GERMANN INSTRUMENTS A/S
Emdrupvej 102 - DK-2400 Copenhagen NV - Denmark
Phone: (+45) 39 67 71 17 - Fax: (+45) 39 67 31 67
E-mail: germann-eu@germann.org, Internet: www.germann.org
VAT # DK 89 43 57 14
Test Smart – Build Right

Rheology using the ICAR Plus – An Introduction

Overview

The aim of this document is to introduce the reader to rheology and with the ICAR Plus how it can be used to evaluate fresh concrete properties. The principles behind how the fresh concrete rheology is measured are described along with the parameters involved. How to control the rheology is also described in general terms. Finally, the thixotropic behavior of concrete is explained as well as how to evaluate this important characteristic. Hopefully the reader will become aware of the benefits of using rheology compared with empirical workability methods.

Importance of understanding concrete fresh properties

Concrete is a granular material with various fresh and hardened properties depending on the mixture proportions. Aside from the obvious importance of hardened concrete properties in terms of strength, durability, etc., fresh properties are very important in terms of the final result of different casting applications. For any given casting application, fresh concrete must flow in a certain way to fill the mold, encapsulate all reinforcements and other embedments, and create a dense structure.

The concrete’s resistance to flow is important since it determines how easy or difficult the casting operation will be. However, if concrete flows too readily it may prone to segregation. The term "stability" is used to describe the ability of a concrete to resist segregation, which results in a non-uniformity of concrete's constituent materials. The more difficult the concrete is to cast, or if it shows a lack of stability, the higher the risk of an improperly cast structure.

Basically, the performance of fresh concrete can be described using two different properties: its resistance to flow and its behavior when it is flowing. Both these properties influence the casting procedure and its result. Thus, for different applications, it is significant to design concrete mixtures to achieve optimum fresh properties. But how do we know when these properties have been achieved? There are various procedures to characterize fresh properties of concrete: empirical methods and scientific methods.

Empirical methods

Workability test methods are inherently empirical and often developed for specific applications. The most widely used method is measuring the slump of concrete using the Abrams cone. The slump value describes the ability of concrete to deform under the influence of gravity. However the slump test does not provide enough information about the flow behavior of fresh concrete. Many other test methods have been developed for various applications. Workability test methods deliver single point results and thus, cannot alone give a full picture of the fresh concrete properties needed to predict performance for different casting processes.

Scientific methods

Rheology is the science of the flow and deformation of matter (liquid or “soft” solid) under the effect of an applied force. The basic principle behind rheological measurements is to deform the material in a controlled way and simultaneously record the material’s resistance to such a deformation. There are different characteristic ways to deform a material in a controlled manner, and a few of them are shown in Fig. 1. The instruments used for rheological measurements are known as rheometers, and most commercial rheometers for concrete use concentric-cylinder or rotating-plate (plate-plate) geometries.

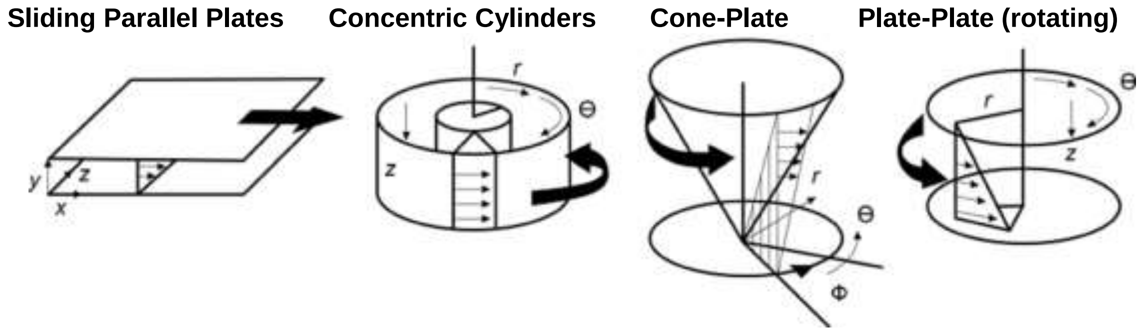


Fig. 1: Four examples of how to deform a material between two surfaces

For the ICAR Plus rheometer, the concentric cylinder geometry consists of an outer cylinder as the container and an inner cylinder such as the four-bladed vane shown in Fig. 2. The reason for replacing a perfectly cylindrical inner cylinder with the vane is to avoid slippage between the rotating inner cylinder surface and the fresh concrete. Another advantage of using the vane is that the action of inserting the vane into the specimen creates minimal disruption to the specimen, which is particularly important for thixotropic materials where shear history influences results. In addition, using a vane can make the whole system lighter in weight, and thus, portable such as the ICAR Plus rheometer (E. Koehler 2004).

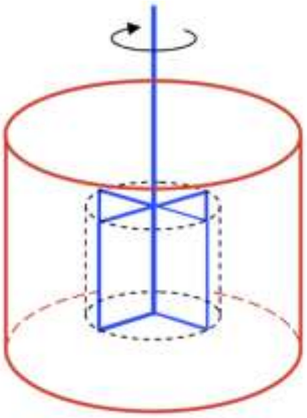


Fig. 2: The concentric cylinder geometry of the ICAR Plus

The use of a rheometer, as opposed to an empirical workability test method, allows one to establish the optimal fresh concrete properties for a particular application.

Rheological measurements and results by the ICAR plus

As described above, fresh concrete properties can be described as a resistance to flow and the behavior when concrete is flowing. In rheological terms, the resistance to flow is called **yield stress**, τ_0 (Pa), and the property controlling behavior during flow is called **plastic viscosity**, μ_{pl} (Pa.s). These parameters can be obtained from rheological tests, such as the Stress Growth Test and the Flow Curve with the ICAR Plus.

For a concentric-cylinder rheometer, the concrete is sheared in the gap between the cylinders and either the inner or the outer cylinder rotates while the other is stationary. Fig.3 shows how the system works in the ICAR Plus rheometer. The inner cylinder, represented by a 4-bladed vane, with a radius R_i (m) rotates while the outer cylinder with a radius R_o (m) is stationary. The rotation of the vane causes the fresh concrete in the gap between the outer cylinder and the vane to be plastically deformed at a rate depending on the rotational speed Ω (rad/s). This rate of plastic deformation is referred to as the **shear rate** $\dot{\gamma}$ (s^{-1}). During the plastic deformation of the concrete, the ICAR Plus rheometer simultaneously records the real rotational speed (rps) and the required torque, T (Nm) to maintain the target rotational speed.

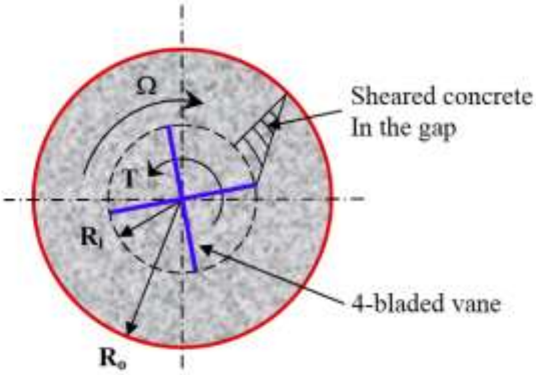
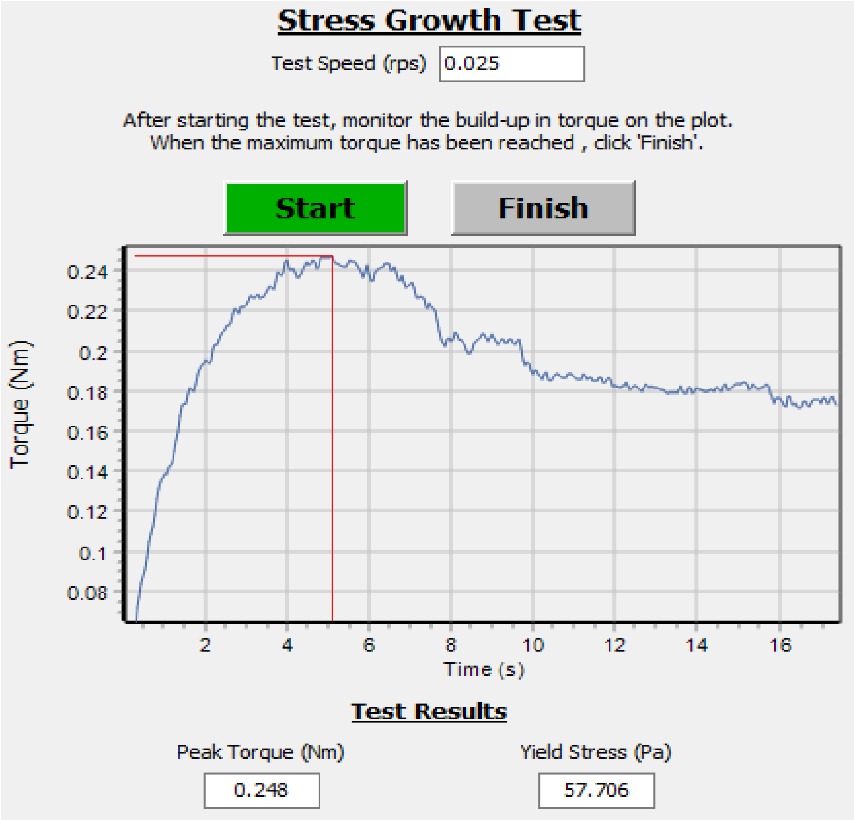


Fig. 3: Principle of a rheological test using ICAR Plus

As mentioned above, there are two major types of measurements for concrete rheology which can be performed by the ICAR plus: Stress Growth Test and Flow Curve Test. The choice of test depends on the rheological property required to be measured.

The Stress Growth Test involves rotating the vane to shear the concrete very slowly at a constant rotational speed and measure the torque. The maximum torque corresponds to the static yield stress, representing the stress needed to be overcome in order to initiate flow from a state of rest. The stress growth test is highly dependent on the shear history of the sample. A typical stress growth plot is shown in Fig. 4.



Stress Growth Test

Test Speed (rps) 0.025

After starting the test, monitor the build-up in torque on the plot.
When the maximum torque has been reached , click 'Finish'.

Test Results

Peak Torque (Nm) 0.248

Yield Stress (Pa) 57.706

Fig. 4: Stress Growth Test

The Flow Curve Test measures the relationship between shear stress and shear rate and computes the Bingham parameters of yield stress and plastic viscosity. The yield stress here is the dynamic yield stress, which is the stress obtained when the rate of deformation slows down from high to low values. Thus it is the stress needed to maintain flow, which correlates to concrete slump values or SCC slump-flow values. In the Flow Curve Test, the rotational speed is normally increased from zero to a relatively high value where it is maintained long enough in order to break down any thixotropic structure. Such a configuration is shown in Fig. 5 where the curve representing rotational speed is marked blue. After this initial and high level, the rotational speed is then decreased stepwise and each step is maintained for sufficient time so that the resulting torque (red curve in Fig. 5) levels out to an equilibrium value before the speed is reduced to the next step.

A graph can now be created by plotting the equilibrium torques values at each speed on the y-axis and the rotational speeds on the x-axis, as shown in Fig. 6. For a flow curve test of concrete, the most common response is linear with the Y-value as the intercept on the torque-axis and the V-value as the slope of the line.

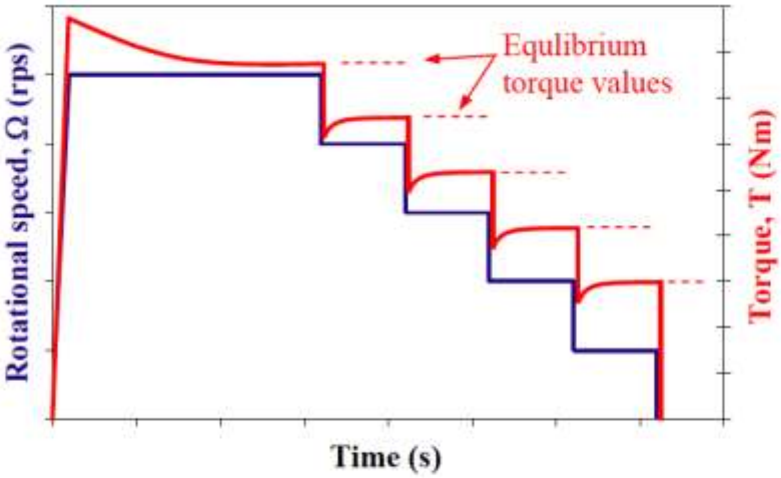


Fig. 5: Typical variation of rotational speed (Ω) with time for concentric-cylinder rheometer

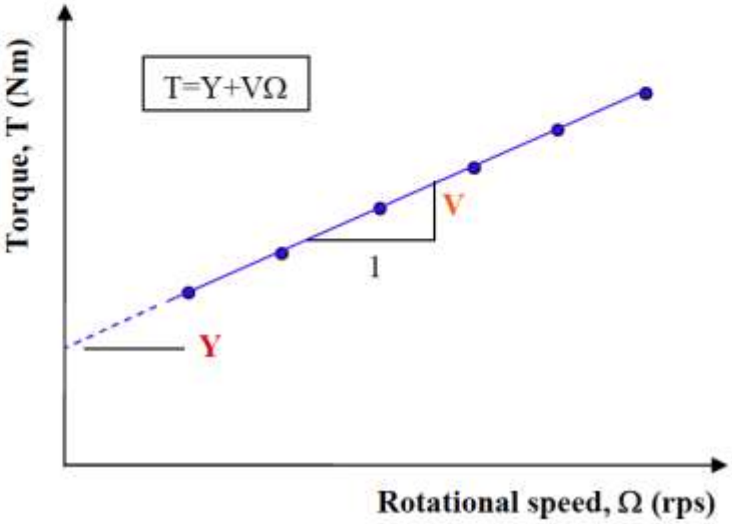


Fig. 6: How the Y-value and V-value parameters are obtained in a flow curve test

Relating back to fresh concrete properties, the Y-value represents the resistance to flow while the V-value represents the behavior once the concrete is flowing. A high Y-value means that the resistance to flow is high, and if exemplified by the slump test, it means a low slump value, or if exemplified by the slump-flow test for SCC (ASTM Standard C1611 / C1611M), it means a lower slump-flow spread. A high V-value means that a conventional concrete will flow slowly when vibrated and will often be described as "sticky." For self-compacting concrete (SCC), it would mean a slow concrete flow when placed in a form, corresponding to a high t_{500}- value (ASTM Standard C1611 / C1611M) when slump flow is measured (where t_{500} is the time to reach a spread of 500 mm after the cone is lifted).

Various models have been developed to idealize flow curves associated with concrete such as Casson, Herschel-Bulkley, Bingham, Power Law, Newtonian, etc. However, the model most commonly used is the Bingham because of a its accuracy in representing most concrete mixtures and its simplicity in only requiring the determination of two parameters, yield stress and plastic viscosity (Koehler 2004). Thus using the Bingham model, the ICAR Plus software converts the Y- and V-values into the fundamental properties of yield stress, τ_0 (Pa), and plastic viscosity, μ_{pl} (Pa s). By doing so, the plot in Fig. 6 becomes the plot shown in Fig. 7. The torque is replaced by shear stress, τ (Pa), and rotational speed is replaced by the shear rate, $\dot{\gamma}$ (s^{-1}). The equation that describes the Bingham Model can be found in Fig. 7.

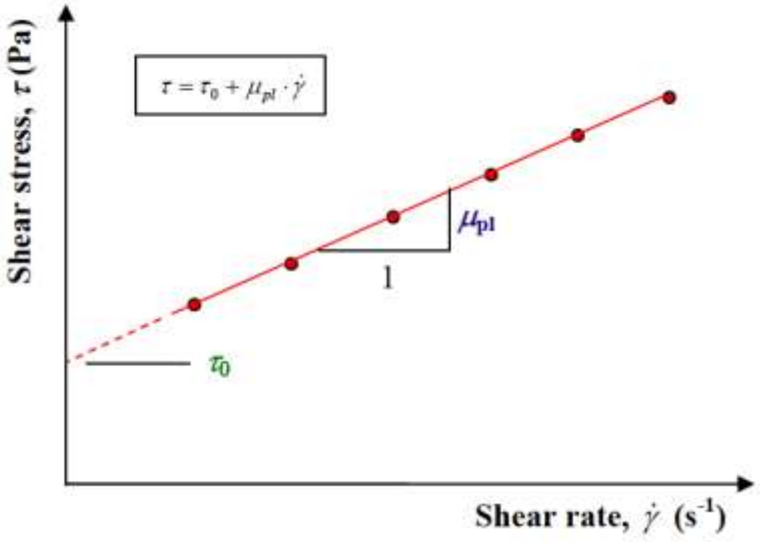


Fig. 7: Fundamental rheology parameters yield stress, τ_0 (Pa),
and plastic viscosity, μ_{pl} (Pa·s), for the Bingham model

Using rheology results

Instead of developing an empirical workability test method for a given application, the scientific way of characterizing concrete rheology is to create target boxes in a diagram with yield stress on the y-axis and plastic viscosity on the x-axis. Examples of such target boxes are shown in Fig. 8. Each target box represents a specific application and shows combinations of yield stress and plastic viscosity that indicates its workability (E. Koehler 2009).

If, by experience, a concrete that works perfectly for a given application is known, then its rheology could be measured. If the acceptable variations for this concrete in terms of yield stress and plastic viscosity are determined, the target box for this application can be formed. Otherwise, target boxes developed by others, can be used.

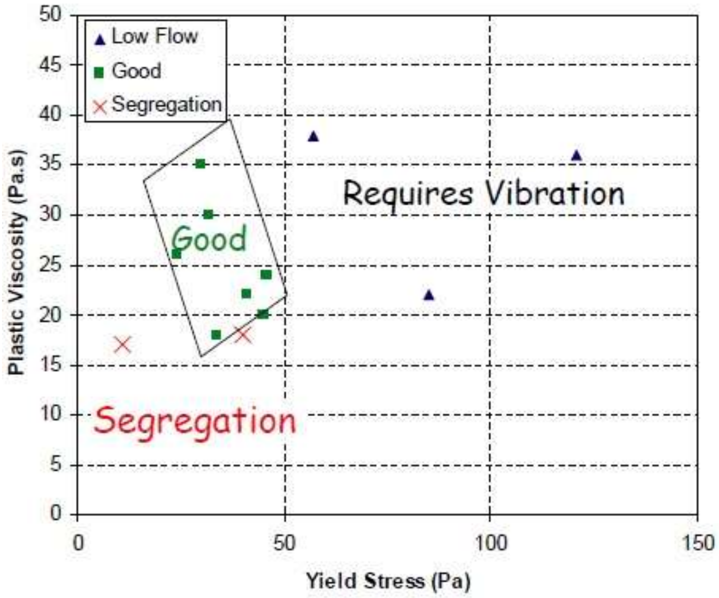


Fig. 8: Workability for self-compacting concrete

There are 3 types of self-compacting concrete (SCC):

- Semi-SCC is an extremely low-viscosity concrete with a certain yield stress. It can be placed readily with little effort and the yield stress secures stability.
- SCC-I has higher viscosity and lower yield stress and is best for horizontal castings.
- SCC-II has a very low yield stress and a higher plastic viscosity for stability and is suitable for vertical and slender structures like walls and columns.

Controlling fresh concrete rheology

Fresh concrete rheology is affected by small changes in the amount or the properties of its constituent materials. If the rheological effects of these changes or materials are known, concrete rheology can be controlled systematically. In Fig. 9, a few of the principal ways of steering the rheology in different directions are shown.

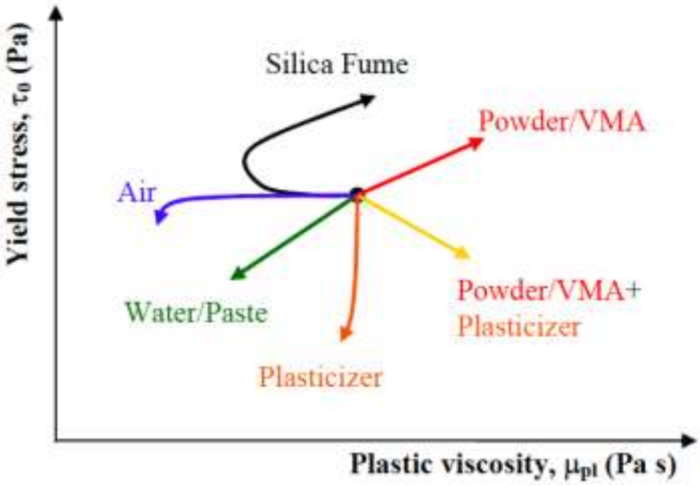


Fig. 9: Principal ways to control the rheology of a concrete mixture

Without going too deeply into the mechanisms, the effects can be explained as follows:

- Adding a fine powder or a suitable viscosity modifying admixture (VMA) binds water and increases the yield stress. The increased particle concentration increases the viscosity.
- Silica fume and entrained air act as roller bearings that reduce the viscosity. Too much silica fume, however, increases yield stress because it binds water.
- Increasing the water or paste volume dilutes the concrete and reduces both yield stress and plastic viscosity.
- Adding plasticizer or superplasticizer disperses fine particle and releases entrapped water. The consequence is a reduced yield stress and some reduction in plastic viscosity.

Naturally, the direction and length of the arrows strictly depend on the specific materials used.

By using knowledge regarding effects on rheology, depending on the material at hand, it is possible to steer concrete rheology into any desired target box. Fig. 10 shows a few examples of how to do this. If we have a concrete represented by the black bullet marked “REF” and we want to create an SCC mixture for walls or columns (SCC-II), one way of doing so is by adding a powder material to increase plastic viscosity. By doing this, the concrete stiffens and we need to add a superplasticizer to reduce the yield stress. Note that a higher plastic viscosity is desired to mitigate segregation. Adding a powder material also increases the paste volume which contributes to a lower yield stress. If instead, we desire a conventional concrete for bridge decks, we want to reduce the plastic viscosity to improve finishability. Many times, a frost-resistant concrete is required, and by adding an air-entraining admixture (AEA) the plastic viscosity is lowered. In addition, we can add a small amount of silica fume to further reduce the plastic viscosity.

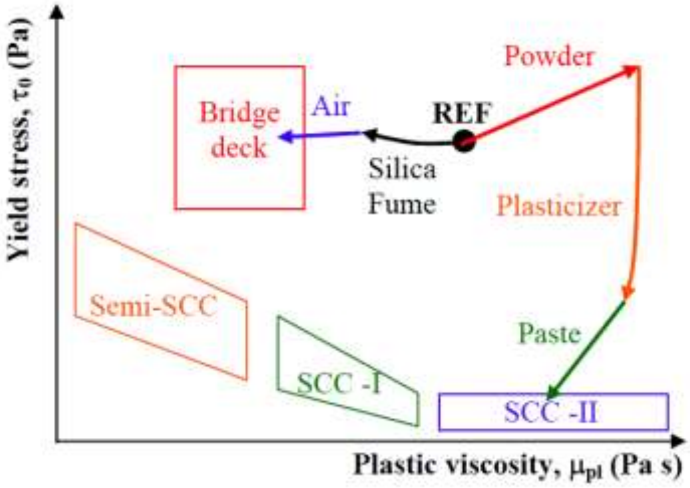


Fig. 10: Examples of how to steer concrete rheology into a specific target box

Thixotropy and structural build-up test

All concrete mixtures are thixotropic to various degrees. This means that even if they are very fluid while being processed (mixed, transported, pumped, and placed into the form) they stiffen with time while at rest. Part of the stiffening is reversible, which means that after resting fluidity can be restored by stirring or mixing the concrete. But concrete also stiffens irreversibly with time due to hydration, which is referred to as slump-loss. The sum of both processes is called structural buildup at rest and this aspect of concrete, especially for SCC, is very important. How the degree of structural build-up affects form pressure can be exemplified by the analytical equation developed by Ovarlez and Roussel 2006:

$$P_{max} = \rho g H - \frac{H^2 A_{thix}}{eR}$$

where ρ is the concrete density (kg/m³), g is the gravitational acceleration (m/s²), H is the concrete height (m), A_{thix} is the structural build-up (Pa/s), R is the placement rate (m/h) and e is the form width (m).

Also, the casting procedure is affected by the structural build-up. The faster and stronger the structural build-up at rest, the lower will be the resulting form pressure. But if SCC is cast in layers, stiffening requires that the time between castings of the layers be reduced depending on the rate of structural build-up. If too long a time passes between layers, they will not intermix but will instead cause a crack-like construction joint. Besides the obvious aesthetic problems associated with crack like surface defects, the joint can also influence the mechanical properties of the structure.

In the Stress Growth Test, the ICAR Plus rheometer measures the structural build-up at rest by shearing the concrete very slowly at a constant rotational speed and measuring the torque. The concrete in the rheometer is left at rest for a certain time, often 10-15 minutes, after which the slow deformation rate is begun. A typical response in terms of shear stress versus strain for a constant low strain rate is shown in Fig. 11. The increase of shear stress due to the increased shear strain is recorded, and after a few seconds of nearly linear increase of the stress (1), a peak shear stress value (2) is reached. This value is referred to as the static yield stress, τ_S (Pa). In order not to disturb the structural build-up too much, it is recommended to stop the rotation as quickly as possible after the peak value is reached. Fig. 11, however, shows the gradual structural breakdown (3) if the strain rate is continued, down to an equilibrium shear stress (4) that corresponds to the applied rate of strain.

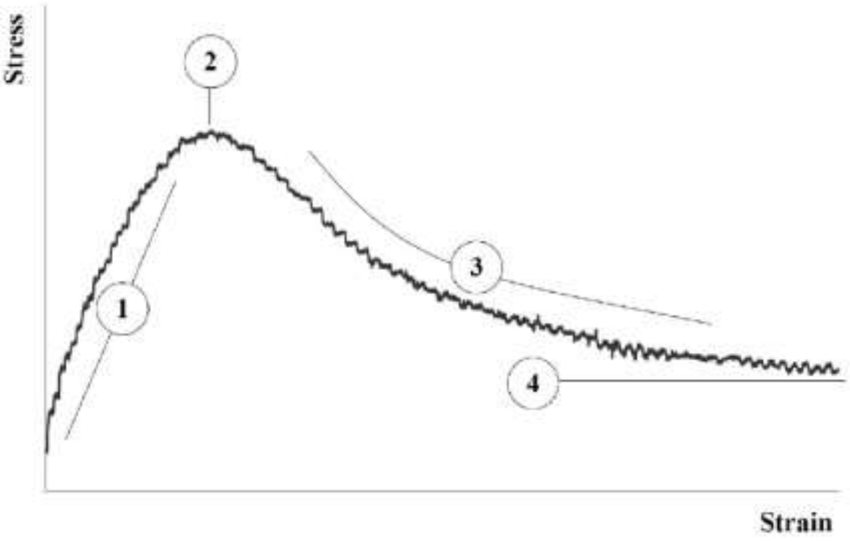


Fig. 11: Stress response of a concrete due to a small, constant strain rate

The concrete is then left at rest another 10-15 minutes, after which the stress-growth test is repeated. If this procedure is followed up to around one hour, the response is, in most cases, a linear increase of the static yield stress with time. The slope of the line is the structural build-up, $\dot{\tau}_S$ (Pa/s) or A_{thix} (Pa/s). Fig. 12 shows results from repeated stress-growth tests on three different SCC mixtures. In this case, the variation between the mixtures was the particle concentration in the paste phase. The unit for the x-axis, WAT+, represents time after water and cement are initially intermixed.

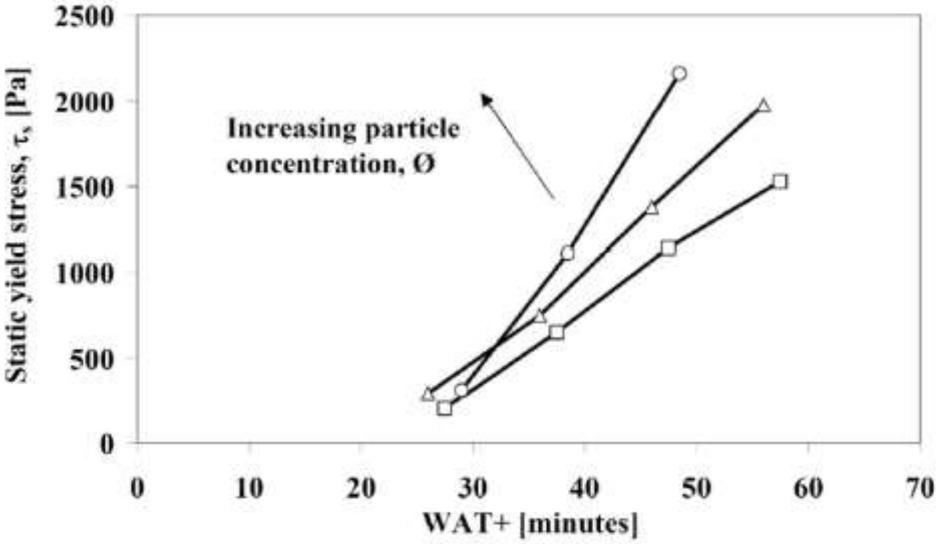


Fig. 12: Linear increase of static yield stress of three SCC mixtures

Concluding remarks

The purpose of this brief document has been to introduce the reader to the science of rheology and how it can be used to characterize the fundamental properties of fresh concrete. Empirical workability test methods are often simple and portable, which is an advantage. However, they lack the ability to capture both of the key parameters characterizing fresh concrete: resistance to flow, and once this resistance is overcome, how it flows. That is why rheological measurements are superior to workability methods. And with the ICAR Plus rheometer, manufactured and sold by Germann Instruments, shown in Fig. 13, simplicity and portability are also fulfilled. We have discussed various topics in which the rheological characterization of fresh concrete is important:

- Creating and using rheology target boxes for different applications
- How to control the concrete rheology and steer it into the desired target boxes
- Structural build-up at rest of SCC, which is important in terms of form pressure and casting procedures

Fig. 13: ICAR Plus Rheometer

Germann Instruments offers consultancy guidance on the use of the ICAR Plus rheometer to improve concrete mixture design and quality control.

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