sometimes been cast on this assumption. In particular under certain circumstances there may be more very high results than very low ones due to the fact that poor quality concrete is likely to be rejected by the site inspectors and not used in the work. However, a very large number of results is necessary to establish significance for departures from normality; since any slight "skewness" does not seriously invalidate the results, a "normal" distribution is usually assumed owing to its great convenience, and the corresponding curve is also shown in fig. 1. It may be seen that the distribution follows the theoretical curve closely although there are appreciable irregularities even with nearly 4,000 results.

However, it was felt desirable to investigate this factor in greater detail. This could have been done by superimposing the histograms for the 1,000 groups of results on each other to determine whether there is a significant departure from normality. However, a simpler, though less reliable, method was adopted, consisting of the evaluation of the ratios

$$l_1 = \frac{\text{mean — lowest observed result}}{\text{standard deviation}}$$

and

$$h_1 = \frac{\text{highest observed result — mean}}{\text{standard deviation}}$$

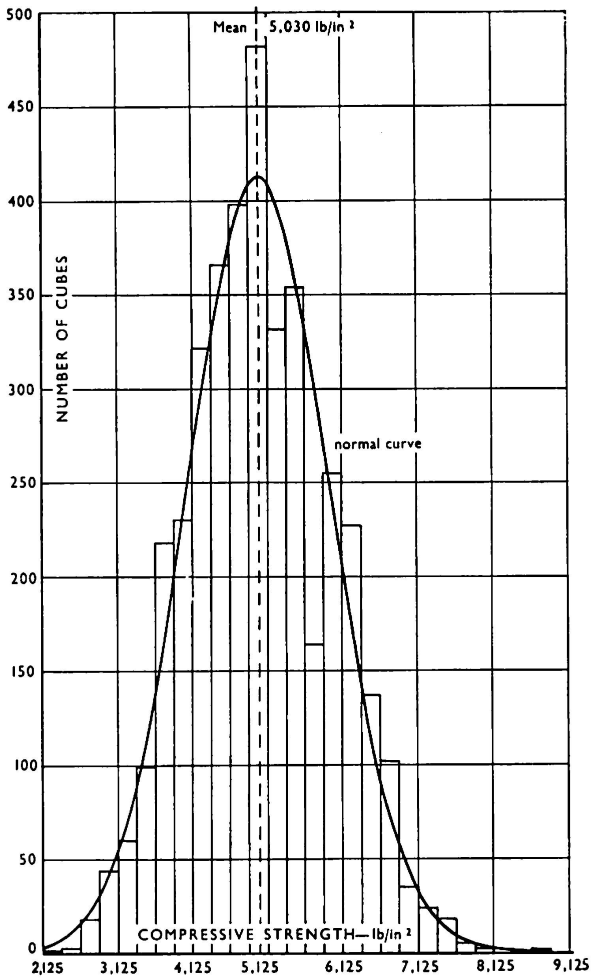

Fig. 1. Histogram for Concrete Cube Strengths.

for each group of results where the required information was available. For a normal distribution these ratios should, of course, be equal, i. e. the average of the ratios l_1/h_1 for each group of results should equal unity. Since the observed lowest and highest results are often spurious, a similar calculation for l_2 and h_2 was carried out for the second lowest and second highest results in each group.

It was found that the grand averages of l_1/h_1 and of l_2/h_2 were insignificantly different from unity so that there appeared to be no overall departure from normality. However, as indicated by the histograms in fig. 2 there is a tendency

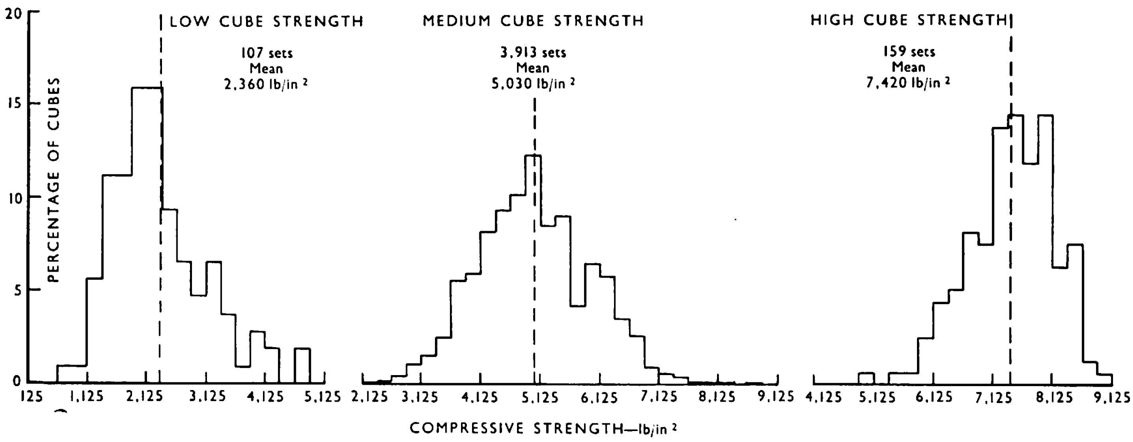

Fig. 2. Forms of Distribution for Concrete of Low, Medium and High Cube Strengths.

for low cube strength concrete results to have a longer tail to the right and for high cube strength concrete results to have a longer tail to the left. This is to be expected as a result of the limitations imposed by zero strength and by the "ceiling" value for a particular type of aggregate. However, slight departures from normality are not likely to have an important effect where the required minimum corresponds to 1 in 25 results falling below. Where, however, a much stricter minimum is specified for concrete of relatively low or relatively high strength, the assumption that the distribution is normal may not be satisfactory.

Relationship Between Standard Deviation and Mean Strength

When the values of the standard deviation were plotted against the mean strength very considerable scatter was at once evident, indicating that within any nominal standard of control, there are wide variations, which appear to increase for poorer standards of control, due probably to varying degrees of care in maintenance of equipment and general supervision. A mean curve was however drawn by eye for each Standard of Control; that for Standard Da is shown in fig. 3. The curves for the other Standards may be obtained by multiplying the figures of the vertical scale in fig. 3 by the following percentages:

La	32	Ab and B	84
Lb	56	C	92
Lc	64	Db	76
Aa	72		

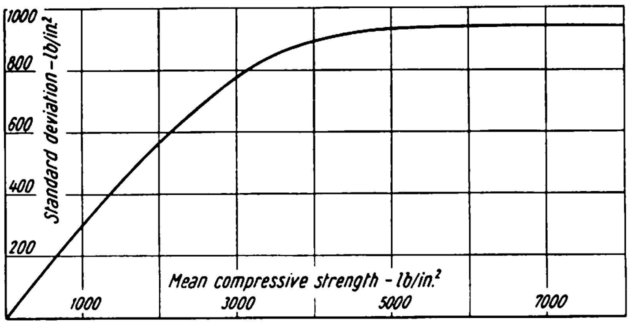

Fig. 3. Relationship Between Standard Deviation and Mean Strength for Standard of Control Da.

It may be seen that this curve is neither a straight line through the origin, indicating that the coefficient of variation is constant, nor a horizontal line, indicating that the standard deviation is constant, for varying values of mean strength.

Different symbols were used for the different ages since it was thought that results for early ages might be more variable. However, it appeared that the age at test has only a small, probably negligible, effect on the standard deviation and has consequently been ignored in the subsequent analysis.

Relationship Between Water/Cement Ratios for Mean and Minimum Strengths

The estimated water/cement ratio required to give the observed mean strength was then plotted against the corresponding value for the estimated minimum for the nine Standards of Control. It was found that the points tended to lie, in each case, on a straight line through the origin, allowing for the appreciable experimental error inevitable in this type of investigation. A pair of dotted lines through the origin was drawn by counting of points to include between them about 80% of the results and the slopes of the mean and limiting lines are given below for the nine Standards of Control.

La	0.92 ± 0.03	Aa	0.82 ± 0.05	C	0.77 ± 0.07
Lb	0.86 ± 0.04	Ab	0.79 ± 0.06	Da	0.75 ± 0.08
Lc	0.84 ± 0.05	B	0.79 ± 0.06	Db	0.81 ± 0.05

The mean slope, which will, for convenience, be called the "control ratio", increases with the Standard of Control but the difference between Standards Ab and C, for example, appears to be much lower than expected. Of particular interest is the improvement resulting from pneumatic operation of the feed to the weighing mechanism (Standard Aa) thus indicating that the normal method of weigh-batching is subject to appreciable error, which is considerably reduced by servo-operation.

The unexpectedly favourable result obtained from the use of continuous mixers (Standard Db) also calls for comment. It would appear that where this type of mixer was required to produce concrete of reasonable quality adequate supervision gave good results. However, the data available for this Standard are rather limited and this conclusion should therefore be regarded with considerable caution.

It should also be noted that the control ratio is subject to fairly wide limits, owing to variations in the results for nominally similar conditions of control, so that there is considerable overlap between adjacent categories. For example, the ratio for Standard C varies from 0.70 to 0.84 (including 80% of the results) and the corresponding range for Standard Ab and Standard B is 0.73 to 0.85. Thus the best conditions of volume batching of aggregates appear to give results almost as good as those for well-controlled weigh-batching although average volume batching is only a little better than comparatively poor weigh-batching. It may also be seen that handling of cement in bulk in fairly large batching set-ups (Standard Ab) does not, in itself, result in better control than that obtainable by using a full bag of cement as the basis of measurement (Standard B).

Variations Within Standard of Control

Rate of Hardening of Cement

The varying rate of hardening of different consignments of cement is often considered to be a major contributory factor to the variation of works test cubes. Since the effect seemed likely to vary with the standard of control, calculations have been made to determine the resulting variation if the cement were entirely uniform.

The standard deviations for Standards of Control Lb and Lc give a measure of cement variability but include also the testing error which is the only variable in Standard of Control La. The standard deviations due to cement variation only were evaluated and were deducted from the variations obtained under normal site conditions (Standards Aa, Ab, B, C, Da and Db). It was found that the percentage reductions in the standard deviation of the works test cubes were constant over the range of mean compressive strength of 1,000 to 8,000 lb/in^2 (70 to 560 kg/cm^2), the values being 12% for poor control (Standard Da), 14 to 18% for normal site control (Standards Ab, B or C), and 26% for servo-operated batching plants (Standard Aa), where consignments are made from a single works. The corresponding figures for sites supplied from a wide variety of sources were 16% for poor control, 19 to 23% for normal site control and 32% for servo-operated batching plants.

On well controlled jobs the effect on the variation of the works test cube results likely to be caused by a change in the supply of cement from various works to a single works is often of particular interest. However, it was found that, while for servo-operated batching plants the reduction in the standard deviation may reach 8%, the values for normal or poor site control (4 to 6%) are comparatively small.

Testing Error

Another of the factors causing variations within any Standard of Control is the "testing error" which can be eliminated almost entirely by increasing the number of specimens in each set. Since however this procedure would inevitably increase the cost of testing, it is felt to be wasteful and it is recommended that, where a reasonably large number of tests is likely to be made, works specimens should generally be tested in pairs at each age. It is then possible to determine the magnitude of the testing error in order to check the relative importance of any excessive inaccuracies in the testing procedure.

The value of the testing error was determined (where applicable) both in terms of the standard deviation and the coefficient of variation, and it was found that the latter measure was approximately constant although still subject to considerable fluctuation. An examination of the data showed that the testing error appeared to be higher for leaner mixes and for concretes containing larger maximum sizes of aggregate. The values of the coefficient of variation for these types of concrete are given below:

Condition	Average coefficient of variation (%)
Overall	5.4
Aggregate/cement ratio greater than 10	13.2
Maximum aggregate size greater than $1^1/_2$ in.	5.9
of $1^1/_2$ in. or 1 in.	5.6
of $^3/_4$ in. or less	4.7

It may thus be seen that large testing errors are introduced when casting dry-lean concrete cubes, presumably due to the fact that it is often extremely difficult to compact this type of concrete adequately in the relatively small section of a standard mould although adequate compaction may well be achieved in the slab. (The same comment is applicable, to a considerably lesser extent, to concrete containing aggregate of large maximum size.) It therefore appears that these test cubes are not a fair representation of the potential quality of this type of concrete and the relevant points, which showed a considerably larger departure than expected from the corresponding mean line, were not included in the subsequent analysis.

Other Factors

The pair of dotted lines which include between them about 80% of all the results, together with the mean line, divide the graphs into four zones of variation, i. e. very high, high, low and very low. The actual proportion of experimental points in each of these zones was compared with the expected percentage of 10 each in the very high and very low zones and 40 each in the high and low zones, to investigate whether either of two factors — size of job and whether concrete was pumped or not — contributed significantly to the variation obtained, for a particular Standard of Control. Since the actual Standard of Control appeared not to affect this analysis, the results were totalled for all the data (approximately half the total number of jobs) where the detailed information was available.

However, it appeared that these two factors are, in themselves, unlikely to have an important effect on the resulting variability which appears to be closely related to the degree of supervision exercised on the job, particularly on the quantity of water added at the mixer.

Application of Results to Concrete Mix Design

The primary purpose of this investigation was to establish a satisfactory method of estimating the mean strength required to comply with a specified minimum value, for different degrees of control. It has been indicated that this relationship is of more complicated form than that of either a constant difference or a constant ratio which have been the bases of earlier methods. However, the relationship between the water/cement ratios required to give these values of strength appears to pass linearly through the origin.

It is therefore suggested that the current method of designing a mix be modified so that reference to the water/cement ratio curve is made for the *minimum* strength and not the *mean* value and that the control function is applied to the water/cement ratio and not to the strength. The water/cement ratio required to give the specified *minimum* strength is obtained from an appropriate curve relating water/cement ratio and strength. This water/cement ratio is then multiplied by the "control ratio" corresponding to the anticipated Standard of Control to give the water/cement ratio required for the *mean* strength.

This modification can perhaps be justified theoretically since the main variations in strength are due directly or indirectly to fluctuations in the water/cement ratio. Hence it seems reasonable to consider this function as the variable on which the control must be exercised. It is worth noting that this modification does not lengthen the current methods in any way.

It has already been indicated that the control ratio for a particular nominal Standard of Control is also dependent to an appreciable extent on the degree of supervision on the site. The following values, corresponding to "poor", "normal" and "good" supervision, have been selected such that three out of five sites will be within the stated limits.

Batching of		Supervision		
Cement	Aggregates	Poor	Normal	Good
By weight (servo-operation)	By weight (servo-operation)	0.78	0.82	0.86
By weight	By weight	0.75	0.79	0.83
By weight	By volume	0.72	0.77	0.82
By volume	By volume	0.70	0.75	0.80

Conclusions

It has been shown that the water/cement ratios required to give the observed mean and estimated minimum values of compressive strength of works test cubes are proportional to each other, the constant of proportionality depending on the standard of control and degree of site supervision. This appears to provide a very satisfactory method of estimating the required mix proportions to comply with a specified minimum value of compressive strength.

It is concluded that the degree of supervision on the site has a much more important effect than the type of equipment employed and that the best conditions of volume batching of the aggregates may give results almost as uniform as those for well controlled weigh-batching, although average volume batching is only a little better than comparatively poor weigh-batching. Relatively smaller variations were obtained from pneumatic operation of the feed to the weighing mechanism, thus indicating that the normal methods of weigh-batching are subject to appreciable error which is considerably reduced by servo-operation.

It has also been shown that the complete removal of the variation in the rate of hardening of cement would reduce the variation of works test cube results obtained on normally controlled sites by about 16% where consignments are made from a single works and by about 21% on sites supplied from a wide variety of sources. The corresponding reduction caused by a change in the supply of cement from various works to a single works is only about 6%, so that it would appear that efforts to reduce the variation of works test cube results should be directed towards more careful control of the water/cement ratio by the adoption of stricter site supervision and more accurate equipment.

Finally, it is concluded that the variation for a particular Standard of Control is unlikely to be significantly affected by the size of the job, by pumping, by the maximum size of the aggregate or by the age of test. Although a "normal" distribution is usually assumed, there appears to be a trend for low mean strength and high mean strength cube results to show slight "skewness", with the longer tail towards medium strength, but this is not considered to have an important effect. However, cubes made with dry-lean concrete are subject to considerable testing error and are thus unlikely to be a fair representation of the potential quality of this type of concrete.

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Summary

Many specifications for concrete as a structural material now state the required minimum compressive strength but the design of suitable mixes is based on a mean strength which must, of course, exceed the minimum. Differing assumptions are currently being made about the form of the relationship between these strengths; the paper describes a survey of the cube results obtained on about 300 British construction sites, where concrete of varying strength levels was produced under different standards of control. The results indicate that the mean and minimum strengths are not related in a simple way but that the water/cement ratios required to give these values of strength are proportional for any one standard of control. This leads to a modification to the method of designing the mix using a "control ratio", which is dependent only on the anticipated standard of control.

It is concluded that the degree of supervision on the site has a much more important effect than the type of equipment employed and that the normal methods of weighbatching are subject to appreciable error which is considerably reduced by servo-operation of the batching plant.

The paper also deals with the components of the overall test cube variation and discusses the relative importance of variations in the cement and in the testing techniques. Figures are given to show the effect of the removal of the variation in the rate of hardening of cement, with and without removal of the testing error.

Consideration is also given to the effect on the variability, for a particular standard of control, of the following factors: size of job, pumping, maximum size of aggregate, dry-lean mixes, age of test and skewness of distribution.

Résumé

De nombreuses normes concernant l'emploi du béton comme matériau de construction indiquent les valeurs minima de la résistance à la compression, mais la composition des mélanges correspondants est basée sur une résistance moyenne à la compression, qui doit naturellement être plus élevée que les valeurs minima. Différentes hypothèses sont couramment avancées sur la relation qui existe entre ces résistances; l'auteur rend compte du dépouillement de résultats expérimentaux obtenus sur cubes de béton, provenant de quelque trois cents chantiers britanniques, le béton ayant été élaboré sur la base de résistances à la compression très diverses et préparé à l'aide de contrôles de dosage différents. Ces résultats montrent que la résistance moyenne et la résistance minimum à la compression ne sont pas liées entre elles d'une manière simple, mais que les rapports eau-ciment qu'il est nécessaire de prévoir pour obtenir ces taux de résistance sont proportionnels entre eux pour chaque type de contrôle. Ceci conduit à une modification dans la méthode de détermination des mélanges, par introduction d'un «facteur de contrôle» («Control ratio»), qui dépend uniquement du type de contrôle du dosage.

On constate que le degré suivant lequel est poussée la surveillance du travail sur le chantier exerce ici une influence beaucoup plus grande que la nature de l'équipement employé et que les méthodes habituelles de dosage en poids conduisent à d'assez notables erreurs, qui peuvent néanmoins être réduites dans une large proportion par l'automatisation des installations de dosage.

L'auteur s'occupe également des écarts totaux des essais sur cubes et étudie l'importance relative des variations des caractéristiques du ciment et de la technique des essais. Les chiffres cités mettent en évidence l'influence qui résulte de la suppression de différents taux de durcissement du ciment, avec et sans suppression des erreurs qui interviennent au cours des essais.

Il prend également en considération l'influence des facteurs suivants sur la variabilité des résultats pour un mode d'essai déterminé: importance du chantier, pompage du béton, granulométrie des agrégats, mélanges à base de béton maigre, âge des cubes, forme de la répartition.

Zusammenfassung

Viele Normen für den Beton als Baustoff geben die geforderten minimalen Druckfestigkeiten an, aber die Zusammensetzung entsprechender Mischungen

basiert auf einer mittleren Druckfestigkeit, welche natürlich höher als die Minimale liegen muß. Allgemein werden verschiedene Annahmen über den Zusammenhang zwischen diesen Festigkeiten gemacht; dieser Bericht beschreibt eine Auswertung der Versuchsresultate, die von Probewürfeln aus ungefähr 300 Baustellen in England stammen, wobei Beton ganz verschiedener Druckfestigkeit und unter verschiedenen Prüfungsbedingungen hergestellt wurde. Die Ergebnisse zeigen, daß die mittlere und die minimale Druckfestigkeit nicht in einfacher Weise zusammenhängen, aber daß die zur Erzielung dieser Festigkeitswerte erforderlichen Wasser-Zementfaktoren für jeden Prüfungstyp proportional sind. Dies führt zu einer Änderung in der Bestimmungsmethode der Mischung, indem ein «Kontrollfaktor» («Control ratio») gebraucht wird, welcher einzig von dem gewählten Prüfungstyp abhängig ist.

Es ergibt sich, daß der Grad der Überwachung auf der Baustelle einen viel größeren Einfluß als die Art der Einrichtungen hat und daß die üblichen Methoden der Gewichtsdosierung zu ziemlichen Fehlern führen, die aber durch Automatisierung der Dosieranlage erheblich vermindert werden können.

Der Aufsatz befaßt sich auch mit den Gesamtabweichungen der Würfelproben und untersucht die relative Wichtigkeit von Änderungen im Zement und in der Versuchstechnik. Aus den Abbildungen geht die Wirkung hervor, die sich aus dem Wegfallen von verschiedenen Erhärtungsgraden des Zements, mit und ohne Ausgleich des Prüfungsfehlers, ergibt. Auch der Einfluß folgender Faktoren auf die Veränderlichkeit bei einem bestimmten Prüfungstyp wurde in Betracht gezogen: Größe des Bauvorhabens, Pumpbeton, Granulometrie der Zuschlagstoffe, Magerbetongemische, Alter der Prüfkörper, Form der Verteilung.