

# A Review- State of Art on Hot Weather Concreting and Rheology of Cement-Based Materials

*Samer Al-Martini*

Associate Professor, Department of Civil Engineering, College of Engineering, Abu Dhabi University, Abu Dhabi, UAE

## **Abstract**

*The objective of this paper is to explore the important mechanisms that control the rheology of cement based materials under hot weather conditions. The effect of hot weather on the fresh and mechanical properties of concrete was investigated. The paper presents some of the practices taken to alleviate the effects of hot weather on concreting. The rheological properties of Portland cement paste and concrete were discussed using both the conventional flow technique and the oscillatory shear technique.*

**Keywords:** *Rheology, cement paste, concrete, high temperature, yield stress, viscosity, thixotropy, compressive strength, slump loss*

**Author for Correspondence:** *Email ID: [samer.almartini@adu.ac.ae](mailto:samer.almartini@adu.ac.ae)*

## **INTRODUCTION**

### **Hot Weather Concreting**

Hot weather adversely affects the quality of fresh and hardened concrete by accelerating the rate of water evaporation and cement hydration<sup>[1]</sup>. Several standards and guidelines have specified a limit for the job site temperature, which if exceeded, concreting work is considered to be conducted under hot weather environment. For example, the upper limit of ambient temperature for the production of good quality concrete, as specified by The American Concrete Institute “Specification for Hot Weather Concreting” is 27°C<sup>[2]</sup>. The American Society for Testing and Materials<sup>[3]</sup> “Standard Practice for Making and Curing Concrete Test Specimens in the Field” requires that concrete should be mixed and initially cured at a temperature not exceeding 27°C<sup>[3]</sup>. In practice, strictly abiding to this limit is not an easy task and needs several precautions that are difficult to be implemented in-situ without additional high costs. Moreover, designing concrete mixtures is intricate since, several

interacting factors influence this procedure including concrete ingredients, placement, compaction, and curing, as well as the specific conditions of the construction site.

The temperature during a typical summer day in hot weather countries often exceeds the above mentioned specifications. For instance, Al-Gahtani *et al.*<sup>[1]</sup> documented that the summer daytime temperature in the vicinity of Dhahran in eastern Saudi Arabia frequently exceeds 40°C. The ACI Committee 305 for Hot Weather Concreting recommends that the trial batches should be made at the highest expected job site temperature while designing concrete mixtures to evaluate the hot weather effects<sup>[4]</sup>.

### **Cement Hydration**

The hydration of cement starts immediately upon contact of cement with water. A rapid evolution of heat takes place during the first few minutes of hydration. Subsequently, the reactions are slowed down significantly for a period of time called the dormant or induction period, in which the thickness of

hydration products around cement grains increases. The induction period typically lasts from 1 to 4 hours depending on the temperature, water to cement ratio (w/c), cement properties and also admixtures. This period of time is necessary to transport, place and consolidate fresh concrete. The hydration reactions are then accelerated again because the layers of hydration products around cement grains collapse due to osmotic pressure thus, allowing further contact between cement and water. The acceleration usually lasts from 8 to 12 hours<sup>[5]</sup>. The hydration process may take up to a year during which the hydration rate is substantially slowed down with time and the hydration products during this stage fill in the porous space densifying the hydrated cement paste<sup>[5]</sup>.

The rate of cement hydration accelerates with rise in temperature. The increased rate of hydration with temperature brings about the stiffening of cement-based mixtures, which is generally referred in concrete technology as “slump loss”<sup>[6]</sup>. The accelerated slump loss reduces the time during which the fresh concrete remains workable to allow for its placement. Such a slump loss is indeed one of the major problems in hot weather concreting and is therefore discussed in more detail below.

**Potential Concreting Problems in Hot Weather Increased water demand** Due to high temperature in hot weather environments, mixing water evaporates rapidly from the fresh concrete surface. Consequently, the concrete quickly loses its workability. To compensate for the water lost due to evaporation, additional amounts of water is to be added in order to achieve a desired slump<sup>[6]</sup>. However, increasing the water content is not recommended because it is known to be the main factor for reducing the concrete’s compressive strength and causing durability problems<sup>[4]</sup>. Hasanain *et al.*<sup>[7]</sup> investigated the evaporation rate of water from a freshly placed concrete surface cast

at different times of a hot climate day. Their results indicated that the rate of water evaporation from freshly placed concrete surfaces depends mainly on the time of casting with the highest rate achieved at around noon time.

### ***Slump Loss and Setting Time***

The above discussed rapid evaporation of water in addition to the acceleration of cement hydration at high temperature are the main reasons for the rapid stiffening of fresh concrete in hot weather regions. Sorka and Ravina<sup>[6]</sup> reported that the increase of temperature from 20–40°C has increased the rate of cement hydration about 2.5 times, which results in rapid slump loss of concrete.

El-Rayyes<sup>[8]</sup> investigated the effect of the ambient air temperature on the time of initial and final setting of concrete mixtures made with a wide range of water-to-cement ratio (w/c) and placed in extremely hot climates. The w/c ranged from 0.35–0.70. The concrete mixtures were initially prepared in a laboratory with a controlled temperature of 23°C. After mixing, mortar was sieved from each concrete mixture and its initial and final setting times were measured in the lab at a temperature of 23°C and outdoors at ambient temperatures ranging from 36–41°C. El-Rayyes<sup>[8]</sup> reported that the increase in the temperature from 23–41°C reduced the initial and final setting time of concrete by about 25%.

### ***Decreased Compressive Strength (28 day)***

As discussed earlier, addition of extra water is required at high temperature to compensate for the fast evaporation. However, adding extra water yields a higher w/c. Concrete placed under high temperature have a lower 28 day compressive strength than that placed under a moderate temperature. This is attributed to a higher w/c, higher concrete temperature at the time of placement or during curing, or both<sup>[4]</sup>. Al Gahtani *et al.*<sup>[1]</sup> found that the compressive strength

of concrete specimens prepared at a normal laboratory temperature, but cured under high temperature was about 6–20% less than that of the corresponding specimens prepared and cured at a normal temperature. They attributed these results to the fact that concrete strength is adversely affected by the acceleration of hydration at early ages when it is cured at high temperatures. High curing temperature produces a protective coating on the surface of hydrated cement grains, hindering the subsequent hydration and producing a non-uniform distribution of hydration products within the hardened cement paste matrix, thus leading to reduced compressive strength<sup>[1]</sup>.

Gaynor *et al.*<sup>[9]</sup> investigated the effect of the initial curing on the compressive strength of concrete. After mixing, some concrete specimens were initially air-cured for 16–20 hours at a temperature of 38°C and then in a moist curing room at 23°C with relative humidity of 95%, while other specimens were only cured in a moist curing room.

The initial curing was intended to simulate poor initial curing for fresh concrete in hot weather. Their results showed that the 28 day compressive strength of specimens initially cured at 38°C was about 11% less than that initially cured in a moist curing room.

### Practices for Mitigating Hot Weather Concreting Problems

To alleviate the harmful effects of hot weather on concrete, it is recommended to place concrete during time periods when the temperature is low and does not exceed the acceptable levels specified by standards.

However, it is not always possible to abide by this recommendation, especially for large projects that dictate continuous concreting work even in periods of the day with high temperature to meet demanding

schedules. Some of the practices applied in hot weather concreting are:

#### *Using Cooled Mixing Water*

Although the mass of water used in mixing concrete is usually the least compared to that of aggregates or cement, cooled water can reduce the temperature of the entire concrete mixture, though this reduction is not substantial. For example, lowering the temperature of the mixing water by 2°C can reduce the concrete temperature by approximately 0.5°C<sup>[4]</sup>. The ACI 305R–99 report presents the expected reduction in the concrete temperature when replacing part of the mixing water having a temperature of 16°C, 21°C, 27°C, or 32°C with a cooled water having a temperature of 7°C. It is reported that the larger the amount of cooled water added as part of the mixing water, the more the concrete temperature is reduced. Moreover, the larger the difference in the temperature between the cooled water (7°C) and the normal mixing water, the more concrete temperature is reduced.

#### *Using Ice as Partial Replacement for Mixing Water*

Using ice as part of the mixing water has been a major means of reducing the fresh concrete temperature<sup>[4]</sup>. Crushed ice is placed in the concrete mixer as a part of the mixing water. Its proportion should not exceed 75% of the total mixing water required. The larger the amount of ice added as part of the mixing water, the more is the reduction of the fresh concrete temperature that can be achieved<sup>[4]</sup>.

The ACI report states that the concrete temperature can be decreased to 20–23°C when replacing 75% of the mixing water with ice. This indicates that this practice is more effective than using cooled water alone. However, it is a costly option requiring additional equipment to be installed at ready mix concrete plants<sup>[4]</sup>.

### **Using Proper Ingredients**

Ingredients of Concrete must be selected properly in order to achieve satisfactory performance of concrete under hot weather. In order to reduce the internal concrete temperature during hydration, the cement content should be kept as low as possible, but sufficient to meet workability, strength and durability requirements. In hot weather conditions, Portland cement is often partially replaced by supplementary cementitious materials such as fly ash or blast furnace slag, which were found to reduce the early rate of heat evolution, thus the better controlling the rise in concrete temperature and the rate of slump loss.

Since aggregates represent 60–70% of the total volume of concrete, their temperature has a significant effect on the fresh concrete temperature. For example, the temperature of concrete increases by about 17°C when the aggregates temperature increases from 16°C to 32°C<sup>[4]</sup>. Therefore, all practical means should be employed to keep the aggregates as cool as possible, such as keeping the aggregates in a shaded storage.

### **Using chemical admixtures**

Chemical admixtures are usually incorporated in concrete to reduce the amount of mixing water, while maintaining an adequate workability<sup>[10]</sup>. Several types of admixtures recognized by ASTM C494 can be used, including: water-reducing admixtures (Type A), retarding admixture (Type B), accelerating admixtures (Type C), water reducing and retarding admixtures (Type D), and water reducing and accelerating admixtures (Type E).

Water reducing admixtures are usually capable of reducing the quantity of mixing water required to produce concrete of a given workability by 5–15%. High-range water reducing admixtures (also called super-plasticizers), on the other hand are capable of reducing the quantity of mixing

water by up to 30%. Super-plasticizers are used for instance to produce the so-called ‘self consolidating concrete (SCC)’, which can be placed with little or no vibration. Self consolidating concrete (SCC) is a highly flowable concrete that can effectively fill formwork without the need for consolidating tools, and is useful, for example, for placing concrete in thin and heavily reinforced sections. Using concrete with high flowability in hot weather environments may help to overcome the adverse effects of high temperature on slump loss<sup>[11]</sup>. Super-plasticizers allow a considerable increase in the initial slump of concrete, thus overcoming the subsequent slump loss, which is useful in hot weather conditions. However, these admixtures are usually developed in countries with mild climates and their behavior can sometimes become different when used in hot climates. Therefore, such admixtures should be tested under high temperature before being recommended for hot weather concreting.

## **METHODOLOGY**

### **Rheology of Cement Paste and Concrete**

Rheology is defined as the science of flow and deformation of matter<sup>[12]</sup>. It investigates the relationship between force, deformation, and time. Broadly speaking, the matter can be everything from an elastic solid to a viscous liquid. Typically, rheology studies the deformation of those materials whose behavior falls between solids and fluids (visco-elastic materials)<sup>[12]</sup>. The science of rheology can be employed for instance for achieving the following goals:

1. To understand the interactions between different ingredients in a material, in order to get an insight into its structure.
2. To control the quality of a raw material by measuring its rheological properties. The acceptance/rejection of a product can be determined based on rheological results.
3. To design a processing equipment such as selecting the appropriate pump to

provide enough power for a material to flow over a sufficient distance in pipelines. The relationship between the pump and flow in pipelines is governed by the rheological properties of the material.

If a force ( $F$ ) is applied to the top of an element as shown in Figure 1, it will produce a shear stresses ( $\tau$ ) expressed in the following equation:

$$\tau = \frac{F}{A} \tag{Eq. (1)}$$

From the solid mechanics theory, the internal resistance to deformation can be determined knowing the rigidity modulus ( $G$ ). As such, the relationship between the applied stress and the resulting strain is expressed in the following equation<sup>[13]</sup>:

$$\tau = G\gamma \tag{Eq. (2)}$$

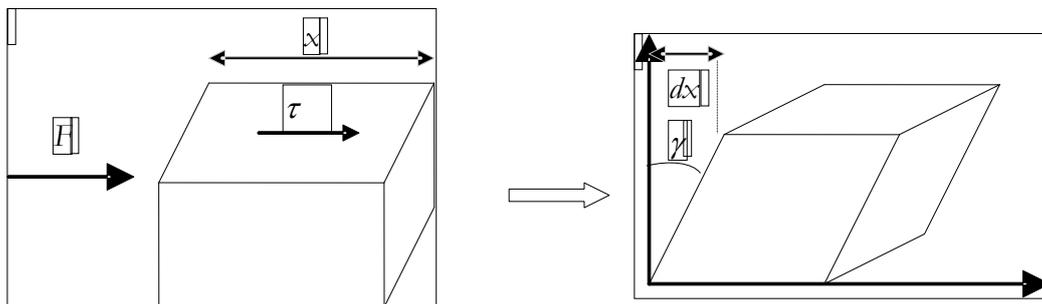


Fig. 1: Description of the Deformation of a Solid Element.

As shown in Figure 1, the applied stress will lead to a deformation ( $dx$ ) during the time period ( $dt$ ) of the applied stress. This deformation can also be expressed in terms of an angle  $\gamma$  (shear strain). The change in shear strain per unit time is<sup>[12]</sup>:

$$\dot{\gamma} = \frac{d\gamma}{dt} \tag{Eq. (3)}$$

If the shear stress is divided by the rate of shear, the viscosity term ( $\mu$ ) can be obtained:

$$\mu = \frac{\tau}{\dot{\gamma}} \tag{Eq. (4)}$$

The previous equation is the Newtonian model, which is the simplest rheological model. The viscosity is physically defined as the measure of the resistance to flow<sup>[14]</sup>. Several means have been used to study the rheology of materials by inducing shear stress. Shearing a material using two parallel plate geometry is shown in Figure 2 has been used to measure the viscosity of liquids. However, this geometry has encountered difficulty when used to test materials with low viscosity, since it is hard to hold such a material between the two plates.

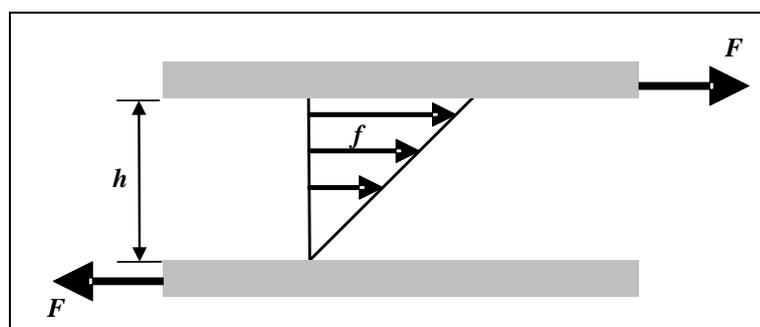
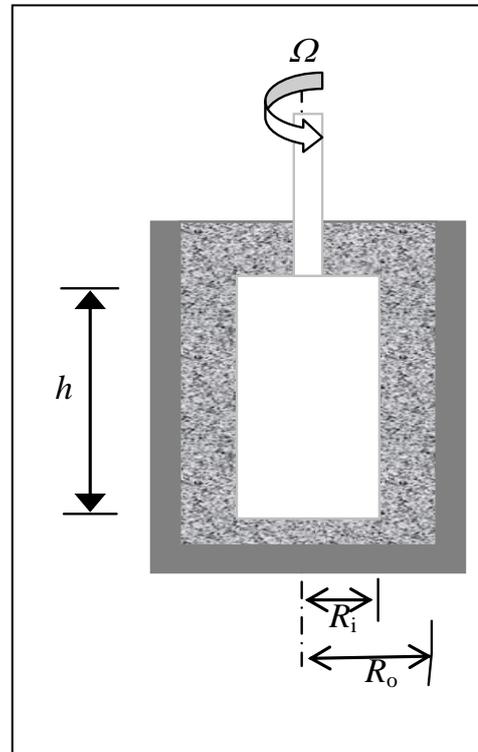


Fig. 2: Sketch of Coaxial Cylinder Geometry.

Using coaxial cylinder geometry is another tool to measure the rheological properties of materials. It is the most commonly used geometry to study the rheological behavior of fluids because the sample can be easily

placed in the gap between two cylinders and the material is sheared by rotating one of the cylinders. A schematic representation of this geometry is shown in Figure 3.



**Fig. 3:** Sketch of Coaxial Cylinder Geometry.

Assume, that a Newtonian fluid fills the annular gap between the two cylinders and the inner cylinder is stationary, while the outer cylinder is rotating at a constant angular velocity ( $\Omega$ ), the viscosity can be determined in the following equation<sup>[15]</sup>:

$$\mu = \frac{T}{4\pi h \Omega} \left( \frac{1}{R_i^2} - \frac{1}{R_o^2} \right) \quad \text{Eq. (5)}$$

Where,  $T$  (Nm) is the torque resistance,  $\Omega$  is the angular velocity of the outer cylinder (rad/s),  $h$  is the height of the inner cylinder (m),  $R_i$  is the radius of the inner cylinder (m), and  $R_o$  is the radius of the outer cylinder (m).

### Newtonian Fluid

Generally, fluids can be classified into two groups: Newtonian and non-Newtonian.

For Newtonian fluids (e.g., water), viscosity is independent of the shear rate and remains constant over the variation of the shear rate as shown in Figure 4. The Newtonian flow is the simplest form. It occurs as soon as the stress is applied, and the shear stress increases linearly with the shear rate. These fluids maintain laminar flow during the applied shear stress. The characteristics of the Newtonian flow behavior are summarized below<sup>[12]</sup>:

1. Viscosity does not change with the shear rate.
2. Viscosity is independent of the time of shearing.
3. Stresses in the Newtonian fluid will suddenly reach zero upon stopping the shearing.

However, whatever is the period of the resting time, when the shearing starts again,

the viscosity is as measured previously.

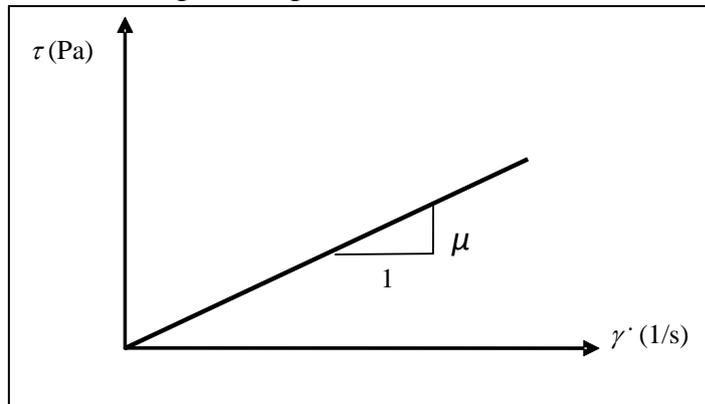


Fig. 4: Shear Stress Vs Shear Rate Curve for a Newtonian Fluid.

Fluids that show Newtonian flow behavior often have low molecular weights. For example, water, glycerol, petrol, and oils are some fluids that show Newtonian flow. Silicon oils are used as a calibration liquid for rheometers due to their reliability as a Newtonian liquid.

**Non-Newtonian Fluid**

The other group of fluids is known as Non-Newtonian fluids. Unlike Newtonian fluids, the viscosity of Non-Newtonian fluids depends on the applied shear rate and the time during which the shear rate is applied; this can be expressed as:

$$\mu = \mu(\dot{\gamma}, t) \tag{Eq. (6)}$$

The structure of time-dependent materials changes with time even if the applied shear rate is constant. Therefore, the viscosity of a flocculated suspension changes with time at a constant shear rate<sup>[15]</sup>.

A certain level of stress must first be overcome before a non-Newtonian fluid starts to flow. The presence of a critical stress means that under static conditions, a Non-Newtonian fluid essentially acts as a solid and will continue acting as a solid until the stress reaches the shear force needed to overcome the internal friction of the material. Bingham has accounted for

this behavior by introducing a yield stress parameter in his equation<sup>[16]</sup>:

$$\tau = \tau_o + \mu_p \dot{\gamma} \tag{Eq. (7)}$$

Where  $\tau_o$  is the yield stress (Pa) and  $\mu_p$  is the plastic viscosity (Pa.s). The measured yield stress value may vary for a given material if the test conditions change. For example, Nehdi and Rahman<sup>[17]</sup> found that the yield stress of cement paste varied if the type of the geometry used in the rheological test change. Roy and Asaga<sup>[18]</sup> noticed that the yield stress of the same concrete varied when mixing techniques change.

The fact that the viscosity depends on the shear rate means that the tested sample does not have a constant viscosity. Thus, the viscosity of a Non-Newtonian fluid is measured at a specified shear rate and is called apparent viscosity. Fluids with Non-Newtonian flow behavior can be further classified as shear thinning or shear thickening fluids. The Power-Law is a two parameter model for describing pseudo-plastic or shear-thickening behavior in materials that show negligible yield stress and a varying differential viscosity. The Power-Law model describes these two phenomenons in the following empirical equation<sup>[15]</sup>:

$$\tau = K \dot{\gamma}^n \tag{Eq. (8)}$$

Where  $K$  is the consistency index and its unit is the viscosity unit (Pa.s). When the flow behavior is shear thinning,  $n < 1$ , and  $n > 1$  for shear thickening behavior. For a Newtonian flow,  $n$  equals to 1.

### Yield Stress

Visco-elastic materials are those that behave as a solid when the applied shear force is not large enough to overcome the internal friction in such materials. When the applied shear stresses become greater than the internal friction, visco-elastic materials starts to flow which are driven by the force that is the result of difference between the applied and friction forces<sup>[16]</sup>. The critical applied stress, beyond which a material starts to flow, is called yield stress and is equal to the internal friction. The material is said to be at its elastic limit when the applied stress is equal to the yield value<sup>[16]</sup>.

The concept of yield stress has been highly debated among researchers. Bingham<sup>[16]</sup> reported the existence of the yield stress and observed that a certain shear force is required to overcome the internal friction of a visco-elastic material to initiate the flow. He further reported that if the shear stress of the flow is plotted against shear rate, a straight line for a given material is obtained, but it would not pass through the origin, and that the yield value is the distance between the origin and the intersection of the line with the shear stress axis.

Barnes and Walter<sup>[19]</sup> suggested that the yield stress is a myth and does not exist. They argued that the yield stress reported by previous researchers was merely the result of experimental limitations at low shear rates. They asserted that no one ever measured a yield stress, and they argued that new advanced instruments would spark off the existence of yield stress. They stated that if a material flows when it is subjected to high stress, it would also flow, however slowly, under low stress.

Several researchers disagreed with the conclusions of Barnes and Walters. Hartnett and Hu<sup>[20]</sup> took up the challenge and attempted to prove experimentally the engineering reality of the yield stress. They used a falling ball viscometer to experimentally test the conclusions of Barnes and Walters. The falling ball viscometer was used to determine the shear stress and shear rate of Non-Newtonian fluids. The procedure to determine these parameters is explained in their research. A nylon falling ball was placed in a falling ball viscometer containing an aqueous Carbopol solution. The downward movements were monitored by taking photographs for long periods of time in an attempt to demonstrate the absence of flow i.e., the existence of yield stress. They reported that no measurable motion of the ball was observed for several months, indicating that the yield stress is an engineering reality, and is not dependent on the rheological model<sup>[20]</sup>.

Astaria<sup>[21]</sup> wrote an article discussing the controversial conclusions of Barnes and Walters<sup>[19]</sup> and Hartnett and Hu<sup>[20]</sup>. Astaria adopted the idea of Hartnett and Hu<sup>[20]</sup> regarding the engineering reality of yield stress. Evans<sup>[22]</sup> stated that yield stress is an important engineering reality, although measuring an exact value of yield stress may be difficult due to equipment limitations. He suggested that the existence of an essentially horizontal region in a double-logarithmic plot of shear stress-shear rate is the most satisfactory proof for the existence of a yield stress.

The yield stress is influenced by the inter-particle forces. Particles equally charged repel electro-statically each other. If the attraction forces become greater than the repulsion forces, particles will remain together, resulting in a highly flocculated material<sup>[14]</sup>. Cement paste is normally flocculated and its yield stress is essentially the stress required to rupture the flocculated structure, initiating macroscopic flow<sup>[23]</sup>.

### Viscosity

Once flow is initiated, a Non-Newtonian particle suspension still tends to resist flow. The viscosity ( $\mu$ ) of a non-Newtonian fluid depends on the shear rate and this relationship can be represented by the following equation:

$$\mu = \frac{\tau}{\dot{\gamma}} \quad \text{Eq. (9)}$$

Where  $\tau$  is the shear stress required for the material to flow, and  $\dot{\gamma}$  is the shear rate. Viscosity is a measure of the resistance of a material to flow<sup>[12]</sup>.

When the volume fraction of a suspension becomes greater than 0.01, particles interact with each other, and start to enter the neighborhood of other particles, causing disturbance of the flow, which increases the viscosity<sup>[14]</sup>. Hydrodynamic interaction forces are developed as a result of the relative motion of the neighboring particles<sup>[14]</sup>. Bimodal suspensions (containing both colloidal and non-colloidal particles) generally display Non-Newtonian viscosity behavior characterized by a competition between viscous forces and colloidal forces. When a bimodal suspension is sheared, the effects of viscous forces become more significant. The effect of viscous forces relative to colloidal forces increases with the increasing shear rate resulting in a variation of viscosity over the shear rate<sup>[24]</sup>. The apparent viscosity (the viscosity at a certain shear rate) of bimodal suspensions may undergo a continuous decrease known as shear thinning, when the shear rate increases until it reaches a stationary value termed the high shear rate limit relative viscosity when viscous forces become dominant<sup>[24]</sup>.

The viscosity of a suspension is largely influenced by the concentration of solids, and therefore several models have been developed relating the viscosity to the volume fraction of solids in the suspension ( $\Phi$ ). Einstein in 1911 developed a model

relating the viscosity of dilute suspensions ( $\Phi < 0.03$ ) to the particle phase volume<sup>[12]</sup>. Einstein's equation neglected the effect of the interactions between particles and did not account for the variations of size, shape, and particle distribution.

$$\mu = \mu_s (1 + 2.5\phi) \quad \text{Eq. (10)}$$

Where  $\mu$  is the viscosity of the suspension and  $\mu_s$  is the viscosity of the suspending medium<sup>[12]</sup>. The particle phase volume is defined as the ratio between the volume fraction of particles in the suspension and the entire volume of the suspension.

Ball and Richmond (1980) developed a model assuming that the effect of all the particles in a concentrated suspension is the sum of the effect of particles added sequentially<sup>[12]</sup>. Based on this assumption, Einstein equation can be written in a differential form:

$$d\mu = (5\mu/2)d\phi \quad \text{Eq. (11)}$$

Where  $d\mu$  represent the increment of viscosity corresponding to the addition of a small volume  $d\Phi$ . The viscosity of the final suspension can be obtained by integrating the phase volume between 0 and  $\Phi$  and the resulting equation is:

$$\mu = \mu_s \exp(5\phi/2) \quad \text{Eq. (12)}$$

However, Ball and Richmond realized that the above equation did not account for the interaction between particles by neglecting the fact that when a particle is added to a relatively concentrated suspension it requires more space than its volume  $d\Phi$ .

Therefore, they replaced  $d\Phi$  with  $d\Phi / (1 - W\Phi)$  and the equation becomes<sup>[12]</sup>

$$\mu = \mu_s (1 - W\theta)^{-5/(2W)} \quad \text{Eq. (13)}$$

Where  $W$  represents "crowding effect". It can be observed that when  $\Phi = 1/W$  the viscosity becomes infinite, and therefore  $1/W$  is the maximum packing fraction ( $\Phi_m$ ).

Kreiger-Dougherty developed an equation for concentrated suspensions. The Kreiger-Dougherty equation accounts for the concentration, size distribution, and shape of particles and it takes the following form<sup>[25]</sup>:

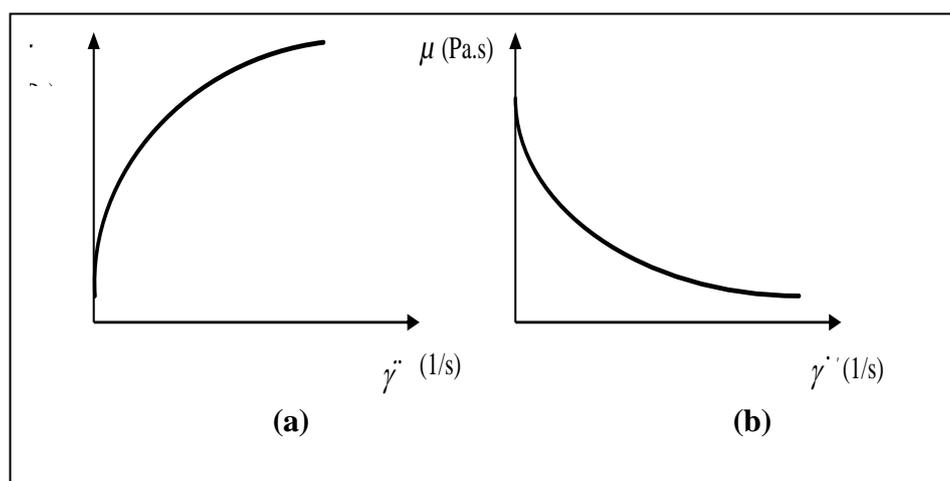
$$\mu = \mu_s \left( 1 - \frac{\phi}{\phi_m} \right)^{-[\mu]\phi_m} \quad \text{Eq. (14)}$$

Where  $\phi_m$  is maximum volume fraction or maximum packing density of solids and  $\mu$  is the intrinsic viscosity. The intrinsic viscosity is defined as the limiting value of viscosity when the concentration of particles in suspension approaches zero and it takes into account the shape of particles.

For example, the intrinsic viscosity for perfect spheres is 2.5, and it is higher for other shapes<sup>[26]</sup>. Szecsy achieved limited success when he implemented the Kreiger-Dougherty equation to calculate the viscosity of fresh concrete. He tried to optimize the Kreiger-Dougherty equation to better suit his experimental results. Although, Szecsy's optimized model gave a better prediction of concrete viscosity than the Kreiger-Dougherty equation, the predicted values were still far from the measured ones.

### Shear Thinning

Shear thinning materials, also called pseudo-plastic materials are characterized by a viscosity decrease with an increase of the shear rate<sup>[12]</sup>. For such materials, the exponent value of the power law model as depicted in Eq. (8) is less than 1 ( $n < 1$ ). In fluids containing particulate suspensions, laminar flow may orient the molecules or particles, reducing the resistance to flow<sup>[27]</sup>. Thus, the additional shear stress required to increase the shear rate by an increment decreases with increasing the shear rate. At rest, the particles of suspensions are flocculated. When sheared, the particles start to separate from each other, and shear thinning materials become less resistant to flow. The higher the shear rate, the more particles are separated, and therefore the less is the viscosity. Some suspensions have non-spherical particles which are arbitrarily arranged when suspensions are not disturbed. The non spherical particles will be oriented in the direction of flow and they become less resistant to flow resulting in decreasing viscosity. Cement suspensions can show shear thinning behavior when it flows. The characteristic diagrams of shear stress-shear rate and viscosity-shear rate of shear thinning fluids are presented in Fig 5.

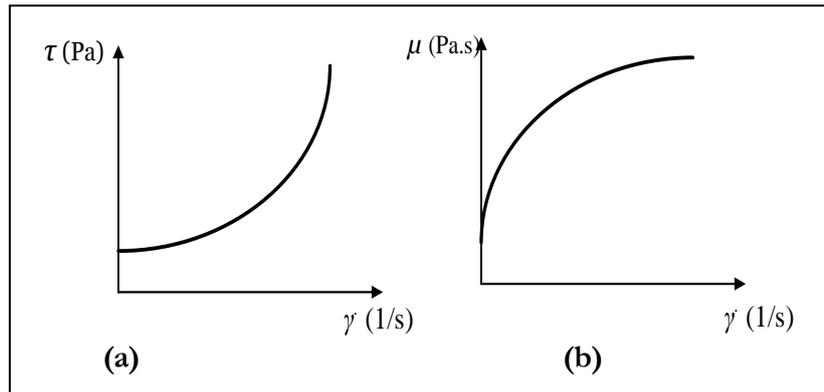


**Fig. 5:** Typical Shear Thinning Behavior: (a) Shear Stress Vs. Shear Rate and (b) Viscosity vs. Shear Rate.

### Shear Thickening

The shear thickening phenomenon, also known as Dilatancy, is often associated with suspensions of irregularly shaped particles in which the liquid exhibits an increase in volume when it is sheared. The viscosity of dilatant materials increases

with the increase of shear rate and the exponent value of the power law model as depicted in Eq. (8) is then higher than 1 ( $n > 1$ ). The microstructure of such materials will rearrange when sheared causing resistance to flow that increases with shear rate<sup>[12]</sup>. Figure 6 shows typical flow curves of a shear thickening fluid.



**Fig. 6:** Typical Shear Thickening Behavior: (a) Shear Stress Vs. Shear Rate, and (b) Viscosity vs. Shear Rate.

### Thixotropy

A thixotropic fluid is a fluid whose internal structure breaks down when sheared, and its internal structure will rebuild when the shear is discontinued. Thixotropic fluids show both shear thinning and time dependent behavior<sup>[28]</sup>. Thixotropy is due to the structure degradation resulting from rupturing flocks or linked particles when the material is sheared.

When the shearing stress is removed, the material structure rebuilds again and is eventually restored to its original condition<sup>[12]</sup>. The hysteresis loop is the standard test for the characterization of a thixotropic material. A hysteresis loop test is a shear sweep from low to high shear rate and back to low shear rate as represented in Figure 7.

If a material is thixotropic, the resulting two curves (up and down curves) do not coincide and the area enclosed between these two curves can be used to measure the degree of thixotropy. It should be noted that

the two successive tests are required to determine whether a material is thixotropic or not; a material is thixotropic when a loop is also obtained in the second test.

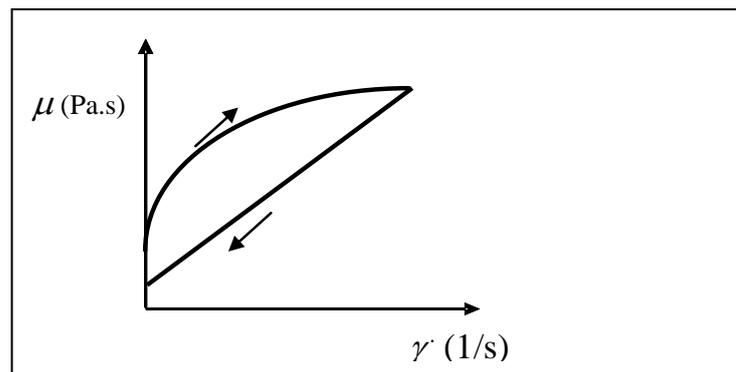
The opposite of thixotropy is called anti-thixotropy or rheopexy. Anti-thixotropy can be encountered for systems whose rate of structure recovery is accelerated by, for example, vibration, and therefore the buildup of structure due to such an effect is greater than the structure break down due to shearing. This phenomenon is also denoted as negative thixotropy, because the measured down-curve becomes higher than the up-curve, leading to a negative value of the enclosed area between these two curves<sup>[28]</sup>.

Many materials such as cement paste can display thixotropic behavior as well as rheopetic behavior. The nature and explanation of the reversible structure breakdown associated with cement paste is further discussed below.

### Cement Paste and Fresh Concrete Rheology

A cement powder is usually composed of a fraction of colloidal particles (less than  $2\ \mu\text{m}$  in diameter) and non-colloidal particles. Generally, about 20% by number of cement particles have a diameter less than  $2\ \mu\text{m}$  i.e., colloidal fraction<sup>[29]</sup>. Cement based materials (cement paste and concrete) are visco-elastic materials, since they behave like solids below a certain stress, and like a plastic fluid beyond the yield

stress. Concrete, for example, acts like a thick fluid and flows out of a concrete truck when enough energy is exerted on it. Cement paste can be considered as a suspension in which cement grains are the particles and water is the medium. Concrete can also be considered as a suspension, where the aggregates are the particles and cement paste is the medium.



*Fig. 7: Typical Hysteresis Loop of a Thixotropic Fluid.*

The yield stress of Portland cement suspensions is influenced by colloidal forces (i.e., Van der Waals attraction and electrostatic attraction/repulsion)<sup>[24]</sup>. The colloidal dispersion process is a result of the interaction forces between particles involving both repulsive and attractive inter-particle forces<sup>[30]</sup>. A weak coagulation takes place in the material when there is a suitable balance between the attraction forces (Van der Waals forces), the electrostatic and steric repulsion forces<sup>[28]</sup>. When the repulsive forces are greater than the attractive forces, particles will disperse to form a system of separated particles, and when the attractive forces are dominant, particles will flock to form a low-density deformable network of touching particles that prevents mass segregation<sup>[30]</sup>.

Cement-based materials rheology depends on inter-particle forces and the volume fraction of the suspension; they may follow the Newtonian law (viscosity is independent of shear rate) when their

particles are fully dispersed, and they exhibit pseudo-plastic, thixotropic behavior (viscosity decreases with increasing shear rate) when their particles are flocculated<sup>[31]</sup>. Chemical admixtures can be incorporated with cement paste to alter inter-particle forces including attractive Van der Waals forces, repulsive electrostatic and steric forces. Electrostatic repulsive forces develop when solute ions are attracted to medium particles to produce a system having particles with similarly charged particles.

On contrary, the steric forces are developed by the attached macromolecules on the surface of particles. These charged macromolecules can have both repulsive electrostatic and steric repulsive forces. Although, chemical admixtures have developed rapidly to improve the rheological properties of cement-based materials, the choice of the best admixture for a particular case is still a matter of trial and error using quality control tests such as Mini slump or Marsh flow tests.

## SUMMARY AND CONCLUSION

Hot weather may create problems for concrete during its mixing, placement, and curing, which can adversely affect the properties of fresh and hardened concrete. Most of these problems are due to the acceleration of cement hydration and the fast evaporation of mixing water at high temperature. The current practice to alleviate hot weather concreting problems such as adding cooled water or ice as part of the mixing water does not provide ideal solutions for hot weather concreting. Super-plasticizers can provide a potential solution for hot weather concreting problems since, they can improve the workability of cement-based materials while reducing the water to cement ratio.

However, such super-plasticizers have usually been developed in countries with mild temperature and their behavior when incorporated in concrete at high temperature has not been fully explored. As such, a super-plasticizer which behaves satisfactory when incorporated in concrete at mild temperature may give disappointing performance when used in hot weather.

Rheological characterization is a tool that can evaluate the rheology of cement-based materials. By examining a suspension of cement particles in water and/or a suspension of aggregate particles in a cement paste, one can apply well established rheological theories. Hence, producing good quality concrete by incorporating super-plasticizers at high temperature can be achieved by controlling its rheological properties. Yield stress, viscosity and the degree of thixotropy are crucial parameters that affect the rheology of cement-based materials.

Cement-based materials are visco-elastic materials which do not flow if the applied shear stress is low and cannot overcome the internal friction. They behave as solid-like materials when the applied stress is less than the yield stress and as a viscous fluid

when the applied stress exceeds the yield stress. When it flows, cement paste follows a shear thinning behavior due to the flocculated structure of its particles. The formation of flocks takes place due to the attractive (Van der Waals) forces between neighboring colloidal particles. Super-plasticizers are usually incorporated in cement-based materials to improve their flow at the fresh state by deflocculating their particles. However, substantial research work is needed to develop fundamental knowledge for the effective use of super-plasticizers in hot weather concreting.

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