CHARACTERISTICS OF STRUCTURAL BREAKDOWN IN PLASTIC CONCRETE AND THEIR POTENTIALS FOR QUALITY CONTROL

by
Osondu J. Uzomaka

· *Civil Engineering Department.*
University of Nigeria Nsukka.

SUMMARY
The structural breakdown of plastic concrete when sheared in. a Couette-type rheometer is discussed with particular emphasis on the significant features of the resultant thixotropic break-down curve. A typical trace has four such significant features which characterise the mix. The significance of these features are analysed in relation to the functional requirements of plastic concrete in practice. Finally, the potentials of these features as on-line quality control parameters are discussed.

NOTATIONS
a is a positive fractional constant
t is any time when the torque is T,
t_o is time corresponding to peak torque (T_o)
T_e is the stable torque
Z is a function of ω
σ_o is the angular velocity
ϕ is the work done in breaking a linkage

INTRODUCTION
The application of classical rheology is now considered the most rewarding approach to the analysis of such properties of concrete which are conventionally referred to as workability (e.g. 1-3). Nevertheless, there are other functional requirements of the mix which demand a different approach from classical rheological studies, which employ coaxial cylinders viscometer. An example of this group of requirements is the pressure exerted by the mix on formwork, the analysis of which demands the shear strength parameters of the mix, determined under a three dimensional stress system. The author has adopted the rheology approach to study the flow properties of fluid concrete mixes employed in geotechnical systems (4). Tattersall (5) has also reported his work with a coaxial cylinders viscometer, and that this work was not very successful. Comparing with the results of the author, Tattersall considered that the higher fluidity of the author's mixes is largely responsible for the author's success (5). However, the author had designed a MKII model of his earlier rheometer to cope with stiffer mixes than those employed in his original study. Pilot tests in this more powerful model have shown results which are consistent with the earlier results (6). More recently, Murata also reported a successful study of concrete mixes in a concentric cylinders viscometer (7).

The above initial studies which have adopted the classical rheology approach, considered the use of the conventional fundamental rheological parameters, namely the Bingham yield value and plastic viscosity, in defining a mix: While this approach is very sound theoretically and therefore Ideal for research purposes, it may not be practically expedient for construction sites, because of the expertise and time required to evaluate the mix accordingly. This limitation constitutes a serious setback from an engineering standpoint since the success of any engineering research depends on how effectively its peculiar technology can be transferred into practice.

To overcome the above limitation, Tattersall has been investigating the use of the power consumed by a mixer as a measure of the flow properties of the mix (5). With the same motivation, the author investigated the possibility of using some features of the breakdown curve obtained from his rheometer tests to specify a mix. This necessitated a detailed study of the structural breakdown of the mix and its characteristic curve, during which he identified some significant features which may be used to specify the mix.

The aim of this paper therefore, is to discuss the results of this investigation. A Typical characteristic breakdown curve is examined, and its significant features are identified. The significance of each of these features is discussed. Then the potentials of the features as quality control parameters are discussed. An outline description of the concrete rheometer and material specification are given for completeness.

EXPERIMENTAL DETAILS:
Description of Concrete Rheometer
The concrete rheometer used for this study employs the principles of a Couette-type viscometer, and was developed specifically for full scale concrete mixes (4). This consists of two co-axial cylinders in which the cup is the rotor and the bob is the stator. Vanes are fitted to both the cup and bob to prevent slippage between the instrument and the test material during test. The essential geometries (in millimeters) are

bob radius	=	125
cub radius	=	158
height of bob	=	93
depth of cup	=	125
bob-vane protrusion	=	25

cup-vane protrusion	=	18	number of cup-vanes	=	15
number 01 bob-vanes	=	12			

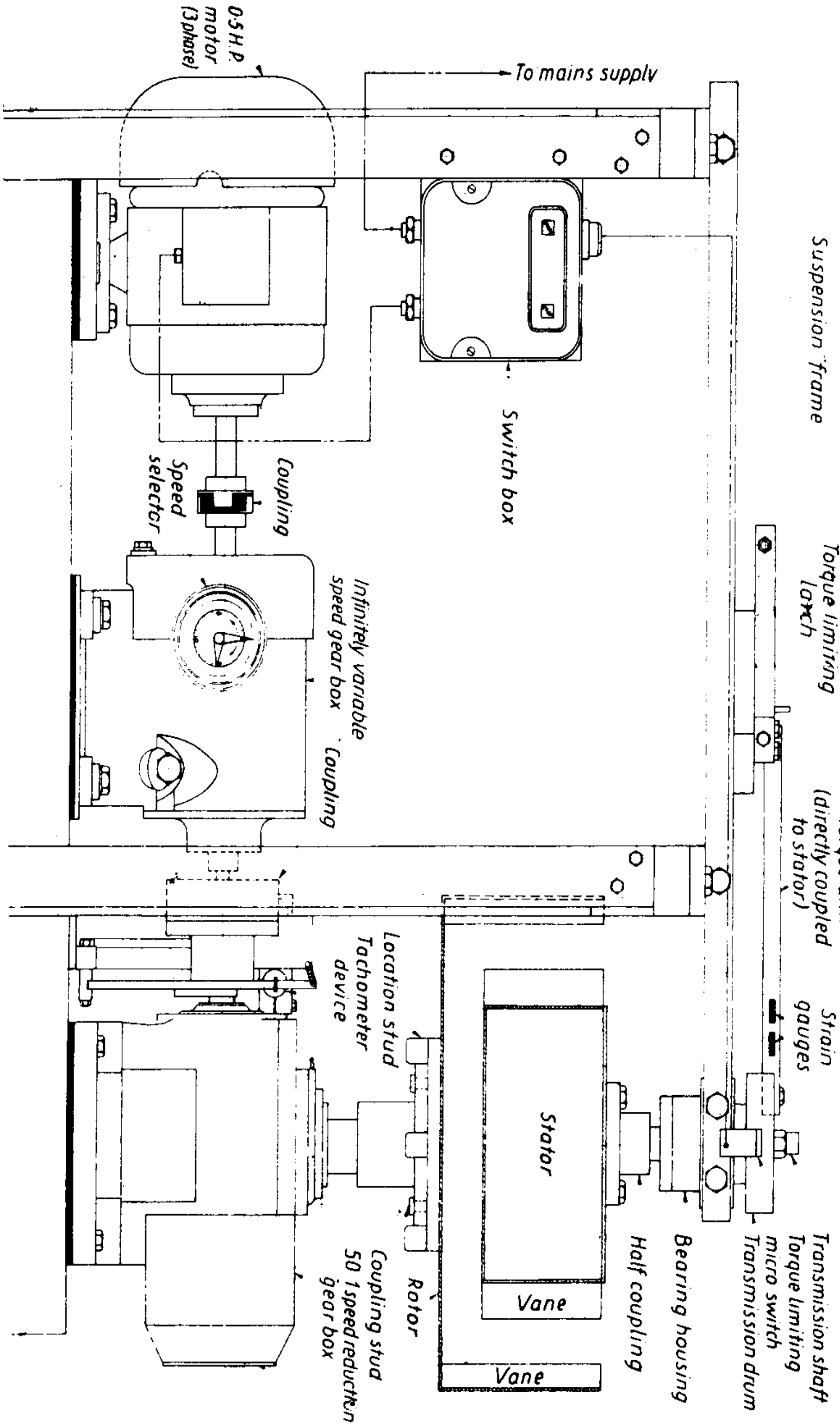


FIG. 1 PROTOTYPE OF RHEOMETER MK I.

(A : rheometer B : U-V recorder)

(C : range selector D : Strain gauge bridge)

The rotor is driven by a 0.75 HP 3-phase A. C. induction motor through an infinitely variable speed gear box and a worm reduction gear box of 50: 1 speed ratio. Four electrical resistance strain gauges are mounted on a mild steel cantilever attached to the stator, to form a torque arm. The strain of the gauges due to the flexure of the cantilever, gives a measure of the torque to which the cantilever is subjected.

The instrument details are shown in Figure 1. A cam and D2 series DC-LVDT transducer system was designed to serve as the tachometer, because commercially available ones were found to be unsuitable for the low speeds of the instrument. An ultra-violet (U-V) recorder was used to obtain a signature trace of torque and speed. The U-V recorder readings were calibrated against torque and speed to determine the instrument constants.

Specification of Concrete Material and Mix

Irregular river gravels, with largest particle size of 19 mm (¾ in.), and sand constituted the particulate system of the concrete mix. Single sizes of the aggregate were combined to conform exactly to various grading curves of Road Research Note 4 (8) as shown in Figure 2. Ordinary Portland

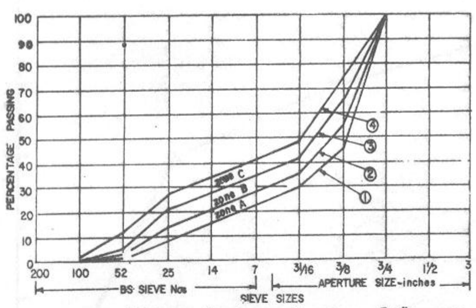


FIG 2 Grading Curves for 19mm (3/4") max. size according to ROAD NOTE (4).

cement and fresh clean tap water were used in the mixes. Mixes of varying proportions were made; a mix specified as W_X a_y g_Z implies the following:

(i) a water/cement ratio, by weight, of O.x.
(ii) an aggregate/cement ratio, by weight, of y.O.
(iii) a grading curve No. z.

These specifications of the mix proportions are given at the relevant sections within the text.

Test Procedure

The concrete was mixed in a cumflow pan mixer, the aggregate and cement being mixed dry for 1 minute before water was added and mixing continued for a further 2 minutes.

The test material was then lightly rodded into the annulus of the rheometer. After exactly ten minutes from the end of mixing, the rheometer test was started. This consisted simply of first starting the U-V recorder, and then the rheometer. The nature of the test material within the annulus was closely observed as shearing proceeded.

ANALYSIS OF THIXOTROPIC BREAKDOWN OF CONCRETE

As the cup rotates on application of rotational shear stress, the stator also tends to rotate due to the viscous drag transmitted by the mix. The stator continues to rotate until the resistance registered by the torque arm becomes equal to the total viscous drag of the mix due to its deformation. During this stage, the particles in the suspension experience varying degrees of both translatory and rotational motion. This combined action may be referred to as a process of rearrangement. The torque rises to a peak (Figure 3) which is considered to represent the maximum shear stress which the mix can resist at a given rotational speed. Before this peak torque is reached, the material has only suffered some degree of deformation, flow of the plastic concrete commencing as the peak torque is reached.

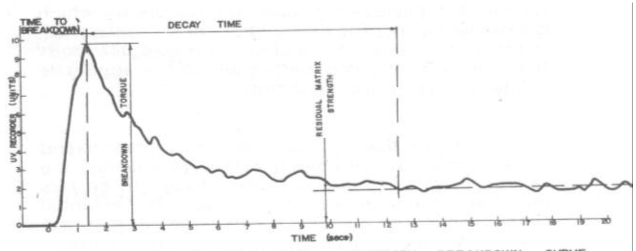


FIG 3 SIGNATURE TRACE OF A TYPICAL THIXOTROPIC BREAKDOWN CURVE

As shear is prolonged, the mix suffers thixotropic breakdown-i.e. the so-called stress melting-in the immediate vicinity of the stator. With the passage of time, this phenomenon is propagated away from the stator. The structure of the material begins to breakdown just as the peak torque is passed, and. Consequently, the peak torque may be termed the breakdown torque. The time from zero to the point were structural breakdown commences, may be designated the time to breakdown.

The structural breakdown is accompanied by segregation (i.e phase separation) of the mix components, this activity being most intense around the cylindrical stator-matrix interface. Eventually, the mix is fluidized, a phenomenon often referred to as shear thinning. Structural breakdown is a progressive process which starts off rapidly, and continuously becomes slower. This phenomenon is reflected by a progressive drop in torque, thus suggesting degradation of the matrix strength. The fall-off in torque value eventually stabilizes; this stabilization; corresponds to the completion of the matrix fluidization. The stable torque may be defined as the residual matrix strength and the time required for its attainment from peak torque, as the 'decay time,

The profile of the breakdown curve can be predicted by a power law (4) of the form

$$(t - t_o) = \frac{-a\emptyset}{2\,Z^a(1-a)}$$

$$(T - T_E)^{-(1-a)} - (T_O - T_E)^{-(1-a)} \qquad (1)$$

This predicative equation differs from that derived for cement pastes-the base for concrete-which is exponential (9). The explanation for this difference, is that Concrete is a more complex rheological body than the cement paste, within which the aggregate is interspersed to form concrete.

When a mix that has been tested is left to stand for a short period of time, and then re-sheared, the secondary peak torque is found always to be less than the virgin peak torque. However, the essential characteristics of the virgin curve are reproduced. The foregoing characteristic behaviour is consistent with results obtained with simpler suspensions such as cement paste (9).

It is apparent from the foregoing discussion that the essential features of the response curve are:

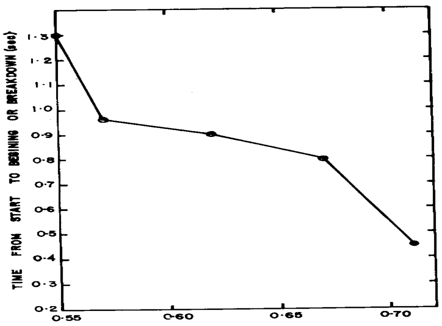
a) time to breakdown
b) breakdown torque
c) decay time
d) residual matrix strength.

SIGNIFICANCE OF ESSENTIAL FEATURES OF BREAKDOWN CURVE

Time to breakdown: The rheometer trace is on a time-base and as the instrument normally rotates at a constant speed, the time to breakdown is a measure of the magnitude of deformation which the mix was capable of enduring before the incidence of structural breakdown. This feature can therefore be used as an index of the capacity of the mix for plastic deformation. It may be termed the deformability of the mix.

The significance, in practical terms, of this property can be seen by considering vertical-pour structures such as columns, shortly after placing. Because of the lateral pressure exerted by the head of concrete, the walls of the shuttering suffer some lateral deflection. The magnitude of deflection which can occur without corresponding local shear failures within the mass of concrete is a function of the capacity of the mix for plastic deformation.

A correlation between deformability and water/ cement ratio for the mixes studied shows three distinct regions (fig. 4).



WATER/CEMENT RATIO

FIG·4.\VARIATION OF TIME TO BREAK- DOWN WITH WATER/CEMENT RATIO (ROTOR SPEED 4 RPM)

a)an initial rapid drop-off in deformability with increase in water/cement ratio;
b)a more gradual drop-off in deformability with increase in water/cement ratio;
c) a final stage similar to (a) above.

The correlation is linear within each region, and the slope of the curve in (a) and (c) above are approximately equal and are about one order of magnitude greater than that of the middle part. The middle range of water/cement ratios may there- fore be designated the stable range of water/ cement ratios, with respect to deformability.

By reducing the aggregate/cement ratio from 4 to 3, i.e. from $W_{62}a_4 62$ to $w_{62}a_3 82$, but keeping other mix parameters constant, the capacity of mix to accommodate plastic deformation increased by 11%. A change in grading, from$w_{62}a_2\delta_2$to $w_{62}a_4\delta_4$ results in a corresponding Increase of 44 % This result is considered logical because the second mix is richer in fines and should therefore tolerate more plastic deformation.

Breakdown Torque: The breakdown torque is a measure of the maximum shear resistance of the virgin structure of a mix at a given shear rate. The shear resistance of the mix is a measure of the effort required to deform it, and hence its stiffness. Thus, using a constant rotational speed, the breakdown torque may be used to reflect how stiff the consistences of various mixes are before they suffer any structural breakdown.

figure 5 shows a correlation between breakdown torque (TB) and water/cement ratio (m), from which it is apparent that the breakdown torque varies exponentially with water/cement ratio.

The shear resistance of a mix can be reduced by reducing either its aggregate/cement ratio using a finer grading. A change in mix composition from $w_{62}a_4\delta_2$to $w_{62}a_3\delta_2$ reduced breakdown torque by $48^{\%}$ while a change
Grading,$w_{62}a_4\delta_2$to $w_{62}a_4\delta_4$ gave a reduction of 74%. As the second mix has more fines content. It may be inferred that the resistance to breakdown of the mixes is largely due to particle interference

Residual Matrix Strength: The residual matrix strength (Tm) is the shear resistance of the mix after the matrix structure has been broken down, and the attendant segregation process is completed. It gives a measure of the degree of breakdown that has taken place within the mix.
The relationship between Tm and water/cement ratio is also exponential (Figure 5). By reducing the aggregate/ cement ratio from 4 to 3 the residua matrix strength is reduced by 45%. Similarly, a change of aggregate grading from No.2 to No. 4 caused a reduction in residual matrix strength of 55%.

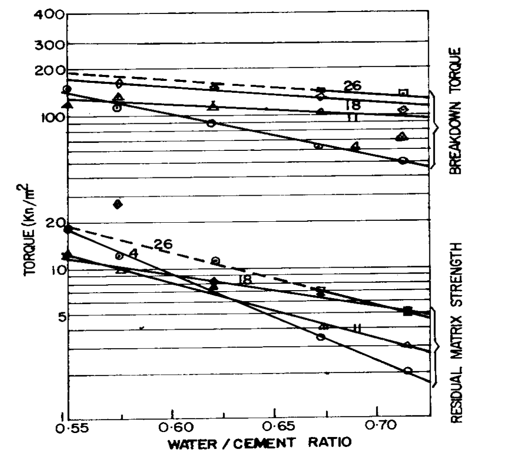


FIG. 5

VARIATION OF TORQUE WITH WATER/CEM·RATIO·

(Figures on curves indicate rpm of rheometer)

However, the residual matrix strength, on its own, does not seem to be of much practical consequence. The ratio of the breakdown torque to the residual matrix strength may be defined as the sensitivity of the mix, sensitivity being an index of the susceptibility of the mix to structural breakdown. The mix sensitivity can provide a basis for assessing the suitability of a mix for compaction by vibratory techniques and also provide a guide to the optimum intensity of vibration required for the mix.

An empirical correlation of residual matrix strength to the breakdown torque for various mixes is shown in Figure 6,

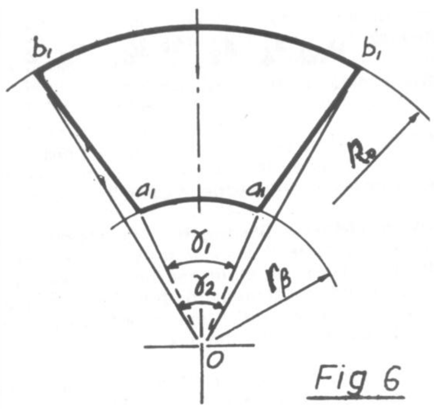


Fig 6

By virtue of the linearity of the curves, variations in water/cement ratio do not appear to affect the sensitivity of the mix. The sensitivity of the mix is therefore a function of the aggregate composition (i.e. aggregate grading and aggregate/cement ratio) of the mix. The curves also suggest that the mixes become more sensitive as the shear rate increases. This trend IS considered logical.

Decay time: The time interval between the onset of structural breakdown and the incidence of stable residual matrix reflects the rate of phase separation in the mix. A fast decay time implies little resistance of the mix to breakdown. Consequently, the decay time is a measure of the resistance of the mix to breakdown. Since breakdown here is largely due to phase separation, the decay time may be used as a measure of the stability of the mix by Richie's definition (10).

The relationship between the decay time and water/cement ratio (figure 7) is exponential. The decay time of a mix can be increased by reducing its aggregate/cement ratio. A change from mix $w_{62}a_4\delta_2$to $w_{62}a_3\delta_2$ increase the decay time by 84% A corresponding increase of 120% was obtained by using a finner grade, viz changing from $w_{62}a_4\delta_2$to $w\ a_4\ \delta_4$

APPLICATION OF RHEOMETER DATA TO QUALITY CONTROL

Requirements of Quality Control tests

A satisfactory quality control test should have the following attributes:

a) the test should measure relevant and definable properties of the mix;

b) the test should be sensitive and consistent;

c) the tests should be able to indicate the cause of any discrepancy;

d) the test should be accurate over a wide range of mixes;

e) the test should be quick and simple;

f) the test rig should be robost for site handling.

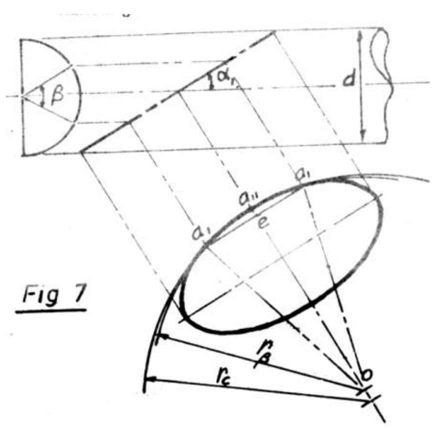


Fig 7

The curve features being proposed have been shown in the foregoing discussions to satisfy the first requirement. The second model of the instrument mentioned earlier on satisfies the fourth requirement, while it is to be able to fulfil the fifth that the present approach is being proposed. The rheometer itself is robust but a site model of the more delicate recording instruments needs to be designed. The rheometer results are discussed in relation to the second and third requirements.

Sensitivity and Consistency

Five mixes. $w_{55}a_4\delta_2$, $w_{57}a_4\delta_2$, $w_{67}a_4\delta_2$, $w_{67}a_4\delta_2$ and $w_{71}a_4\delta_2$ having different water/cement ratios but otherwise identical, were tested to assess the sensitivity of the rheometer to changes in water/cement ratio which is the most fundamental variable of a concrete mix.

There being no absolute criteria for the assessment of the sensitivity and consistency of such concrete instruments, a comparative approach was adopted. The British Standard slump test (11) is usually adopted for site quality control, and was therefore chosen as a basis for comparison. In addition a modified slump test was carried out. The modification consisted simply of pouring the concrete into the cone **without tamping**. Preliminary tests confirmed the vebe to be very insensitive to such high 'workability' mixes.

Three independent tests with fresh mixes of each group were carried out and a plot of the average values of the various parameters against water/cement ratio is given in Figure 8. The standard slump test seems insensitive to variations in water/cement ratios greater than 0.62. The modified test is apparently more sensitive to water/cement ratio than the standard. Theoretical considerations further suggest that the modified slump test is a better descriptive test for concrete mixes used in geotechnical process, and it was observed that the tamping in the standard test simply produces a solid cone at the base of the slump cone which relates more to the tamping effort than to the mix itself.

From the rheometer test, variations of three parameters with water/cement ratio are shown in Figure 8. The greater sensitivity of these parameters to changes in water/cement ratio than the slump values is apparent. Results discussed earlier also showed that the rheometer is also sensitive to changes in both aggregate/cement ratio and aggregate grading.

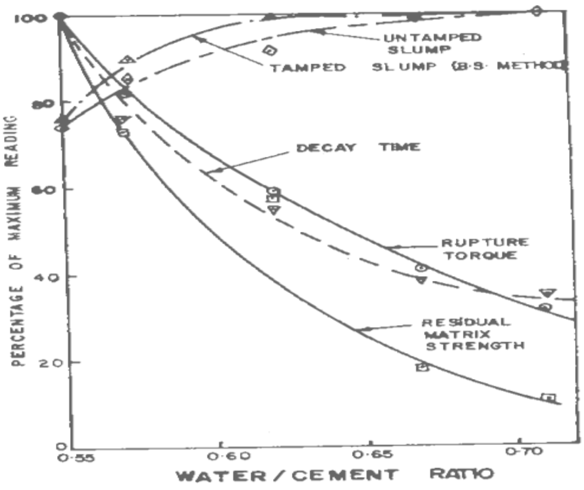


FIG. 8. CORRELATION OF VARIOUS MIX PARAMETERS WITH WATER CEMENT RATIO.

The relationships between these two of these mix parameters (breakdown torque and decay time) and water/cement ratio are also shown in Figures 5 and 7. The variation about the regression line in Figure 5 is very small, having a maximum value of 2 % of the recorded breakdown torque; the correlation coefficient is 1. The rheometer can therefore detect a 002 change in water/cement ratio on the basis of the breakdown torque readings. The statistic variation about the regression line indicates that the instrument can distinguish between two mixes having a water/cement ratio difference of 0.1 on the basis of measurements of decay time

The coefficient of variation, which is a dimension-less quantity, was chosen as the basis of comparing the reproducibility of the test methods The results given below are based on six independent tests using mix $w_{57}a_4\delta_2$.

Standard slump test	7%
modified slump test	6%
breakdown torque	4%
decay time	24%

Lower coefficient of variation indicates better reproducibility and the rheometer is again seen to perform better than the conventional slump on the basis of the breakdown torque. The decay time is not as distinctly defined on the trace as the peak torque hence the relatively wider scatter in the decay time readings. However, this could be improved with further experimentation, using more suitable recording equipment.

The reproducibility of the slump test, taken together with its poor sensitivity, may actually be worse than it appears, insensitivity being possibly manifested as reproducibility.

Indication of Cause of Inconsistency in Test Results:-It is not possible to obtain any indication of the mix variable which has caused an inconsistency in the test results from the slump test, or from any of the conventional tests. Variations in any of the following:

a) water/cement ratio
b) aggregate grading
c) aggregate / cement ratio

will result in a change of mix consistence. Table 1 gives a summary of the effects on the essential parameters of the rheometer when the three mix variables are altered; The quantities are expressed as a ratio of the corresponding quantities for the standard mix.

Table 2 summarises the trends shown in table l. The effect of reducing the aggregate/cement ratio is, in essence, the same as making the aggregate grading finer. It is not surprising, therefore, that the effects of these two changes in the rheometer results show similar trends. A study of table 1 and 2 shows that it is possible from an examination of rheometer traces to state the likely source (water/cement ratio or aggregate/cement ratio) of a consistent discrepancy in the test results which could not be ascribed to normal variations. A change in water content produces a similar change in both the breakdown torque and decay time while a change in aggregate quantity or grading produces a change in the breakdown torque which is opposite to the corresponding change in decay time.

It is noteworthy that a change in aggregate grading caused a 74% reduction in breakdown torque and a 133% increase in decay time, while the corresponding changes due to a change in aggregate/cement ratio are a 48 % increase in decay time. Further investigation could well show that the differences in the degree of changes in the instrument data due to aggregate/cement ratio and aggregate grading are sufficiently significant to permit a distinction to be made between inconsistencies caused by these two mix variables.

CONCLUSION

It is shown in the article that apart from the fundamental rheological parameters. i. e. the Bingham yield value and plastic viscosity, useful features which are also characteristic of plastic concrete can be obtained from an analysis of the thixotropic breakdown curve. These features are also sufficiently sensitive to changes in the mix variables. It is also possible to indicate the cause of inconsistent quality by studying the variations in the features. Although a knowledge of the fundamental parameters is necessary for any systems analysis, their determination is both time consuming and expensive. This makes their use for purely on-line site quality control purposes less attractive. For such purposes, the most relevant of the qualities discussed in this article can be used. These qualities are determined from single test runs, thus making their use more economically viable. Although the rheometer test in this form will be classified as 'one-point test', nevertheless the qualities referred to are related to the fundamental rheological properties of the material, unlike other one-point tests such as slump and compacting factor tests whose parameters are arbitrarily defined. Consequently, the test, is still preferable in the proposed form to other types of 'one-point' tests.

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Table 1: effect of mix variables on essential parameters of the rheometer

Identification Number	w/c ratio	Mix a/c ratio	Grading curve	Mix variable altered	Breakdown Torque ratio	Decay Time ratio
1	0.62	4	2	Standard	1.26	2.33
2	0.67	4	2	Water/cement ratio	0.83	0.67
3	0.62	4	4	agg. grading	0.26	2.33
4	0.62	4	2	agg. Cement ratio	0.52	1.84
5	0.57	4	2	Water/cement ratio	1.38	1.34

Table 2: Interpretation of results given in Table 1

Identification Number	water/cement ratio	aggregate/cement ratio	Aggregate grading	Breakdown torque	Decay Time ratio
1	None	None	None	None	None
2	Increase	None	None	Decrease	Decrease
3	None	None	Finer	Decrease	Increase
4	None	Decrease	None	Decrease	Increase
5	Decrease	None	None	increase	increase