A contribution from ACI Committee 238, Workability of Fresh Concrete

Role of Rheology in Achieving Successful Concrete Performance

Properties must be balanced to manage segregation, surface finish, pumping pressure, or formwork pressure

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This article provides a basic introduction to concrete rheology, as well as some insight into how rheology can be applicable to concrete construction. The fresh state performance of concrete is not only important for proper concrete placement and finishing but also for its hardened state properties. Yet, the most commonly used workability test methods are based on empirical methodologies, such as slump tests. Even self-consolidating concrete (SCC), which is governed by the property of flowing under its own weight,[1] is typically classified based on the results of empirical tests such as slump flow, V-funnel, L-box, and J-ring tests. To improve quality control and performance of concrete, workability measurements based on fundamental principles instead of empirical tests are pertinent.

Rheology is the science that seeks to characterize the flow and deformation of materials using fundamental principles of stresses and shear rates. Similar to how the hardened state mechanical properties of concrete are characterized by stresses and strains, rheology provides the user a way to objectively and quantitatively assess the fresh state properties of concrete by relating the shear stresses and shear rates.[2] Furthermore, rheology is a science that can be applied to various cement-based systems, including but not limited to grouts, SCC, fiber-reinforced concrete, and traditionally vibrated concrete.

This introduction to concrete rheology begins with a listing of basic terminology (refer to the textbox), and is followed by explanations of typical measuring instruments and testing procedures used to determine rheological properties. The concepts of rheology are then further applied to five different practical applications: mixture design and quality control, segregation, pumping, formwork pressure, and surface finish.

Measurement Tools and Procedures

Tools and devices

Rotational shear rheometers are standard equipment used to characterize the rheological properties of fluids. Such equipment is commonly used in asphalt binder testing laboratories (state, federal agencies, and producers); for example, refer to ASTM D7175[13] and AASHTO T 315.[14] These devices apply continuous shear to the sample through rotational movement at controlled torque or speed. Rheometers for concrete must be specifically designed due to the large particle size of the aggregates. Most geometrical configurations for concrete rheometers are based on coaxial cylinders shown in Fig. 2(a). The coaxial cylinder geometry consists of an inner cylinder (a bob) inserted into an outer cylinder (a cup). Various geometries can be used for the bob, including but not limited to a solid cylinder,[16] vane,[17] and a double spiral.[18] The vane and double-spiral geometries can be used in place of the inner cylinder of a coaxial cylinder rheometer to prevent slippage.[19] Another commonly used rheometer geometry for concrete is the parallel plate, as shown in Fig. 2(b).[20,21] The surfaces of the coaxial cylinder and parallel plate should be textured or roughened to prevent slippage between the concrete and rheometer surface.[21] Concrete rheometers have been used on various types of concrete classes (for example, SCC and fiber-reinforced concrete), but are not well-suited for stiff concretes (for example, zero-inch slump concrete).

Although rotational concrete rheometers have been successfully used to measure concrete rheology, a series of tests has shown that results from different rheometers do not agree with each other in absolute terms, caused by differences in experimental techniques and instruments.[22-24] Nevertheless, these results have been shown to rank different mixtures in a

Terminology

Rheology—the science of flow and deformation of matter.[2] For fluids, relationships can be described by plotting the shear stress versus the shear rate.

Bingham model—a linear approximation of the shear stress-shear rate relationship of a material or fluid (Fig. 1), described by two material parameters: yield stress and plastic viscosity. Most cement-based materials can be described as Bingham materials that follow this model. The Bingham yield stress, or dynamic yield stress, of cement-based materials is related to the slump[3,4] or slump flow.[5]

Yield stress—the stress required to initiate material flow. Typically, two types of yield stresses are considered:

- **Static yield stress**—the stress required to transition from a solid-like to a liquid-like behavior (going from rest to flow)—that is, starting from a static state and going to a dynamic state. As most cementitious materials exhibit thixotropy, the static yield stress increases over time[6,7]; and
- **Dynamic yield stress**—typically taken as the apparent stress where the material transitions from a liquid-like behavior to a solid-like behavior (going from flow to rest). The dynamic yield stress is an extrapolated value based on the flow curve (shear stress versus shear rate) and is often based on measurements performed on the "down" flow curve (the shear stress-shear rate curve obtained from measurements in which the shear rate is decreased from a high shear rate to a low shear rate; shown in Fig. 1).

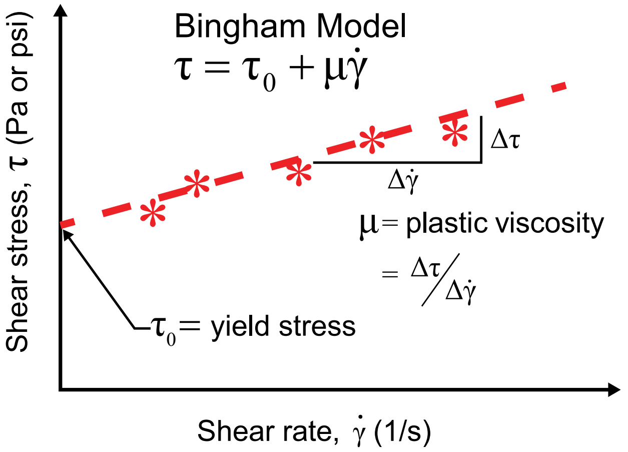

Fig. 1: Representation of Bingham model. The stars represent experimentally determined data points that are approximated using a straight line

Viscosity—a measure of a material's resistance to flow after flow is initiated. The higher the viscosity, the higher the material's resistance to flow. This term is generally used to describe materials that show liquid-like behavior and it provides a way to fundamentally quantify the "measure of the resistance of a fluid to deform under shear stress."[8]

- **Plastic viscosity**—the slope of the shear stress-shear rate relationship as described by the Bingham model (Fig. 1).

Thixotropy—the reversible material stiffening with time of the material at rest, and its ability to refluidize when sheared.[9,10] Per definition, thixotropy has a physical nature due to particle agglomeration[11,12] and it is not the same as stiffening due to hydration, which is chemical in nature. Cement-based materials are more complicated than ideal Bingham materials because the rheological properties of cement-based materials will also vary with time.

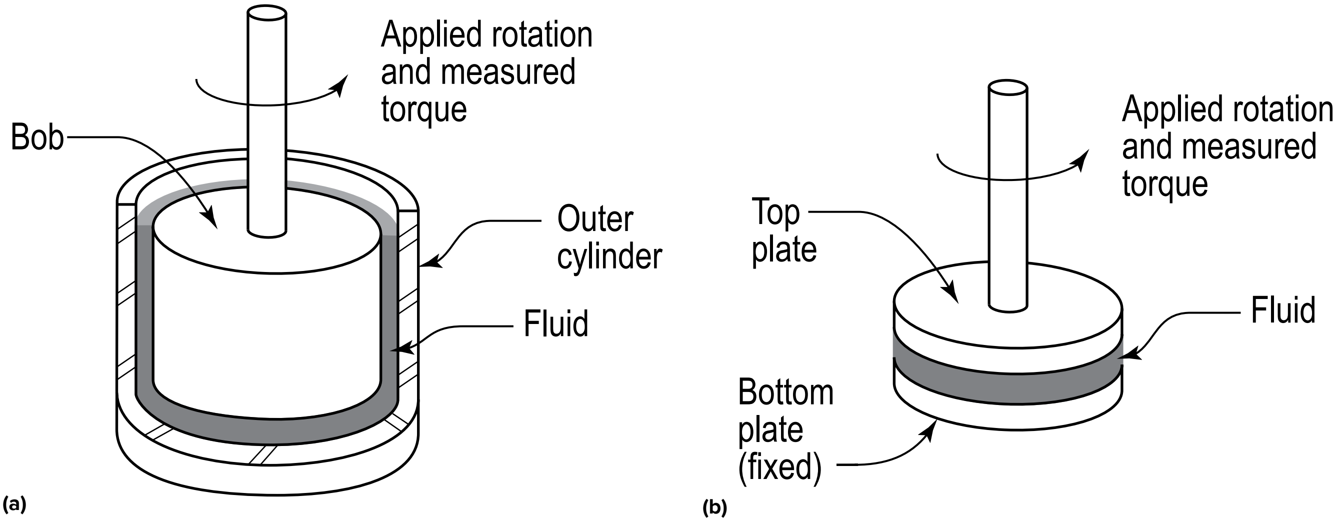

Fig. 2: Typical rheometer configurations: (a) coaxial cylinders; and (b) parallel plates (adapted from Reference 15)

similar fashion. Another way to compare results from different rheometers would be to calculate relative plastic viscosity as described in Ferraris and Martys.[25] To enable more meaningful comparisons among laboratories and their rheometer, efforts are underway at the National Institute of Standards and Technology (NIST) to develop a standard reference material (SRM) that would be used to calibrate the rheometers.[26,27] RILEM Technical Committee 266-MRP, Measuring Rheological Properties of Cement-based Materials, is in the process of developing guidelines for the use of rheometers in characterizing cementitious materials. Also, ASTM C1749[28] provides guidelines to use rheometers to measure paste.

Procedures

There are two major types of measurements for concrete rheology: the flow curve test and the stress growth test. The choice of test depends on the rheological property required to be measured.

Flow curve test

A flow curve test is performed by shearing concrete at different shear rates and measuring the resistance to flow. In most cases, a constant, high rate of shear is initially applied to bring the sample to a reference state to normalize the effects of thixotropy on the measured shear stress.[29-31] The shear rate is then decreased in increments and the corresponding torsional resistance values are converted into shear stresses. Because the data are taken at decreasing shear rates, the results are often referred to as the down curve. As shown in Fig. 1, if the data are fitted with a linear function, the intercept is the Bingham yield stress (dynamic yield stress) and the slope is the plastic viscosity.

Stress growth test

The stress growth test is used to determine static yield stress (going from rest to flow), and how this property increases with resting time. The static yield stress at rest is the consequence of workability loss, which includes thixotropy, hydration, and other factors. The test is performed with a rheometer by applying very low shear rate to concrete initially at rest, increasing the strain until the concrete begins to flow (yield). The maximum shear stress from the shear stress versus shear strain (or time) plot is equal to the static yield stress, as shown in Fig. 3. The static yield stress is dependent on the shear rate or strain applied. These parameters need to be selected carefully to minimize the effect of the material setting evolution on the measurement of the static yield stress.[32]

Implications of Inappropriate Rheological Properties

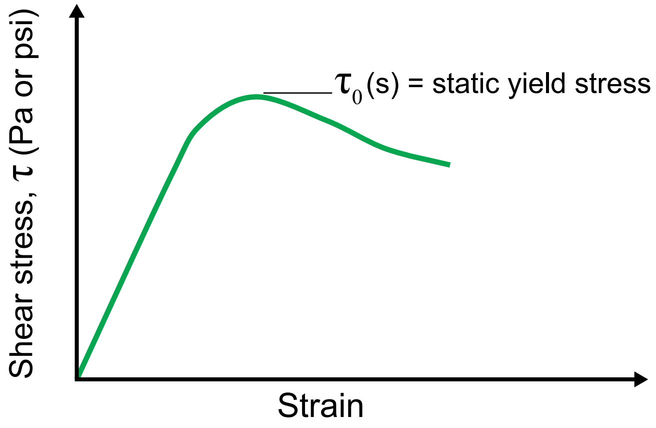

Fig. 3: The stress growth test is used to determine the static yield stress

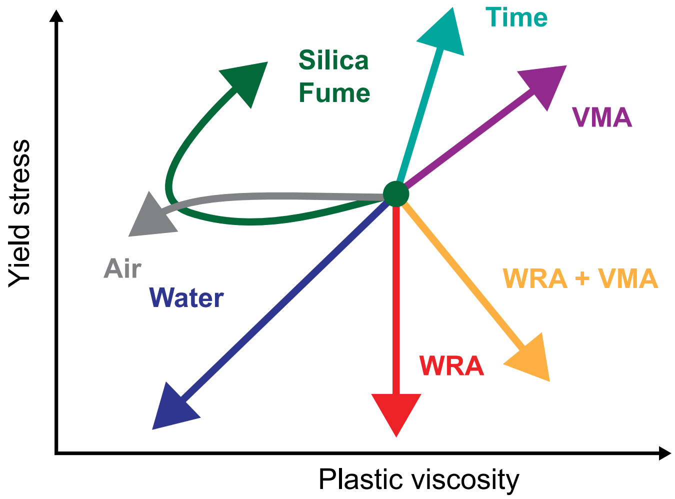

Fig. 4: The effect of an increase in specific constituent materials on concrete rheological properties (adapted from Reference 35)

In the applications discussed herein, rheological properties are tailored through the mixture design process. Nearly all aspects of the mixture proportions, including powder content, water-cementitious materials ratio (*w*/*cm*), supplementary cementitious materials (SCMs) content, aggregate properties and content, and admixtures play an important role in concrete rheology. Yield stress and plastic viscosity of the paste increase as *w*/*cm* decreases and as the cement becomes finer.[33,34] These properties are further modified (up or down) by the incorporation of SCMs. Due to the incorporation of aggregate, the yield stress of concrete is higher than that of the paste alone. Aggregate angularity, surface texture, maximum particle size, gradation, packing, and content can all have a significant effect on the viscosity and yield stress of concrete. Admixtures such as viscosity-modifying agents (VMAs) and water-reducing admixtures (WRAs)—normal-, mid-, and high-range—can also enhance placement, consolidation, and finishability of concrete and even increase thixotropy without the need to adjust the water content. Figure 4 summarizes some of the general effects that different components can have on properties. For example, increasing the water content can decrease both the yield stress and plastic viscosity. On the other hand, the use of a low dosage of silica fume can decrease viscosity, while higher dosages can lead to increase in both yield stress and viscosity. It should be noted that, except for the WRA + VMA behavior, Fig. 4 shows the effect of individual components only and does not consider the interactions between multiple components added. The synergistic effect of adding WRA and VMA to a mixture will depend on the dosages and types of the admixtures employed; thus, the WRA + VMA line shown in Fig. 4 is for illustrative purposes and should not be interpreted as indicating, for example, that a WRA has a greater effect on plastic viscosity than a VMA.

Limiting variations in concrete properties for a job requiring high volumes of concrete can present a difficult challenge. Thus, once a mixture proportion has been approved for a project, implementing a continual quality control process is crucial. Rheometers that are more rugged and designed for field use are available to accurately quantify and monitor the concrete performance during processing (mixing, pumping, casting, finishing, and so on). Frequent monitoring of the rheological properties not only serves to ensure that the proper concrete is being placed but also acts to inform the batch plant if changes are necessary and in what direction the changes need to be made. However, in situations where one does not have access to a field rheometer, effort should be made to characterize the rheological properties of the mixture in the lab and then correlate those rheological properties with the field-friendly workability test method(s) that will be used on the jobsite. In the following sections, specific applications will be highlighted to show the influence of rheological properties on the performance and quality of concrete.

Segregation

In many concrete applications, increased flowability facilitates placing and finishing, but increasing the flowability beyond the capabilities of a particular mixture design can result in segregation. Segregation leads to a mixture that is not homogenous and may hinder mechanical properties and reduce the service life of concrete. Segregation can be observed in different forms whether it is the aggregate migrating within the paste or mortar phase, or excessive amount of the water phase of the cement paste migrating to the surface of the concrete (for example, bleeding).

The yield stress of the suspending matrix (typically that of the paste or mortar phase)[36] is a key rheological parameter to ensure that a concrete mixture would have adequate segregation resistance. The magnitude of the desired yield stress will depend on the application; however, the yield stress alone of the suspending liquid (paste or mortar) may not be sufficient to keep the fine and coarse aggregate particles suspended in the paste or mortar, respectively. An elevated plastic viscosity of the suspending liquid can slow down the segregation. Additionally, if the concrete is at rest, the yield stress increases due to thixotropy limiting further migration of the aggregates. In this way, if a low yield stress concrete is designed, a relatively high viscosity and thixotropy is necessary to minimize segregation effects.[35]

Common approaches to modify yield stress and viscosity include varying dosages or types of fines (such as limestone powder), SCMs,[37-39] and use of chemical admixtures.[40-42] Additionally, decreasing the maximum aggregate size helps decrease segregation,[29] and having a well-graded aggregate packing creates an enhanced particle lattice effect (smaller particles holding larger ones in position) that can help keep aggregates suspended.[43,44]

Pumpability

Two major problems can occur during concrete pumping. The first problem is blockage during start-up, which is mostly the consequence of a nonpumpable mixture design (usually a result of a high coarse aggregate fraction) or inappropriate selection or preparation of the pumpline (lack of or inadequate priming).[45] The second problem is excessive pressure during pumping, which can be caused by high flow rates, small pipes, or inappropriate rheological properties of the concrete.

Although the velocity profile in concrete during pumping is complex, as particles move to form the lubrication layer near the pipe wall,[46] relatively simple correlations between pumping pressure and plastic viscosity have been proposed.[47] The lower the viscosity of the concrete, the lower the pressure needed to pump (Fig. 5). If the viscosity is low, pumping pressure can increase when the yield stress increases (slump or slump flow decreases).[48] It was shown that, in most cases,

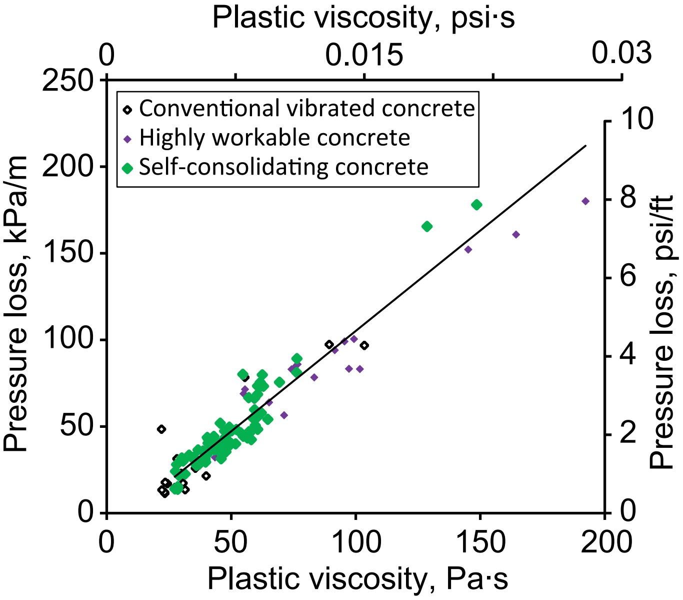

Fig. 5: The pressure loss (expressed per unit length of straight pipe, 100 mm [4 in.] in diameter at a flow rate of 8 L/s [2 gal./s]) is well correlated to the plastic viscosity of concrete, as shown above for three concrete types with widely varying workabilities (adapted from Reference 51)

viscosity is more dominant than yield stress to determine pumpability.[49]

The most significant way to reduce pressure during pumping is by enlarging the pipe diameter. Increasing the pipe diameter from 4 to 5 in. (100 to 125 mm) can roughly decrease pumping pressure by a factor of two.[50] Decreasing the flow rate and/or viscosity of the concrete are other alternatives to reduce pumping pressure. For conventional concrete, decreasing the yield stress (increasing the slump) can also reduce pressure.[44]

It should be noted, however, that the actual flow behavior in pipes is more complex. The reader is referred to recent, extensive studies on the characterization of the lubrication layer for more information.[49,51]

Formwork pressure

In placing conventional concrete within formwork (and in general), vibration is required to achieve proper consolidation. As the vibration is applied, yield stress is lowered, allowing consolidation to occur. When the vibration is removed, the high thixotropic nature of normal concrete restores the high yield stress. Although the high yield stress of conventional concrete is responsible for requiring vibration, the high yield stress combined with high thixotropy is advantageous because it also results in low formwork pressure.[12]

SCC is a highly flowable concrete. However, an SCC mixture must be capable of handling high flow while providing adequate segregation resistance. Because of its high flowability, SCC does not require any external vibration to consolidate it; thus, faster casting rates can be achieved during construction. However, its low yield stress can result in high formwork pressure.[12] Underestimating the pressure can lead to deformed formwork with malformed structures or, in the worst case, a formwork collapse. Overestimating the pressure is an economical issue due to the high share of formwork cost to overall cost of concrete construction.[52] Besides the balance between formwork strength and cost, use of SCC in areas where formwork pressure is a concern requires careful attention to thixotropy. In other words, as the SCC rests in the form, yield stress and viscosity increase, reducing the amount of vertical pressure that is translated horizontally to the formwork. The faster this rate of increase in rheological properties occurs, the lower the formwork pressure.

Increasing thixotropy from a mixture design perspective has been the focus of much recent research. Some ways to enhance thixotropy include the use of chemical admixtures (such as VMAs), SCMs (such as silica fume), and reducing *w/cm*.[11,13,53,54]

Quality of surface finish

The quality of the surface finish of concrete is linked to a project's aesthetic requirements. Primary aesthetic issues include the homogeneity of the color (or tint), roughness of the surface, reproduction of formwork details, and the presence and size of bug holes. Several standards define the surface finish of concrete or mortar (for example, NF P 18-503,[55] AMA Hus 98[56] or BS 8110-1,[57] and CIB No. 24[58]).

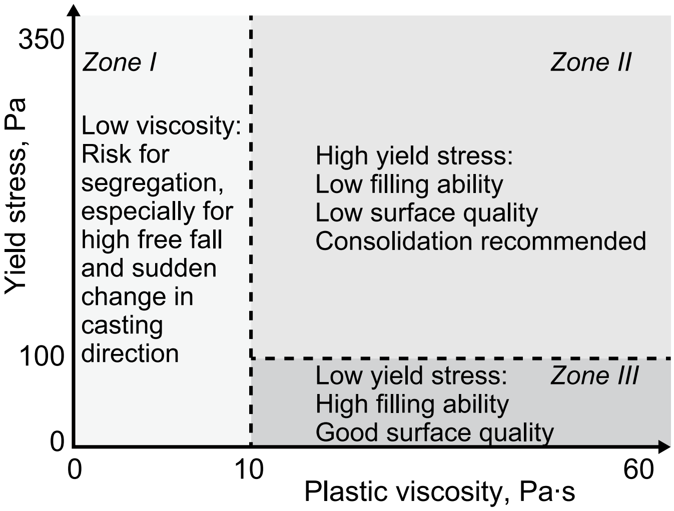

Fig. 6: Influence of rheological properties on surface finish of SCC cast in L-shaped elements (adapted from Reference 60)

Surface finish is affected by a variety of parameters, including mixture proportions, setting time, formwork surfaces, type of release agent, casting technique, placement speed and temperature, yield stress, and plastic viscosity.[59] Figure 6 shows three zones defined by ranges of yield stress and plastic viscosity of SCC, illustrating that the fresh concrete behavior and surface finish are affected in different ways. If the plastic viscosity of the mixture is too low (Zone I), there can be an elevated risk for segregation during casting, especially in placements with large free-fall height and/or changes in the direction of concrete flow during casting. Segregation can affect the surface finish, as it can result in regions with very high or very low paste content. However, if the yield stress of the mixture is too high (Zone II), the mixture can stabilize large entrapped air bubbles, preventing them from leaving the system. In a non-SCC mixture, such issues can be alleviated by additional consolidation using vibration. This will temporarily lower the yield stress, thus enabling unwanted air bubbles to rise. The necessary consolidation energy is dependent on the yield stress and plastic viscosity of the mixture. However, because SCC mixtures do not warrant vibration, it is important to ensure that the balance between viscosity and yield stress is such that the mixture is in Zone III, as this will enable large entrapped air bubbles to rise to the surface. While mixtures in Zone III will generally have good surface quality, it should be noted that bubbles will rise slowly in mixtures with very high viscosity or in mixtures that exhibit high thixotropy (the static yield stress increases rapidly when the concrete is at rest).

A low yield stress with a balanced viscosity can be achieved through the use of SCMs or chemical admixtures (for example, water reducers), decreasing *w/cm*, or increasing the paste volume.[61]

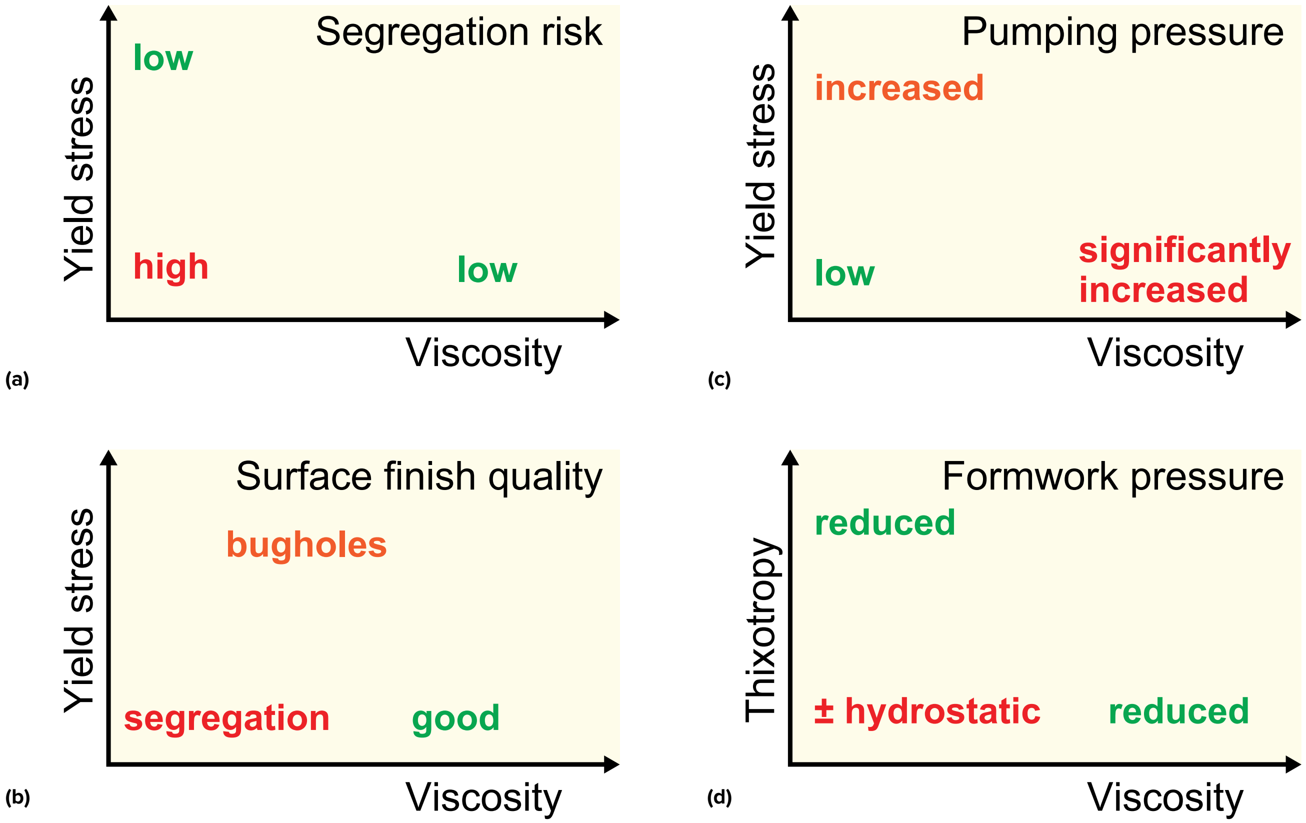

Fig. 7: Summary of the impact of rheological parameters on concrete performance: (a) segregation; (b) surface finish; (c) pumping pressure; and (d) formwork pressure

Conclusions

The science of rheology can be used to gain a fundamental understanding of concrete workability. The rheological properties of concrete need to be balanced to achieve specific goals such as limiting segregation, producing a good surface finish, minimizing pumping pressure, or controlling formwork pressure. In other words, adjusting a property to achieve one goal can have detrimental effects on other goals. Reducing yield stress and plastic viscosity to reduce pumping pressure will result in an increased risk for segregation, and increasing the yield stress to reduce formwork pressure may result in the need for additional consolidation to obtain adequate surface finish.

Rheology can be an effective tool for specifying, designing, and managing concrete workability, revealing concrete characteristics that are not indicated by slump alone. Results from different rheometers can be correlated and can be used to describe multiple aspects of workability. In contrast, empirical tests, such as the slump test, measure a value that is specific to the test method and may not be sufficient to ensure proper performance for the multitude of processing steps (pumping, surface finish, formwork pressure, and so on) that a concrete mixture must endure. Consequently, it is difficult to compare results from one type of empirical test to another without conducting multiple tests to describe different aspects of workability. Using rheometers to determine rheological properties would provide more relevant information on the quality of the concrete.

Figure 7 summarizes the key points of this article:

- Segregation can be controlled by increasing the yield stress or the plastic viscosity, but it should be noted that increasing both parameters too much will lead to very stiff concrete;
- Good surface finish can be achieved by having adequate viscosity—not too low, as the risk for segregation increases, but not extremely high, as the air bubbles will not be able to escape. If the yield stress is elevated, consolidation is recommended to remove air;
- Pumping pressure mainly decreases with a decrease in viscosity. Decreasing the yield stress also decreases pumping pressure, but to a lesser extent; and
- Formwork pressure can be reduced by using a high yield stress concrete, or using a highly thixotropic concrete in slow filling conditions.

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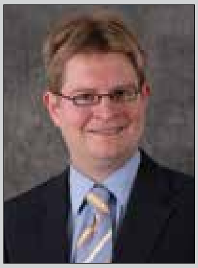

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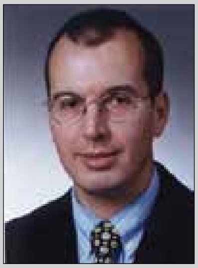

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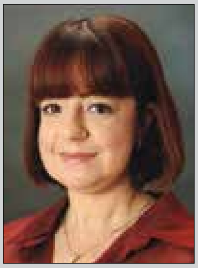

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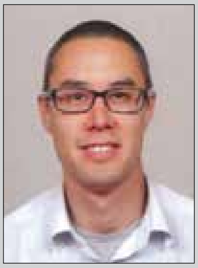

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