

CONCRETE THIXOTROPY

Keywords: aggregate segregation; formwork pressure; plastic viscosity; pumpability; rheology; rheometer; static yield stress; thixotropy; yield stress.

Introduction

Fresh concrete can exhibit different rheological behavior when at rest than when flowing. This difference is due to thixotropy, which can have important consequences for formwork pressure, multi-lift casting, slip-form paving, pumping, and segregation resistance. This TechNote defines thixotropy and distinguishes it from other changes in rheological properties; discusses the origins of, test methods for measuring, and factors affecting thixotropy; and concludes with its applications.

Description of thixotropy

Rheology is the science dealing with the deformation and flow of materials and is typically described based on the relationship between shear stress and shear rate, as shown in Fig. 1. Viscosity (η) is the ratio of shear stress to shear rate at a given shear rate.

Concrete rheology is most commonly characterized in terms of the Bingham model (Fig. 1), which is defined in terms of yield stress (τ_0) and plastic viscosity (μ_{pl}) (ACI 238.1R).

Two measures of yield stress are typically reported. Static yield stress ($\tau_{0\text{-static}}$) is the minimum shear stress to initiate flow from rest. Dynamic yield stress ($\tau_{0\text{-dynamic}}$) is the minimum shear stress to maintain flow.

Plastic viscosity is the change in shear stress divided by the change in shear rate, for the shear stress greater than the dynamic yield stress. For Bingham materials, plastic viscosity is independent of shear rate, but the viscosity depends on the shear rate and is typically referred to as apparent viscosity (η_{apparent}).

Thixotropy is a reversible, isothermal, time-dependent decrease in viscosity when a fluid is subjected to increased shear stress or shear rate (Mewis 1979). The change in viscosity is considered reversible because the viscosity will increase to its original value when the shear stress or shear rate is decreased to its original value. The change in viscosity due to thixotropy is considered to be isothermal to distinguish changes in viscosity due to thixotropy from changes in viscosity due to changes in temperature. The change in viscosity is considered to be time-dependent because the change in viscosity occurs over a period of time, rather than instantaneously when the shear is applied or removed.

Thixotropy should be distinguished from irreversible changes in viscosity. Such changes may be caused by hydration, as manifested by slump loss and setting. In addition, segregation can result in a more paste-rich region of concrete with lower viscosity. Although the original nonsegregated composition could be restored by remixing, changes in viscosity due to segregation should not be considered thixotropy.

Therefore, changes in viscosity can be attributed to both reversible and nonreversible phenomena. In this way, the effects due to thixotropy can be separated from effects due to other phenomena, such as setting. In practice, there is often no relevance in differentiating the reversible and irreversible processes because it is the overall increase in viscosity when concrete is at rest over time that will influence the fresh state performance, such as concrete segregation resistance or formwork pressure (Billberg 2009).

Thixotropy should be distinguished from shear-thinning characteristics of a fluid, wherein the viscosity decreases with increasing shear rate. Thixotropy is time-dependent and can be observed at a constant shear rate, whereas shear thinning characteristics are shear-rate-dependent, not time-dependent.

Origins of thixotropy

Thixotropy is due to two main aspects: 1) structural build-up when concrete is at rest; and 2) structural break-down when concrete is under a shear or flow.

When a concrete mixture is at rest, particles in the cement paste flocculate and move together with time, forming a

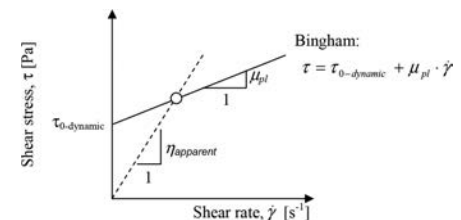


Fig. 1—Bingham rheological model.

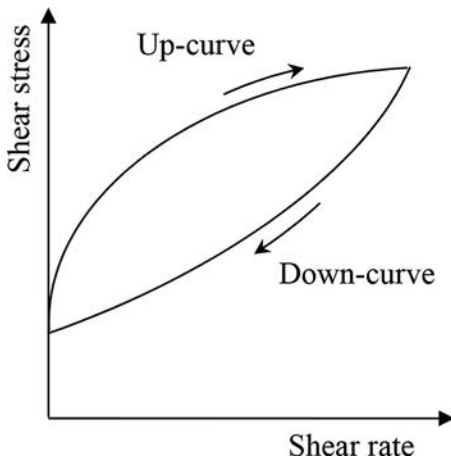


Fig. 2—Typical hysteresis loop for measuring thixotropy.

three-dimensional, networked internal structure. This internal structure results in an increase in concrete viscosity. Flocculation is the result of Van der Waals attraction and Brownian motion (Shaw 1992).

If this same concrete is subjected to shearing, the flow can result in breaking up of flocs due to rupture of interparticle links and flocculation due to particle contacts (Wallevik 2003). At a constant rate of flow, a balance between breakup of flocs and flocculation will be reached with time. The internal structure will be reduced compared to the at-rest state, resulting in a decrease in concrete viscosity.

Measuring thixotropy

Multiple methods are available for measuring thixotropy of cement paste, mortar, or concrete. As discussed previously, concrete experiences both reversible and irreversible changes in viscosity. Thus, directly measuring the reversible change due to thixotropy is challenging (Ferron et al. 2007). Thixotropy can be characterized based on the degree of material structural build-up or breakdown.

The hysteresis loop test and constant shear rate tests require the use of rheometers, which may include concentric cylinder geometry (Billberg 2009), vane geometry (Khayat et al. 2008; Koehler and Fowler 2008), or parallel plate geometry (de Larrard et al. 1997).

Hysteresis loop test method—The hysteresis loop test (Ferron et al. 2007) is conducted by using a rheometer to apply a range of shear rates to concrete initially at rest. To perform the test, concrete is placed in a rheometer, and left at rest for a defined period of time to allow structural build-up to occur. Rest time, typically on the order of minutes, could change from test to test depending on the materials, equipment, and application considered. The shear rate in the rheometer is increased from zero to a predetermined maximum level and then decreased back to zero. Typically, the time period over which the shear rate is increased (up-curve) is equal to the time period over which it is decreased (down-curve). The response in terms of material shear stress is recorded and plotted against the shear rate, resulting in flow curves as shown in Fig. 2. Any difference between the up- and down-curves is termed hysteresis.

When the material is sheared at an increasing rate, the structure of the material gradually becomes more and more broken. When the material is then sheared with a decreasing rate, the gradual building up of the structure begins again; however, the rate of the structural build-up is slower than the rate of the breakdown that has occurred during the up-curve. Thus, a hysteresis loop is formed by the up-curve and the down-curve as shown in Fig. 2.

Thixotropy of the material is quantified by the area enclosed between the up- and down-curves of the hysteresis loop, which relates to the energy needed to break down the reversible microstructure of the tested material. Thus, a highly thixotropic mixture is typically characterized by having a large area within the hysteresis loop. If the up- and down-curve coincide perfectly (that is, the enclosed area equals zero), the material is considered nonthixotropic. The hysteresis loop test is greatly dependent on the testing procedures and equipment. The test should merely be used as a preliminary indicator of thixotropic behavior and not for quantitative measurements. This is because the influences of shear rate and time are coupled; that is, the shape of the hysteresis loop can be affected by the rate at which the shear rate is increased or decreased.

Constant shear rate test—The constant shear rate test is conducted by measuring the shear stress of a material initially at rest and then sheared at a constant rate. At the start of the test, for a material that has been left at rest for some time, the flocculated particle

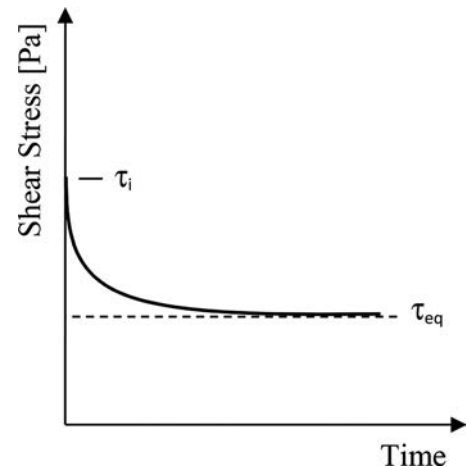


Fig. 3—Shear stress decay at constant shear rate.

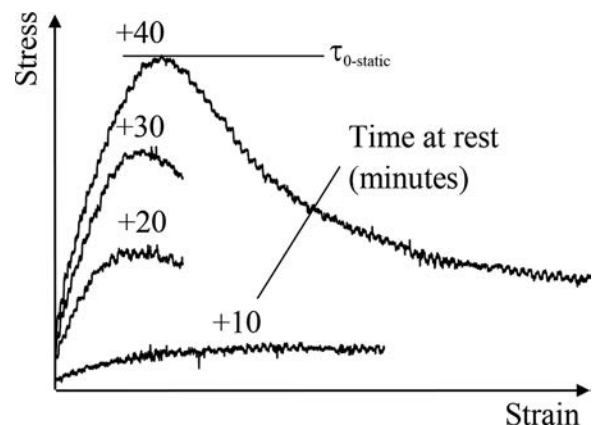


Fig. 4—Static yield stress measurements (Billberg 2009).