CHAPTER 5

RHEOLOGY AND SETTING OF CONCRETE

5.1 Introduction

Rheology may be defined as the science of the deformation and flow of materials, and is concerned with relationships between stress, strain, rate of strain, and time. The term rheology deals with the materials whose flow properties are more complicated than those of simple fluids (liquids or gases). The rheological principles and techniques as applied to concrete include handling and placing of freshly mixed concrete, and the behavior of its constituent parts, namely, cement slurries and pastes. The rheology of fresh concrete like workability includes the parameters of stability, mobility and compactability, which are necessary to determine the suitability of any concrete mix as shown in Fig. 5.1. For the purpose of discussion of rheological properties of fresh concrete these parameters are redefined in terms of forces involved in the transmission of mechanical stresses on the concrete. The fresh concrete is subjected to normal and shearing forces during its handling and placing.

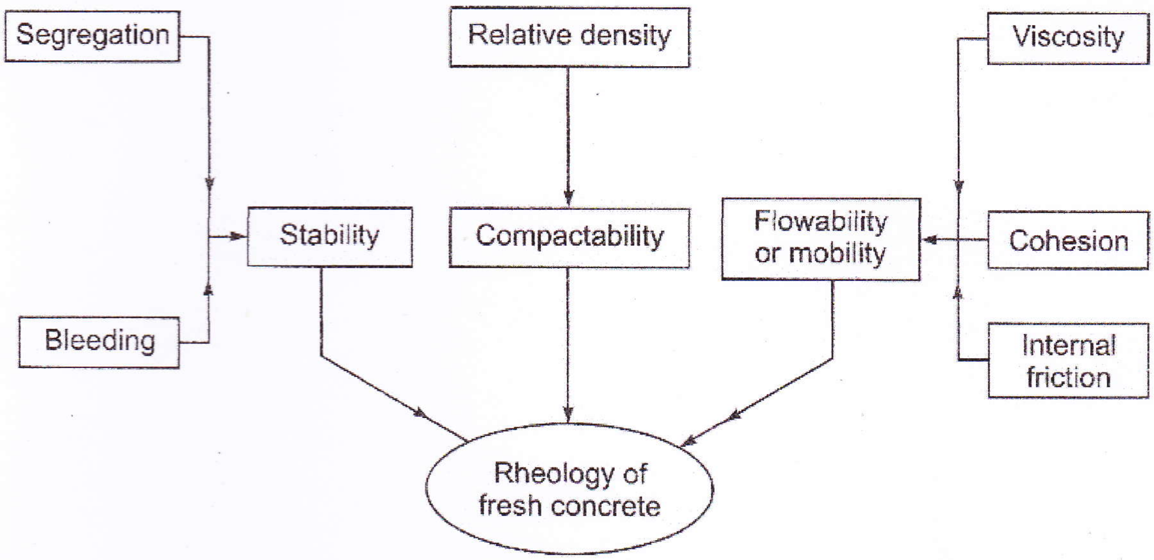

Fig. 5.1 Parameters defining the rheology of fresh concrete

Stability is defined as a condition in which the aggregate particles are held in homogeneous dispersion by matrix, and random sampling shows the same particle size distribution during transportation, placing and compaction. The stability of concrete is measured by its segregation and bleeding characteristics. Segregation is defined as the mixture's instability caused by weak matrix that cannot hold individual aggregate particles in homogeneous dispersion. The resistance to segregation depends upon the cohesion between the particles of the mix. Segregation can occur in concretes of both wet and dry consistencies. Segregation in wet mix can occur when the water content is such that the paste cannot hold aggregate particles in the distributed position while the concrete is transported, placed and compacted. Dry segregation takes place when a concrete with low water-cement ratio results in a crumbly mix during handling However, the crumbly mixes are often satisfactory when the concrete is vibrated, as during vibration the matrix becomes fluid momentarily and develops cohesion

and shear resistance. On the other hand, bleeding occurs when mortar is unstable and releases free water. Bleeding should be controlled and reduced to a minimum.

mobility of fresh concrete is its ability to flow under momentum transfer, i.e. under mechanical stresses. The flow is restricted by *cohesive*, *viscous* and *frictional* forces. The cohesive force develops due to adhesion between the matrix and aggregate particles. It provides *tensile strength* of fresh concrete that resists segregation. The viscosity of the matrix contributes to the ease with which the aggregate particles can move and rearrange themselves within the matrix. At low stresses no flow occurs and the mix behaves as a solid of extremely high viscosity. As the stresses increase, the bond strength between particles becomes insufficient to prevent flow and the viscosity gradually decreases and the concrete behavior changes to that of a liquid. The *internal friction* mobilizes when a mixture is displaced and the aggregate particles translate and rotate. The resistance to deformation depends on the *shape* and *texture of the aggregate*, the richness of the mixture, the water-cement ratio, and the type of cement used. Thus, the angle of internal friction plays an important part in the mobility of a concrete mixture. The relative mobility characteristics at the construction site can be measured by using Vee-Bee test in conjunction with basic compacting factor test.

compactabiliy measures the ease with which fresh concrete is compacted. compacting consists of expelling entrapped air and repositioning the aggregate particles in a dense mass without causing segregation. Compactability is measured by the *compacting factor test*. The test has some limitations as the cohesive mixture sticks in the hoppers of the test apparatus and the mixtures with low or very low workabilities produce wide variations in results. The compacting factor test can be extended by taking two additional measurements. The first measurement consists in determining the density of concrete in its loose, uncompacted state by placing concrete into the base container of the standard apparatus from a hand scoop without compaction. The other measurement determines the density of mechanically vibrated concrete sampled from the same batch; the concrete is loosely placed and compacted in three layers in the base container with a 25-mm diameter internal vibrator. These two measurements plus the values obtained from the standard compacting factor test give an indication of the relative ease with which a mixture changes from its loose to the compacted state. Thus the knowledge of rheological properties of concrete is beneficial in selecting concrete mixtures that can be efficiently compacted in the forms. The current workability tests, e.g. slump, compacting factor, Vee-Bee, and other remoulding tests are of limited scope because they measure only one parameter. These tests are termed *single-point tests.*

5.1.1 Representation of Rheological Behavior

The *ideal liquids* which follow Newton's law of viscous flow, i.e. shear stress being proportional to the rate of shear strain, are termed Newtonian liquids. The constant of proportionality may be used as a physical constant characteristic of the materials. The flow behavior of fresh concrete does not conform to it. The ratio of shear stress to shear rate is not constant but depends upon the shear rate at which it is measured, and may also depend on the shear history of the concrete sample being investigated. However, at low shear rates that are important in practice, the behavior can be represented by a straight line which does not pass through the origin, i.e. which has an intercept on the stress axis. The intercept indicates the minimum stress below which no flow occurs. The fact that concrete can stand in a pile (as in the case of the slump test) suggests that there is some minimum Stress necessary for flow to occur at all. The minimum stress is called yield stress and designated by the symbol τ_o. Thus the simplest flow equation of concrete illustrated in (Fig. 5.2) can be written as

$$\tau = \tau_o + \mu\gamma \quad (5.1)$$

Where τ_o is the yield value indicating the cohesion of the material, μ is a constant having the dimensions of viscosity and termed *plastic viscosity*. This mathematical relationship is called the Bingham model. The constants τ_o and μ arc the parameters characterizing the flow properties of the material. Thus Bingham model relates the shear stress of the material expressed in terms of its cohesion to plastic viscosity and the rate at which the shear load is applied.

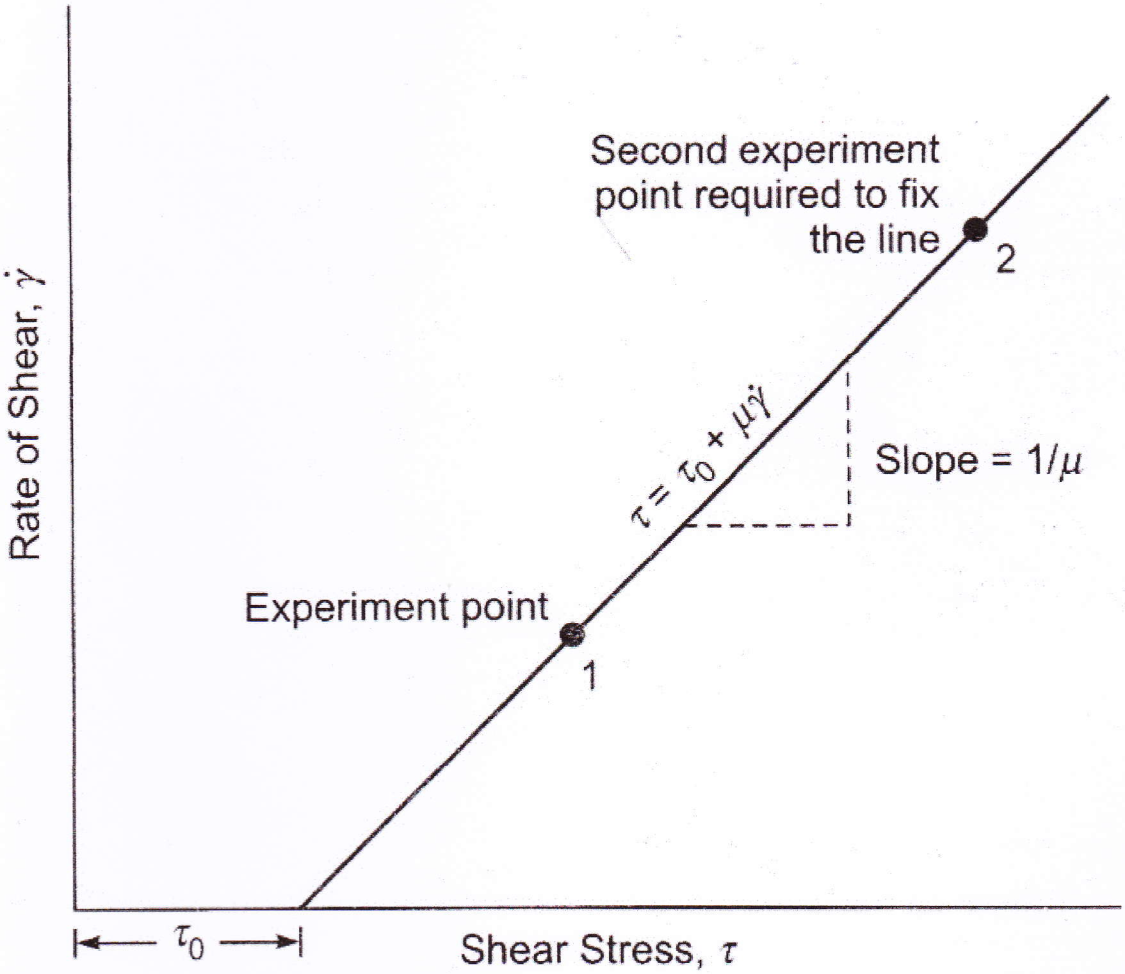

Fig. 5.2 The Bingham model that used in expressing the rheology of concrete

5.1.2 Measurement of the Rheology by the Modified Slump Test

A simple, robust and inexpensive field test method, Fig. 5.3, has been proposed by Ferraris C. F. et al 1998. In his method for simplification the rheological behavior of the concrete is reduced to two physical properties or parameters, namely, *yield stress* and, *plastic viscosity*. Currently, the most common field test, the *slump test*, is related only to the yield stress. However, the *plastic viscosity* of the concrete is assuming increasing importance in modern concretes. For *high-performance concretes*, it frequently constutes, the critical parameter that controls *pumpability* and. *ease of finishing*. This section describes the modified standard slump test apparatus, test procedure and calculation that make it possible to evaluate the *two Bingham rheological parameters*, i.e. the *yield stress* and *plastic viscosity* in the field. The method characterizes the plastic viscosity based on an average rate of slumping in the slump

test. Thus, measurement of the time necessary to reach an intermediate height between the initial and final values appeared a *period* to be a good means of differentiating among the concretes according to their plastic viscosity. The range of concretes that can be characterized in this manner is approximately that for which the slump is greater than 100 mm. Thus to determine the plastic viscosity, the time necessary for the upper surface of the concrete in the standard slump cone test to slump 100 mm is measured. In the procedure, a plate is allowed to slide on a centrally located rod as the means for monitoring the time to reach the 100 mm slump. The partial slump time is measured with a stopwatch controlled by the operator on the basis of a visual criterion (such as in the Vee-Bee test). The stopwatch is started at the point when rising up the cone is started, and is stopped when the sliding plate placed on the fresh concrete reaches the stop of the rod.

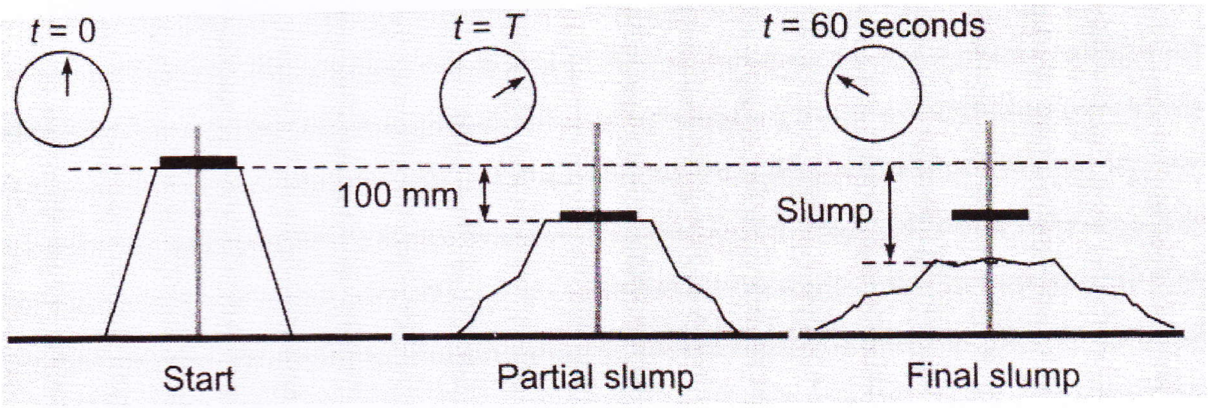

Fig. 5.3 Schematic diagram of the modified slump cone test (T is the slump time)

Procedure for Measuring the Slump Time

The dimensions of the apparatus and the test set-up are shown in Fig 5.4. The concrete is placed in the same manner as in the standard slump test. The steps involved in the procedure are

1. The rod attached to the horizontal base of the standard slump test apparatus carefully cleaned and greased down to the stop.
2. The base and the inside wall of the slump cone are moistened using a sponge.
3. The slump cone is placed on the base with the rod centered with respect to opening at the top of the cone. The cone is fitted on the base with attachment provided for this purpose.
4. The cone is filled in three layers of equal volume with each layer being 25 times with the standard tamping rod.
5. The surface of the concrete is struck off level with the top of the cone.
6. The part of the rod that projects above the concrete specimen is cleaned using a rag.
7. The sliding or the upper plate disk is brought down along the rod until contact is made with the surface of the concrete. The disk is provided with a rubber O-ring seal to prevent fine materials from interfering with its fall.
8. The mould is raised vertically while starting the stopwatch having a least count of 0.01s.
9. While the concrete is slumping, the disk is observed continually (through the top of the cone) and the stopwatch is stopped as soon as the disk stops moving.
10. Once the slump has stabilized, or no later than one minute after the start of the test, the disk is removed and the slump is measured with a ruler.

The final slumps obtained with the standard and the modified tests are compared in Fig.5.5. Semi-empirical models have been proposed for the yield stress and for plastic viscosity as a

function of the final slump and slumping time. The modified test can be used as a field quality control test. However, the method is limited to concretes with a slump of 120 to 260 mm. The mass of the disk (212 g) increases the vertical stress on the sample by a maximum value equal to its weight divided by the upper area of the cone frustum, i.e. 0.27kPa. When the disk reaches the stop, the height h of the concrete is 200 mm. Hence, the vertical compression stress at the base of the sample equals ρgh (where ρ = 2400 km/m^3 which is the approximate density of the fresh concrete and g is the acceleration due to gravity), i.e. about 4.8 kPa. It is thus seen that the vertical stress to the disk is at most of the order of 6 percent of the stress due to the concrete. The friction of the concrete along the rod would tend to reduce the final slump. The fundamental rheological parameters based on the modified slump test can be estimated from the relation

$$\tau_o = \rho\,(300 - S)/270 \qquad (5.2)$$

where ρ is the density expressed in km/m^3, τ_o is the yield stress in Pa, and S is in mm. The relation provides a reasonable value of the Bingham yield stress. However, it is found to consistently underestimate the yield stress in the low slump range, typical of self-leveling concretes. The error averages to 195 Pa for the yield stress in the range of 100 to 2000 Pa.

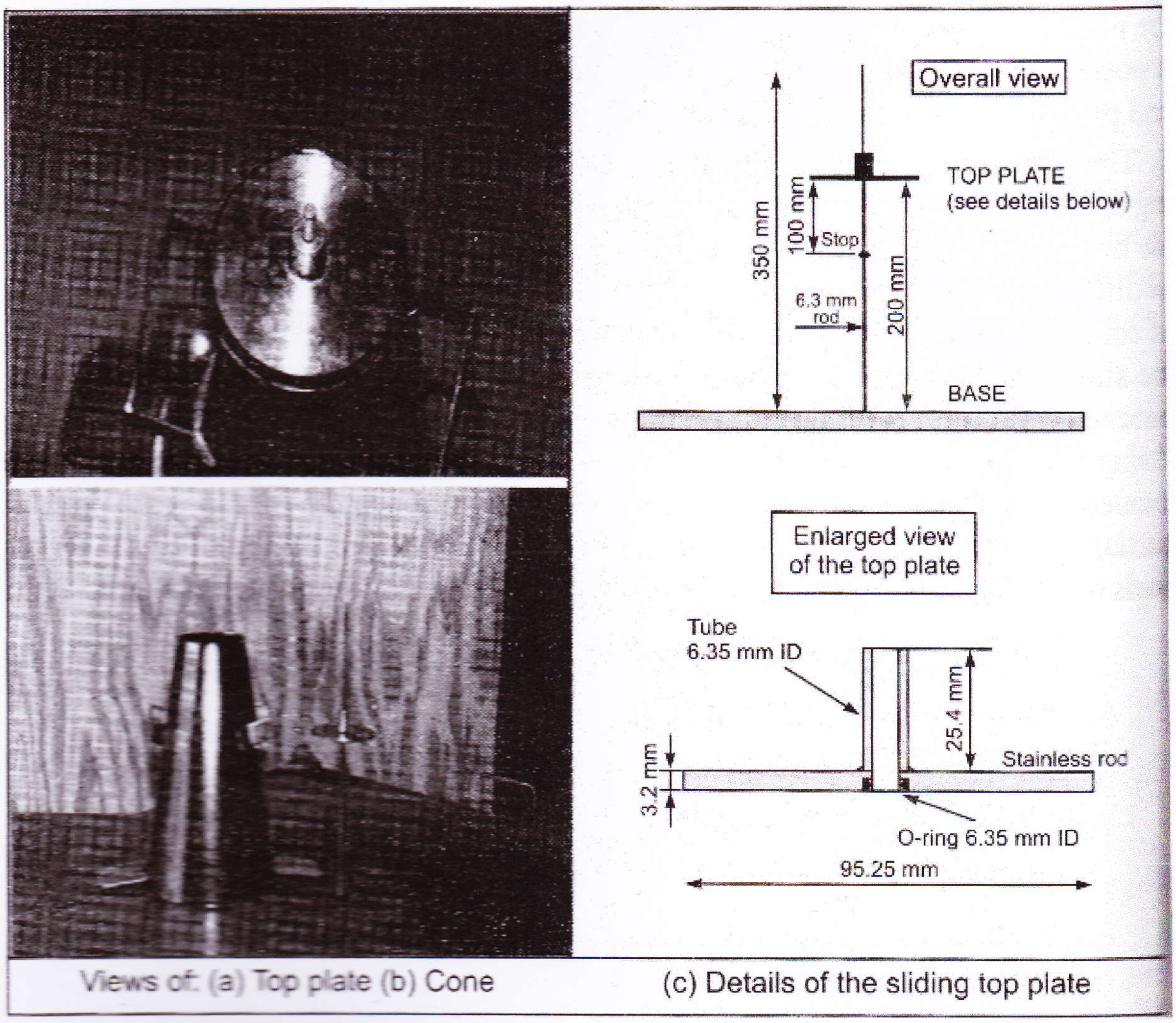

Fig. 5.4 The details of the modified slump test apparatus

For very fluid mixtures, the following empirically improved equation can be used:

$$\tau_o = \rho(300 - S)/347 + 212 \qquad (5.3)$$

Thus, this test will be more useful in determining the plastic viscosities of concretes with HRWRAs (High Range Water Reducers Admixtures).

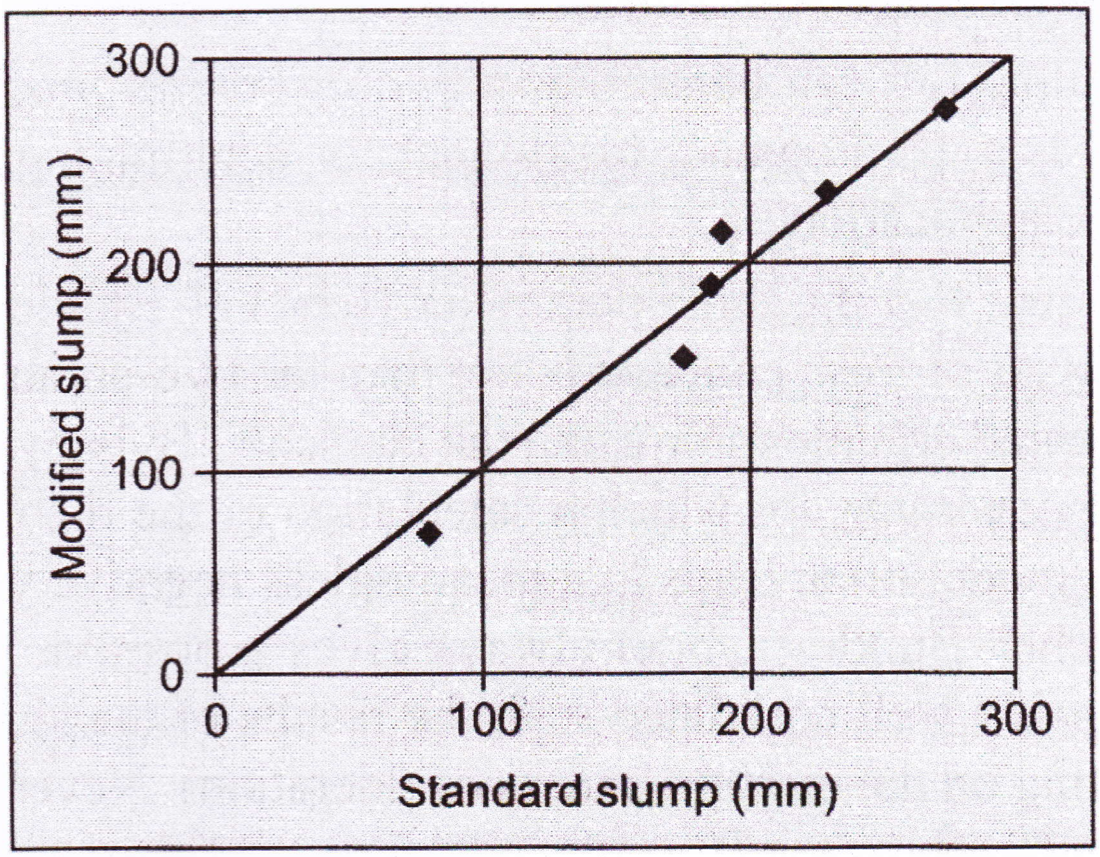

Fig. 5.5 Comparison between the values of the standard slump test and the modified slump test

5.2 Setting of Concrete

Setting is defined as the onset of rigidity in fresh concrete. It is distinct from hardening, which describes the development of useful and measurable strength. Setting precedes hardening, but it should be emphasized that both are gradual changes, which are controlled by the continuing hydration of the cement. We can view setting as a traditional period between states of true fluidity and true rigidity. The penetration tests used to measure the times of setting are purely arbitrary measurements. Figure 5.6 shows that initial set and final set, as measurement by ASTM C 403, don't correspond exactly to any specific change in concrete properties, although it is useful to consider that initial set represents approximately the time at which fresh concrete can no longer be properly handled and placed, while final set approximates the time at which hardening begins. Fresh concrete will have lost measurable slump prior to initial set, while measurable strength will be achieved sometimes after set.

5.2.1 Effect of Hydration Setting

5.2.1.1 Role of C_3S

It should be remembered that the cement hydration begins as soon as water is added at the mixer. Setting is controlled primarily by the hydration of C_3S. The period of fluidity corresponds to the dormant period (stage 2) of C_3S hydration. Setting occurs when the dormant period is terminated and rapid hydration of C_3S occurs in stage 3. Initial set corresponds approximately to the beginning of stage 3 and final set to its midpoint. \thus, initial set is marked by the beginning of a rapid temperature rise of the concrete, which will reach a maximum rate at final set. Setting is also accompanied by a decrease in electrical conductivity and an increase in the velocity of sound waves propagating through the paste. Measurements of either of these properties could form the basis of an adequate test for setting.

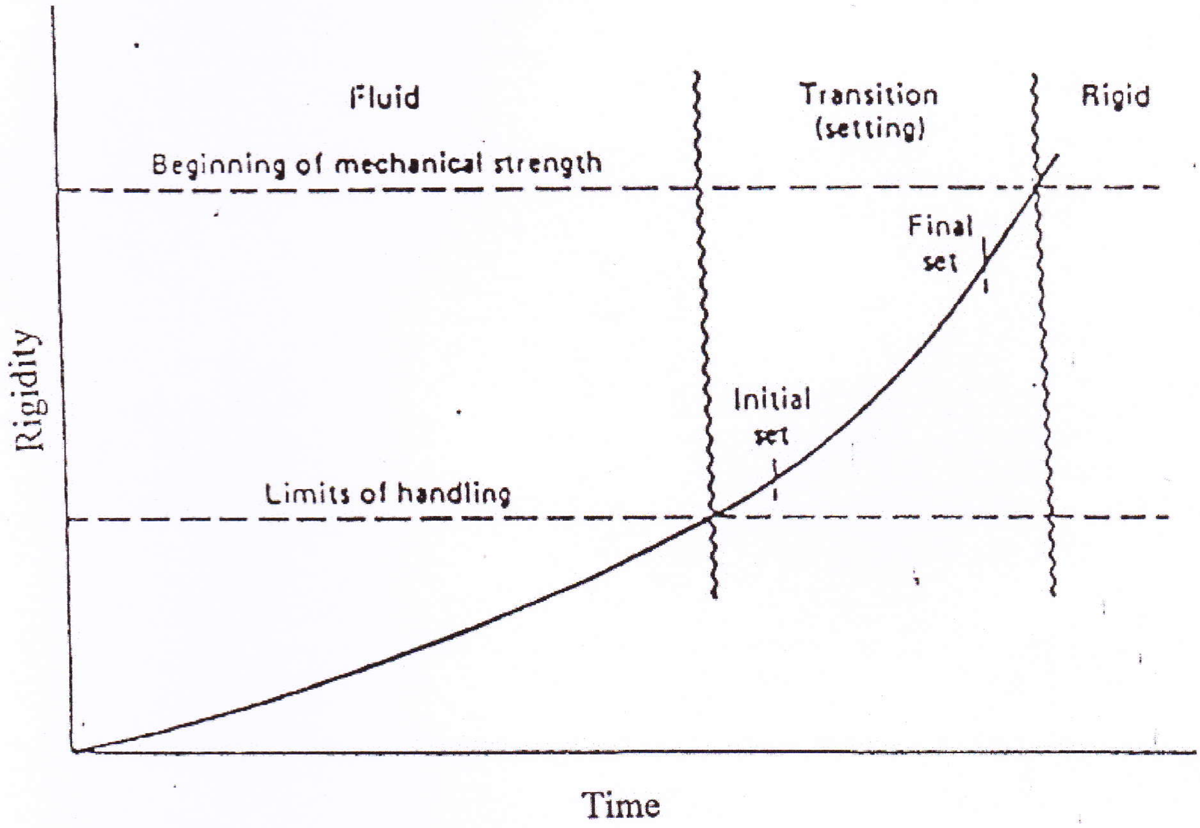

Fig. 5.6 Process of Setting and Hardening

5.2.1.2 Role of C_3S and Gypsum

When using ordinary Portland cements (the five ASTM types), C_3S plays a relatively minor role in determining setting behavior except in the cases of abnormal set discussed below. Gypsum is always inter-ground with modern cements; it reacts with C_3S to help control the setting time.

5.2.2 Abnormal Setting Behavior

Abnormal setting of concrete was a problem in earlier times but is much rarer now. The different types of abnormal setting behavior are shown in Figure 5.7. They are most likely to be encountered under certain conditions when an admixture is used (usually a set retarding admixture). Two major types of setting problems may be encountered: false set and flash set.

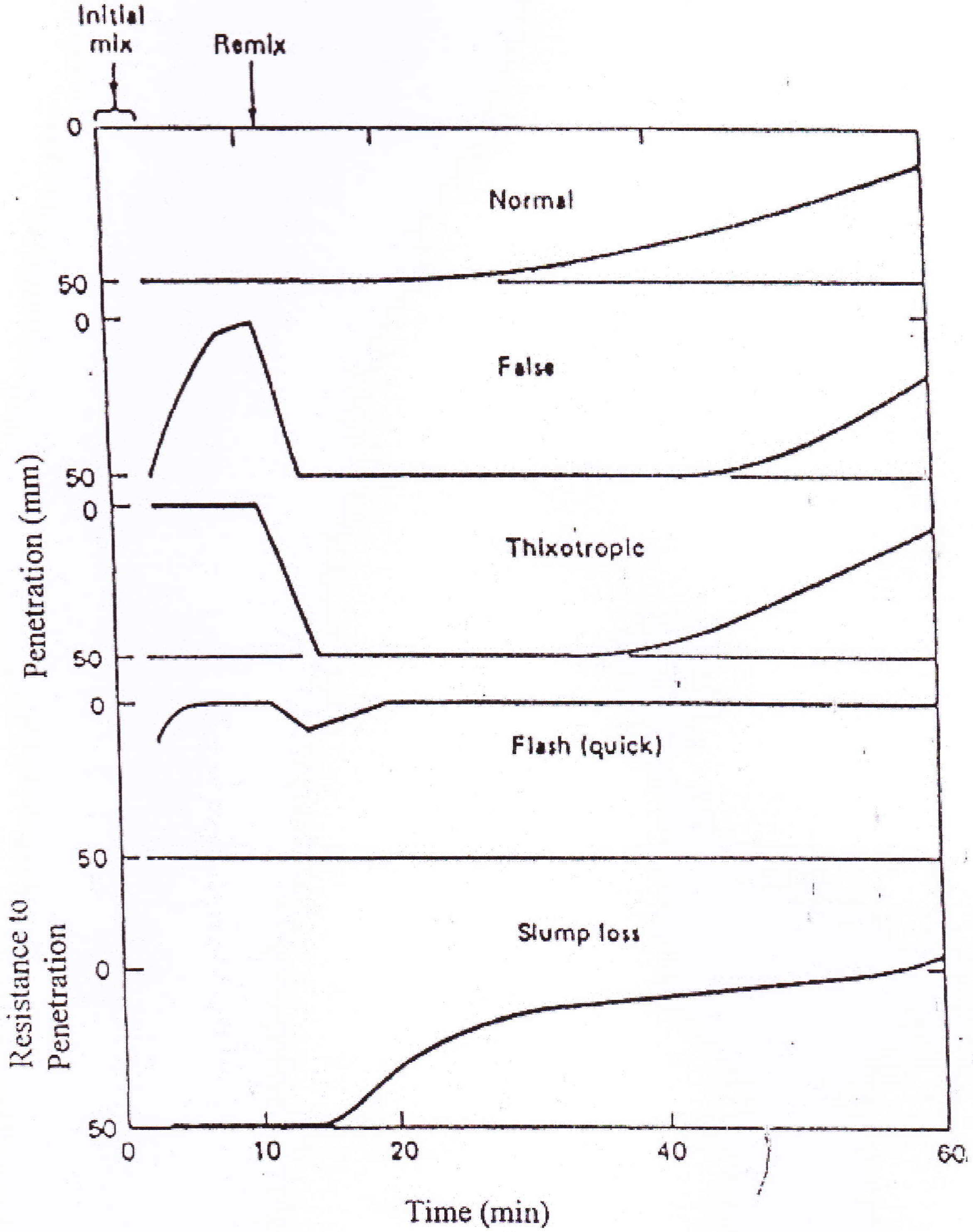

Fig. 5.7 Diagrammatic Sketch of Different Types of Set of Cement and Mortar, and Slump Loss of concrete

5.2.2.1 False Set

A concrete may stiffen rapidly a short time after mixing is completed (see Figure 5.7). Fluidity is restored by remixing and the concrete will then set normally; thus, false set has more nuisance value than anything else. This phenomenon is sometimes called plaster set because it is most often caused by crystallization of gypsum. When gypsum is inter-ground with clinker, the material in the grinding mill can get quite hot because of the high-energy

input during grinding. The temperature can rise high enough (120 C^0 or 250 F^0) to cause the gypsum to partially dehydrate to calcium sulfate hemihydrates, will rehydrate back to gypsum and form a rigid crystalline matrix, but because there are only small amounts of plaster in the concrete, very little strength can actually develop and the plaster set can easily be disrupted by further mixing. The formation of the hemihydrates during grinding is minimized by cooling the grinding mills. A small amount of hemihydrates may still be formed but will mostly rehydrate while mixing is continuing and thus is harmless. However, a set-retarding admixture can also delay rehydration of the hemihydrate until after the mixing sequence is completed. In this way, cement that normally behaves satisfactorily may exhibit false set.

False sat may also be caused by the excessive formation of ettringite soon after mixing is completed. Ettringite has crystal morphology similar to gypsum and thus can cause "plaster set" in an analogous way. Ettringite crystallizes most rapidly during the mixing period, but if its formation is delayed or extended in the presence of an admixture, false set can also occur. There is evidence that set-retarding admixtures can accelerate the initial hydration of C_3A, and thus cause false set by increasing the formation of ettringite. In some high alkali cements and formation of syngenite (KCS_2H) may cause false set.

5.2.2.2 Flash Set

If the C_3A in the cement is very reactive, flash set (or quick set) may occur. Flash set is caused by the formation of large quantities of monosulfoaluminate or other calcium aluminate hydrates. This is a rapid set that can not be disrupted by further mixing indicating that some strength has developed. Thus, flash set is a more severe condition than false set. Fortunately, flash set has been largely eliminated as a problem with normal Portland cement by the use of gypsum to control C_3A hydration to the point at which flash set may occur. When C_3A and gypsum contents are high the formation of ettringite can cause flash set.

5.2.2.3 Prevention of Abnormal Set

Correcting a problem of abnormal set may be most simply accomplished by merely changing to another equivalent admixture, eliminating the use of the admixture, or changing the amount of gypsum added to the cement. Research has shown that a little prehydration of cement (i.e. principally C_3A) before the admixture is added may solve the problem. This could be most easily done by delayer addition of the admixture.

4.3 References

1- Amr. E. Salama, and Gouda M. Ghanem, "Concrete Technology", Lecture notes for students of the 2nd year Civil, Civil Engineering Department, Faculty of Engineering, Mataria, Helwan University, Cairo, Egypt.

2- M. L. Gambhir, "Concrete Technology-Theory and Practice", Text book, The McGraw Hill Education Private Limited, New Delhi, Fourth Edition.

4.4 Problems

1. Draw the following with net sketches

a. parameters defining the rheology of concrete
b. The Bingham model that used in expressing the rheology of concrete
c. Test procedures of the modified slump test
d. Details of the sliding plate of the modified slump test

e. The process of hardening of concrete showing on the curve the time period suitable manufacturing concrete starting from mixing until finishing the surface of concrete.
f. Different types of setting of cement

2. Mark the right choice a, b, c, or d that makes the following statements correct.
- Rheology of fresh concrete includes the following except (a) stability, mobility and compactability of concrete (b) knowledge of water-cement ratio (c) study of forces involved in transmission of stress through concrete mass (d) deformation curve of fresh concrete
- The conventional workability tests, e.g. slump test, compacting factor test, Vee-Bee test and remoulding tests are termed single-point tests because (a) they measure one parameter of workability (b) they are conducted at one place (c) each gives complete information about the workability (d) all of the above (e)
- Rheological or flow equation of fresh concrete is expressed by (a) Newton's model (b) Bingham model (c) Le Chatelier's model (d) Neville model (e) none of the previous choices
- The following combinations of conventional workability tests help to achieve a better understanding of rheology of concrete (a) slump and compacting factor tests (b) ee-Bee and compacting factor tests (c) slump and Vee-Bee tests (d) compacting factor and remoulding tests
- Rheological properties of concrete are independent of (a) water-content (b) aggregate shape, texture and grading (c) type of mixer (d) temperature (e) type of cement
- The flow properties of fresh concrete are mainly dependent upon (a) the factors affecting resistance to deformation (b) the water-cement ratio (c) the richness of the mixture (d) shape and texture of the aggregate (e) fineness moduli and gradings of the aggregates
- C_3S plays a relatively minor role in determining (a) workability of concrete (b) the setting of cement (c) the strength of concrete (d) the fineness of cement
- Setting is defined as (a) The complete hardening (b) the starting of loosing workability (c) the onset of rigidity in fresh concrete (d) none of the other choices
- Initial set corresponds approximately to (a) the beginning of hydration process (b) the end of the third stage of hydration of C_3S (c) with the initial formation of the gypsum crystals (D) the beginning of stage 3 of hydration process
- False set is sometimes called (a) final set (b) plaster set (c) cement set (d) concrete set
- Concrete workability cannot be regained after (a) adding water to dry concrete mix (b) removing cement from the buckets (c) false set (d) flash set
- Flash set of concrete results from (a) the absence of enough gypsum in cement (b) the high powder content in concrete (c) false set (d) hard plate effect in compression test