

The achievement of uniformity of straining during concrete cube testing in South Africa

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The need for checking on the extent of non-uniform straining of concrete cubes by testing machines in South Africa is reviewed. The magnitude of the effect of non-uniform straining on apparent cube strength is reported. The existing 'strain column' method for preventing non-uniform straining by testing machines is compared to a proposed new procedure in which the amount of strain non-uniformity that occurs in the course of normal cube testing is measured, after which the effect it has had on the cube's strength is determined.



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INTRODUCTION

If a concrete specimen does not have uniform longitudinal strain across its section when it is tested, it will fail at a lower load than it could have carried, giving an incorrectly low value for the concrete's strength. However, other parts of the test system – the sampling, cube manufacture and curing, platens' surfaces and rates of straining – also have potentially large influences. Furthermore, even when correctly determined, the cube strength is only a guide to the behaviour of the concrete in a completed structure. It could therefore be said that emphasis on the uniformity of straining by testing machines is unnecessary. However, non-uniformity of straining can have a large effect on the measured strength, and, compared to other influences, is relatively easy to control. Therefore it is suggested that there is no reason for it to be a source of uncertainty when low specimen strengths have caused concern about a concrete structure's viability.

There is also a general economic reason for having uniform strains and so seeing the full potential strength of concrete specimens throughout the construction process: the concrete will then not be made stronger than it needs to be.

In the distant past, someone wishing to ensure that cubes were uniformly strained would choose a reputable manufacturer and buy as good a quality of testing machine as could be afforded. There was no recognised check on the machine's ability to deliver uniform straining. Beginning with Tarrant (1954), concern began to be expressed that different machines, apparently of good quality and despite accurate force calibration, gave significantly different strengths to specimens from batches that were made as similar to each other as possible. For example, figure 1, from Dewar *et al* (1971), shows the variation in strengths given by the machines belonging to the biggest ready-mix company in the UK. One machine, believed to be a very stable one, was chosen to be the reference and the others compared to it. Where the horizontal axis in figure 1 is positive, it indicates machines that were giving higher strengths than the reference machine, possibly because they were more uniformly straining their specimens. (Force measurement inaccuracies have been minimised in this study.)

Investigative work of this kind culminated in the issue of BS1881 Part115:1983 which described a device for checking three aspects of a testing machine's performance:

- Concentricity of the marked centre of the lower platen with the centre of the spherical seating of the ball joint behind the upper platen. If these are not concentric, then every time a specimen is tested, an eccentric force is applied to the machine, which can result in non-uniform straining of the specimen.
- Ease of rotation of the upper platen when the specimen is raised into contact with it and must push the platen round until it is seated down onto the upper face of the specimen. On some machines this force is big enough to initiate machine movements which can ultimately cause one side of the specimen to be cracked in tension at the maximum compression load.
- Resistance to rotation of the whole machine, especially the upper platen, once load has begun to build up on the specimen and is being applied eccentrically to the machine.

Resistance to rotation of the whole machine, the last item above, is measured at two load levels, giving a total of four numbers that can be empirically interpreted into checks on the machine's performance.

The device itself is a solid cylinder of steel, 100 mm diameter by 200 mm high, which was called in BS1881 a 'strain cylinder'; has colloquially been called a 'Footemeter' after its inventor, Peter Foote; and has recently been called the 'strain column' in the European standard EN12390:2000.

It has been suggested (Luker 2000) that improvements in instrumentation and computing power have now made available a new way of checking the performance of a concrete-testing machine: by measuring the strains that the machine imposes on test specimens.

Contained in this present paper is a review of the pros and cons of the strain column method and the strain measurement method of achieving the objective of improving the quality of concrete testing in

South Africa and thereby deriving economic benefit.

PRESENT STANDARDS AND PRACTICE IN SOUTH AFRICA

SABS Standard Method 863:1994 describes the determination of the compressive strength of hardened concrete. It states that the testing machine must comply with BS1881 Part115, which includes the requirement that a testing machine must pass all four parts of the strain column test. However, passing the strain column test has seldom been required in South Africa by people submitting cubes for testing, or by others using the test results. A notable exception is the Department of Transport, which, even before the strain column test was included in the SABS Standard Method, required all machines testing concrete on its jobs to pass the strain column test when they were first established in their work location.

Little is known about the quality of the concrete-testing machines in South Africa as regards their ability to uniformly strain a specimen and so give its full potential strength. Luker (1996) reported that of 32 machines tested over a period of four years, 19 failed one or more aspects of the strain column test requirements. However, no other compilation of strain column testing has been published.

Despite its data coming from the UK, some guidance to the present situation in South Africa may be obtained from figure 1. If, in this figure, it is assumed that variation in strengths given by the different testing machines was only caused by non-uniform straining, then the horizontal scale becomes percentage difference from the cubes' potential strengths under uniform straining, but with the origin of the scale unknown. From recent experience gained by the present author in measuring cube strains given by a variety of testing machines, it seems unlikely that this scale's origin would lie further to the right than the last column of the histogram. That is, the machine that produced the cube test results whose mean was between 8 % and 10 % higher than the reference machine was probably straining its specimens very close to uniformly. This would place the origin of a new horizontal scale (to represent difference from potential strength) at approximately 9 % on the original scale.

The average difference from potential strength of all the tests reported in figure 1 is then 10,9 %. In trying to relate this figure to the present South African situation the following must be taken into account:

- There may have been other reasons for the machines in the figure 1 survey giving different strengths from the reference machine, for example platens with flat but rough surfaces

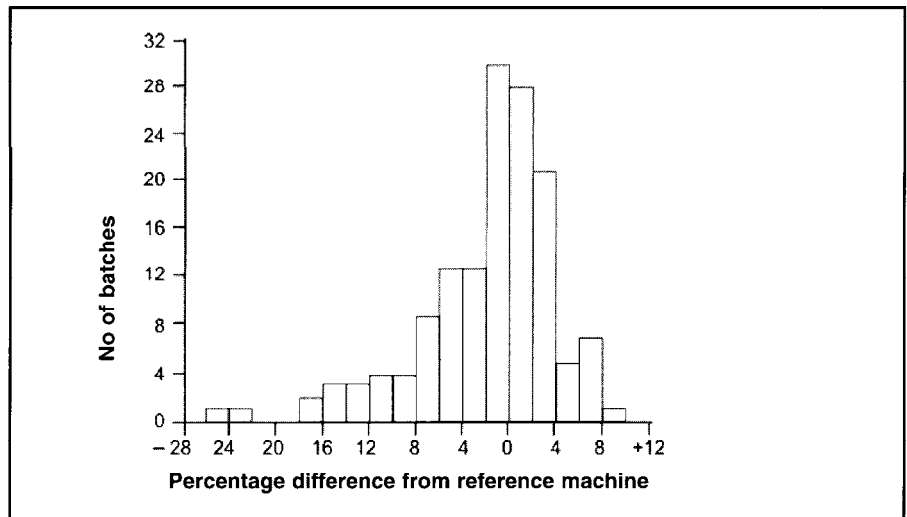


Figure 1 Comparative cube tests on machines belonging to Ready Mixed Concrete Ltd, UK

(higher strength), or bumpy but smooth surfaces (lower strength). Therefore the 10,9 % figure must be considered to be the upper bound for the mean of the non-uniform straining effect in this UK survey.

- Because of new machines bought in South Africa in recent years that have passed the strain column test, the average quality of machines may be better than that of the UK ready-mix company in the 1970s.

MEASUREMENT OF LONGITUDINAL STRAINS IN A CONCRETE COMPRESSION TEST

Before describing what can be done with information about the strains in a concrete test specimen, it seems appropriate to discuss the practicality of strain measurement as a part of ordinary compression testing.

Even before the peak load in a test is reached, the concrete on the outside of the specimen can begin to fracture and become detached from the rest. Therefore strain measurements cannot be done by attaching a device onto the specimen itself. Instead the distance between the platens is measured, at a minimum of three points round the specimen and at a convenient distance away from it (eg the outer edge of the platens) to enable the movements of the platens relative to each other in the direction of their compressing movement to be determined. The longitudinal strains in the specimen are assumed to be the same as the strains on the distances between the platens and are found by interpolation between the measurement points.

The apparatus used to measure the distance between the platens in this research project so far has been linear potentiometers read by an analogue to digital converter card in a PC. This apparatus was chosen because it is inexpensive, but it is not sufficiently robust and

waterproof for use in a commercial laboratory environment. Other, more suitable, displacement transducers can be made using various basic principles, for example capacitance, eddy current proximity sensors, LVDTs and devices using the Hall effect. Prices of such devices as fitted on a testing machine, with a dedicated electronic instrument to record their measurements, plus load, and to process the values into a result, will depend upon quantities manufactured and a numerical estimate is not made here. However, preliminary enquiries have indicated component prices sufficiently low to encourage the work reported in this paper.

When graphs of load against strain are plotted, a 'bedding in curve' is usually seen at the beginning as the platens settle into intimate contact with the loaded faces of the specimen. This is illustrated by line A on figure 2. The true origin of such a graph in the testing of materials that are known to have a linear initial region of their stress-strain behaviour is usually taken to be the intersection with the strain axis of a line extrapolated from the point of greatest slope (or the point of contraflexure as it may be called).

Occasionally, if there is non-uniformity of straining across the area of the specimen at the beginning of a test, a line such as B in figure 2 can occur for part of the specimen. This has particularly been seen in two circumstances:

- when the upper platen is initially tilted relative to the specimen when they first touch and the specimen must give a large force to rotate the platen into intimate contact
- when the specimen is at a large eccentricity from the centre line of the upper platen

Because it is not clear how the true strain origin should be fixed for line B, a test where such a line occurs cannot be interpreted in terms of measured strains, and there must be suspicion that sufficient non-uniformity of strains existed at peak

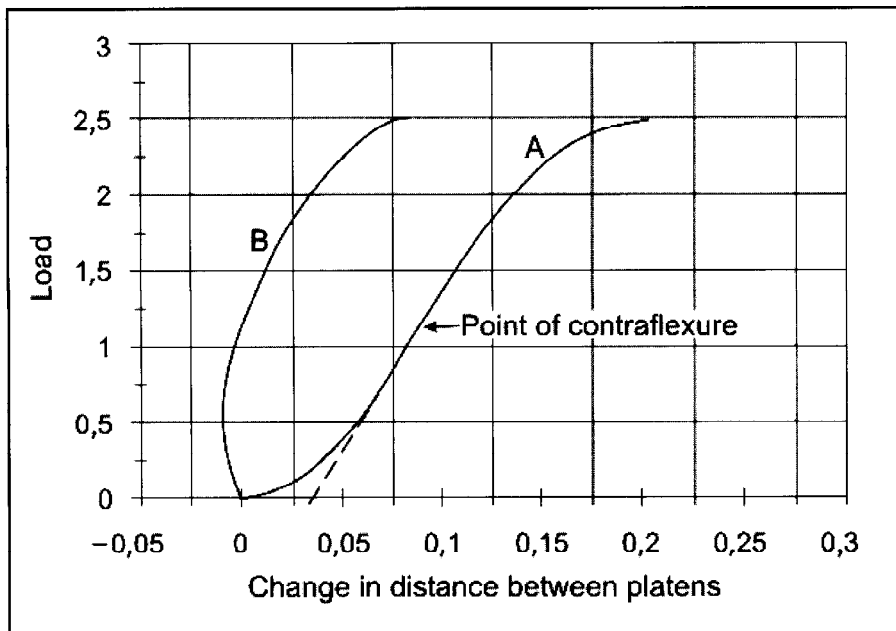


Figure 2 Examples of load v platen displacements graphs from a cube test

load to cause its value to be significantly lower than the specimen's potential.

For the measurement of strains in standard compression tests to be done as a normal part of the procedure, it is desirable that the determination of the true origin of the strain axis be automated. A

procedure that has been found to work is to fit a third degree polynomial to different parts of the measured load and displacement data until the best correlation coefficient has been found for those functions that have a point of contraflexure. If the best correlation coefficient is

sufficiently high then that function can be used to find automatically the true origin at the intersection of the function's line of greatest slope with the displacement axis.

INTERPRETATION OF MEASURED STRAINS INTO THE EFFECT ON APPARENT CONCRETE STRENGTH

The graph axes of figure 3 are useful parameters to show the effect of non-uniform strains on apparent concrete strength. On the horizontal axis is 'strain-ratio', which is a measure of the non-uniformity of the longitudinal strains in the specimen. It is defined as:

$$\text{Strain-ratio} = \frac{(\epsilon_{\max} - \epsilon_{\min})/2}{\epsilon_{\text{mean}}}$$

Where: ϵ_{\max} and ϵ_{\min} are the maximum and minimum longitudinal strains (compressive strain taken as positive) found on the plan area of the specimen at peak load on it.

$$\epsilon_{\text{mean}} = (\epsilon_{\max} + \epsilon_{\min})/2$$

The small diagrams below the horizontal axis illustrate the pattern of strains across the specimen for different values of strain-ratio. When the strain-ratio is 0, the strains are uniform over all of the specimen. When the strain ratio is 1, the strains vary between zero at one point on the specimen and the maximum strain on the opposite side. It is possible for the strain ratio to be greater than 1, but then there is tensile strain present in the specimen. The pattern of strains in a specimen, and hence the strain-ratio, will vary during a test. For points on figure 3 it is the value at peak load.

The vertical axis parameter of figure 3 is termed 'test efficiency' and is the apparent strength given by a machine for a cube as a proportion of the strength that the cube would have had if it had been uniformly strained during the test. Lines on figure 3, which enable a strain-ratio measured at peak load in a cube test to be interpreted into a test efficiency, can be drawn either from theory or from empiricism. For example, the dotted line on figure 3 is drawn making the theoretical assumption (Luker 2000) that the stress-strain graph for the concrete is a parabola up to the peak, and an identically shaped parabola after the peak.

An empirical relationship for the graph can be obtained using a batch of (say) 20 specimens that have been made to be as identical as possible. Some of the specimens are tested centrally on a machine so as to get as close to zero strain-ratio as possible. Then, to get a wide spread of strain-ratios, the remainder of the specimens are tested at progressively greater eccentricities from the machine's centre line. (The relationship

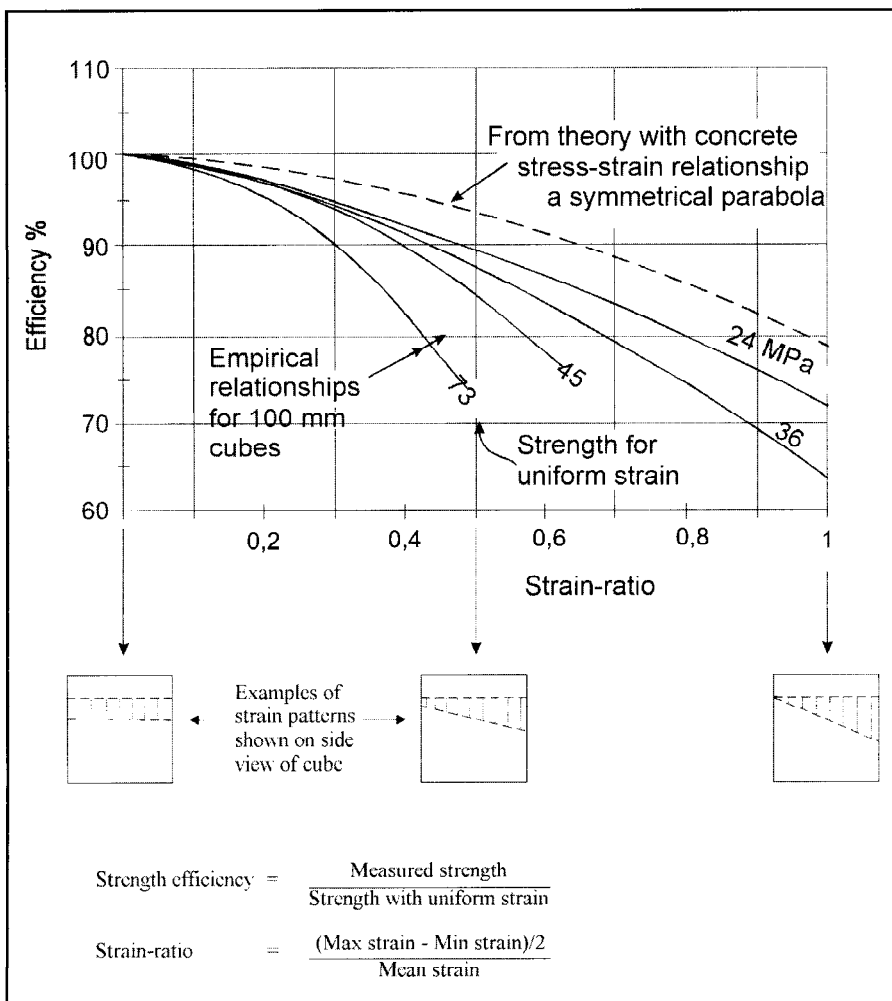


Figure 3 Relationship between strain-ratio and strength efficiency

between the eccentricity and the strain-ratio will depend on the stability of the machine, particularly the ball joint on the upper platen.) Initially the result of each test on a specimen is plotted as a point on a graph of apparent strength (ie measured maximum load divided by area) against strain-ratio, for example figure 4(a). A smooth best-fit curved line is then drawn through the points, and the intersection of this line and the vertical axis defines the uniform-strain strength for the batch of specimens, that is, 100 % 'test efficiency'. The vertical axis can now be converted to values of test efficiency by dividing the test result strength of each specimen by the uniform-strain strength, giving figure 4(b). For example, the line on figure 4(b) is that plotted on figure 3 as an empirical relationship and labelled 36 MPa.

PROPOSALS FOR THE STANDARDISED USE OF STRAIN MEASUREMENTS TO CHECK THE QUALITY OF CONCRETE TESTING

The use of the strain-ratio at peak load will be first considered, and then the way in which its measurement may be standardised.

Use of a strain-ratio value

Ideally we would have enough information on figure 3, either empirical or theoretical, to be able to interpret a strain-ratio into a test efficiency and so correct the apparent strength shown by the machine into the uniform-strain strength for the cube. However, not enough similar-specimen tests have so far been done to give sufficient confidence for such an empirical strength adjustment to be made. Theoretical strength adjustment is also not yet possible because not enough is known about all possible influences on the shape of the strain-softening part of the stress-strain graph for concrete.

Work is proceeding on the empirical and theoretical interpretations to extend the use of figure 3, but for now it is proposed to simply set an upper limit to the peak-load strain-ratio that a machine may give to a cube for the machine's performance to be considered acceptable. On presently available evidence (figure 3) this is proposed to be 0,3 for concrete strengths up to 40 MPa and 0,2 for strengths from 40 to 70 MPa. No recommendation can yet be given for strengths above 70 MPa. The strain-ratio should be reported at the same time as the apparent cube strength given by the machine, for the information of the responsible person who will use the cube strength value. If the strain-ratio for a cube test falls above the recommended limits, this need not invalidate the test, but the implications

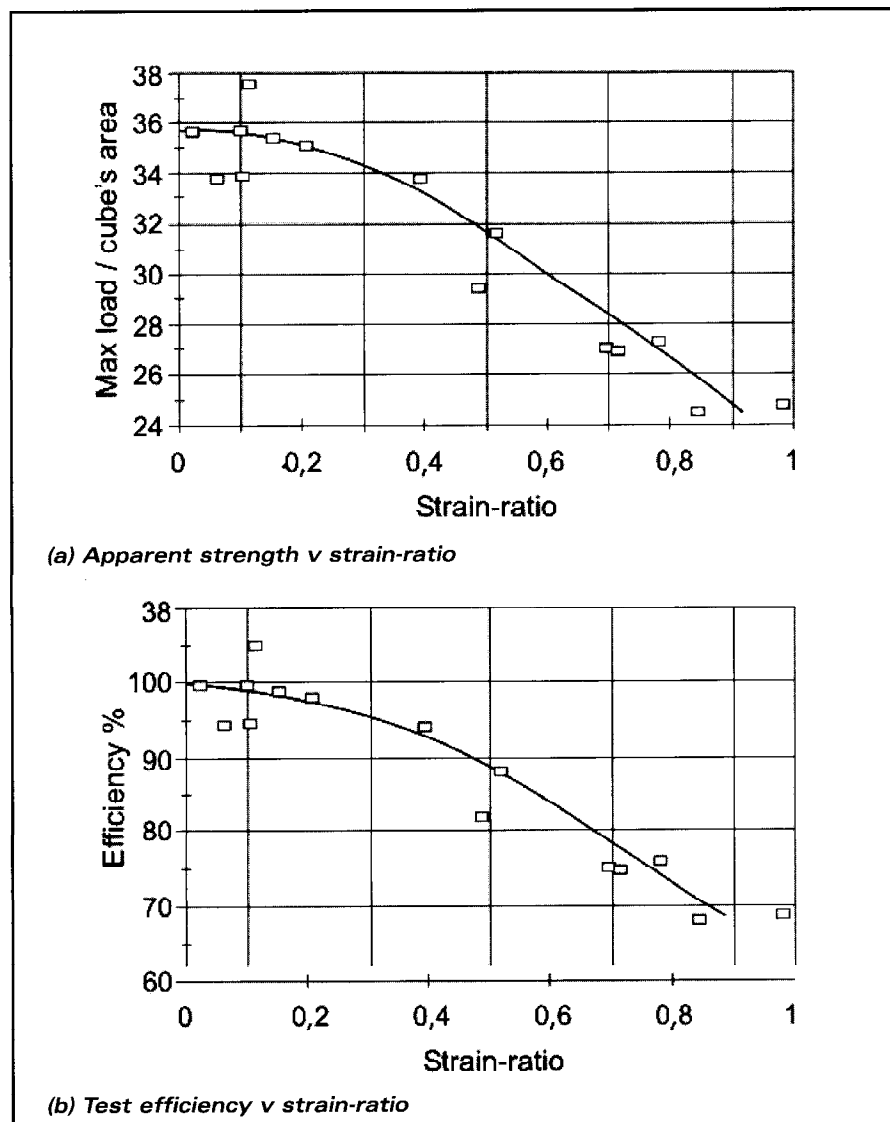


Figure 4 Example of determination of empirical relationship between test efficiency and strain-ratio

for the accuracy of the test result may need to be considered by the responsible person.

Standardised determination of strain ratio for a test

Displacement measurement

The change in distance between the platens needs to be measured at a minimum of three points. The absolute accuracy of the movement measurements is not important, but all devices must have linear response and have the same calibration. A checking procedure could be specified as follows:

Position the testing machine platens and displacement measurement transducers as they would be for starting to load a specimen, but without a specimen in the machine. Support a dial-gauge of 0,002 mm precision on the lower platen so that it measures the change in distance between the platens. Record the initial readings of the dial-gauge and the displacement transducers. Raise the lower

platen by approximately 0,2 mm as shown on the dial-gauge and record the displacement transducers' readings. Repeat the movement and readings. Raise the lower platen by approximately 0,3 mm, take readings and repeat. Raise the lower platen by approximately 0,4 mm, take readings and repeat. Care must be taken during the whole exercise to ensure that the upper platen is not accidentally tilted. For each of the six sets of readings of total movement:

- (i) Determine the maximum difference D between any two displacement transducer readings.
- (ii) Calculate the mean of the readings, M.
- (iii) Express D as a percentage of M.

At each stage of the increasing movement of the platens, from 0,2 mm to 1,8 mm, the magnitude of D/M should not exceed 4 %.

Strain calculations

The word strain has been used throughout this paper so far only because it is colloquially common in the subject being discussed. In every case it could have

been replaced by 'change of length'. Furthermore, because the mechanisms of straining and fracture in a concrete specimen under compressive test loading produce localised deformations after peak load (Shah *et al* 2000), in the fracture mechanics theory used to represent the behaviour of concrete it is necessary to use the parameter 'change in length' rather than 'strain'. However, for the purposes of this paper, the term 'strain' will continue to be used when it seems to aid the clarity of the text, even though the measurements of change in distance between the platens are never actually divided by the original length to give a strain parameter value.

The calculations needed to determine the strain-ratio at peak load can be described as follows:

(i) For each displacement transducer:

- (a) Determine the true origin of the graph of load on specimen *v* displacement. (Refer section 3 and figure 2.)
- (b) Determine the displacement from zero to the point of maximum load on the specimen. Because measurements of load and displacements can easily be done at five per second with inexpensive electronics, simply taking the displacement value that was read at the same time as the biggest load value is adequate.

(ii) Using the coordinates of the positions of the displacement transducers relative to two orthogonal axes at the centreline of the lower platen, fit a three-dimensional function to the measured peak-load displacements at each of the transducers.

(iii) Use the function from (ii) to interpolate to the sides of the specimen and find the positions and values of the maximum and minimum longitudinal strains in the specimen.

(iv) Calculate: $\text{strain-ratio} = (\epsilon_{\text{max}} - \epsilon_{\text{min}}) / \epsilon_{\text{mean}}$

These calculation steps (i) to (iv) will need to be programmed into a small computer or dedicated electronic instrument, and although relatively simple, they are still subject to programming errors. A test is therefore needed to check that the program provided in the equipment by the supplier gives the correct result. Such a check can be done using a set of raw data that can be operated on by an inspector's program and the program in the test machine. By incorporating an outlet port that gives parallel access to the measured load and displacement data during a test, in a standardised format, an inspection instrument or small computer can check the test machine's result. This test could be done at the supplier's prem-

ises and need not be repeated if access to the program is then sealed by the inspector.

PROS AND CONS OF THE STRAIN COLUMN METHOD OF ENSURING ADEQUATE UNIFORMITY OF STRAINING OF CONCRETE CUBE TESTS IN SOUTH AFRICA

Advantages

- The testing machine itself is manufactured to give uniform straining to the specimens it tests, and therefore does this without any other equipment being added.
- The machine is required to be checked annually with the strain column, the same interval as the force calibration check, and could be done by the same person.

Disadvantages

- The additional cost of making a new machine that is sufficiently stable to pass the strain column test is significant.
- Despite the high cost of a new machine able to pass the strain column test, in many cases it would not be economical to try to improve an existing machine so that it could pass.
- If a machine fails the strain column test it is not possible to say how badly it has failed, which is frustrating to a machine owner. The inventor of the test, Peter Foote, has said (1970) that the numerical results of the test cannot be related to the variation from the uniform-strain strength that the machine may give for a specimen. To choose the pass/fail boundaries, Newman *et al* (1972) conducted comparative cube tests between 17 machines at the same time as strain column tests. The boundary lines were then chosen (somewhat arbitrarily) between those machines that seemed to give the most consistent results and the rest. It was decided at the time to use these boundaries on a trial basis to see how many machines were condemned by them, and to adjust the boundaries if necessary. Although no formal study was done to assess the cost of replacing the failing machines, the consensus must have been that it was acceptable because the pass/fail boundaries have never been changed, and have now been included in the European standard.
- Inconsistencies have been found by the present author in the results of strain column tests carried out a short

time apart on the same machine. For example, when the lubricant on the ball joint warms up, it may then fail the 'resistance to rotation' part of the test. It has also been found that, rotating horizontally, the ball joint slightly can change a fail in this part of the test to a pass.

- Deterioration of a testing machine could cause it to give low strengths, but this would only be noticed when it was next examined with the strain column.
- The cost of an inspectorate to carry out the strain column test in South Africa will be high. Although it can be done at the same time and by the same person who calibrates the force measurement accuracy of the machine, it will add significantly to the time spent by that person on the machine. The purchase cost of the strain column and its electronic controller is very high, and if the European standard is to be followed, it must itself be checked every two years.

PROS AND CONS OF THE STRAIN MEASUREMENT METHOD OF ENSURING ADEQUATE UNIFORMITY OF STRAINING OF CONCRETE CUBE TESTS IN SOUTH AFRICA

Advantages

Immediate benefits

- The strain measurement method (SMM) gives a clear scale of performance of a testing machine. It is not just a pass/fail criterion like the strain column method (SCM).
- The actual effect on a cube test of fundamental machine faults that cause non-uniform straining is seen, for example non-colinearity of the centreline of the bottom platen with the centre of the ball point on the upper platen, and insufficient stability when the specimen imposes an eccentric load on the machine.
- Because the SMM can be used on all tests, the effect of occasional errors such as incorrect centring of the specimen in the machine is also seen.
- For every test the strain-ratio value is given, either reassuring the owner of the cube that it has been properly tested, or possibly providing a reason for a low strength value.
- As empirical and/or theoretical information is added to the graph shown in figure 3, more confidence will be gained in converting a strain-ratio value into a uniform-strain (full potential) strength for the concrete.

This will enable testing machines that may fail the strain column test to continue to be used. It will also enable new machines to be made to lower standards than those needed to pass the strain column test, and hence sold at a lower price.

- Having measured the strains, the Young's modulus for the specimen is easily calculated. Although a value from a specimen will not be the same as the concrete in the structure, and subsequent empirical adjustment will be necessary, it will be better than empirical interpretation from the crushing strength (Addis 1986) that is frequently used at present.
- The SMM can be added to any testing machine, regardless of size, age or method of operation. It therefore has the potential to improve the quality of concrete testing in South Africa more rapidly than the SCM. Although the SCM can identify machines that are less than satisfactory, they may not be replaced for a long time because of the cost.
- The cost of the inspection for the SMM is likely to be less than for the SCM, because
 - the check on the calculation method for the strain ratio only needs to be done once if it is then inaccessible to future alteration
 - the only equipment needed to check the displacement measurement is a dial gauge, and the procedure is easy enough for the owners of the machines to carry out checks themselves before paying for an official inspection
 - no check on the accuracy or linearity of a load measurement device used in the SMM is needed because the only purpose of the load readings is to determine which scan of the displacement transducers coincided with the peak load on the specimen – the absolute value of the load is not needed

Potential future benefits from strain measurements

- The concrete compression test can become strain-rate controlled instead of the present standard (believed by the present author to be similar worldwide), which specifies that the rate of rise of load should be maintained. The latter is nonsensical, as it is clearly impossible when the peak load is approached, and leads to two undesirable consequences:
 - Machines with automatic controllers and strong hydraulic pumps increase the rate of straining as the concrete's fundamental stress-strain graph curves plastically, so increasing the peak load. Although manually operated machines should also be operated in this way to comply with the standard, in practice they are not.

Recent work (Eibl & Schmidt-Hurtienne 1999) has shown that the effect of strain rate is greater than earlier work indicated, so that different rates of straining in different machines may be producing significant differences in strength.

- As the rate of straining is increased, the likelihood of an unstable, even explosive failure of the specimen is increased. This is a nuisance to clear up, and is one of the reasons why the operators of manually controlled machines do not try to maintain the specified rate of load increase.
- If the test is strain-controlled, then it is possible for the full shape of the stress-strain graph, including the falling branch, to be measured. After the peak of the graph, if the rate of transfer of energy from the machine to the specimen is lower than the specimen's fundamental behaviour in compression can absorb energy, then the test will remain stable and measurements of load and compression strain can continue. This depends on the stiffness of the machine and the sensitivity of control of the fluid in the hydraulic ram. (Hudson *et al* 1972).

Improvements in strain control of compression testing machines (Shah *et al* 1981; Okubo & Nishimatsu 1985) have enabled measurement of the strain softening region to be done (Van Mier *et al* 1997) on machines other than those (eg Barnard & Turner 1962) specially designed for the purpose. This gives rise to the hope that determination of the full shape of the stress-strain graph for a concrete mix may become a routine procedure. Knowledge of the full shape of the stress-strain graph is important because it affects the degree of ductility (and therefore suddenness) of failure of components of a concrete structure (Kemp 1998). The use of high-strength concretes is becoming increasingly common, and these are significantly more brittle in their stress-strain behaviour than those of lower strengths.

Disadvantages of the SMM

- If the initial rotation of the ball joint of the upper platen requires a large force from the side of the specimen, causing non-uniform strains in the specimen before the platen is firmly seated, the SMM will not include them in the determination of the strain-ratio. However, it is a simple matter to check the ease of rotation without resorting to the strain column. If the upper platen can be tilted by hand, then the force that needs to be exerted by the specimen will be negligibly small, providing the size of the specimen is appropriate to the

size of the machine's upper platen, and more particularly, its ball joint. Small specimens can still be tested in big machines if the upper platen is rotated by hand to be parallel to the lower platen before raising the specimen into contact with the upper platen. This is in any case a desirable preliminary as it checks the ease of rotation and helps prevent the kind of load v displacement graph (line B in figure 2) whose true origin cannot be determined.

- The displacement measuring transducers may cause some inconvenience to the access for putting in and removing the specimens. However, providing the platens do not deflect excessively during a test, the transducers can be positioned on the outer sides of the platens, well clear of the specimen, and can be made to swing out of the way if bumped during the work operations.
- If a testing machine already has an electronic controller, then measurements of load and platen displacements, and subsequent computation of the strain ratio, can be entirely automatic. However, if an independent electronic controller for the SMM measurements and computations is needed, then the operator will need to press a button connected to it once at the start of the test and again at the end of it.

CONCLUSIONS

The benefits to be derived from improving the quality of concrete testing in South Africa – that is, more confidence in the test results and an overall saving on the cost of concrete – probably amply justify the expense of achieving that improvement. However, lack of knowledge of the condition of existing testing machines, and to a lesser extent lack of knowledge of the cost of the strain column method and the strain measurement methods of improving concrete testing, prevent confirmation of this supposition.

The information presented in this paper shows the strain measurement method to be feasible and sufficiently desirable for it to be added to SABS Method 863.

Preparations by the CSIR are already under way to establish a system of checking strain columns so that they can be used with confidence to assess testing machines. This facility could be extended to the acquisition of an instrument or small computer to check manufacturers' strain measurement equipment for accurate calculation of a strain ratio from measured load and displacement data.

If both systems are available, the owners of testing machines will become the arbiters of which system is the better, that is, the one that achieves the objective of improving the quality of concrete testing at the lowest cost.

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