Cement and Concrete Research 41 (2011) 1279–1288

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Rheology as a tool in concrete science: The use of rheographs and workability boxes

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ARTICLE INFO

Article history:
Received 14 August 2010
Accepted 12 January 2011

Keywords:
Rheograph
Workability box (A)
Fresh concrete (A)
Rheology (A)

ABSTRACT

Rheology can supply valuable and practical information regarding the properties of fresh concrete, how to reach an optimization of the product and how to attain it by the use of rheograph. Otherwise, the optimization is largely based on feeling. The rheograph reveals in a systematical way the effects of diverse changes on the rheological behavior of the cement based suspension and thus is a convenient and essential tool to compare different concrete types and examine the behavior relative to changed quantities of constituents. Effects of many admixtures as well as the basic constituents of fresh concrete have been revealed in rheographs. In principle the effect of two or more constituents can be added in a rheograph to estimate the combined effect, which constitutes a so-called vectorized-rheograph approach.
Different applications and types of concrete like slipform, underwater, and high strength, are described by workability boxes. New rheograph with boxes for various types of self compacting concrete is proposed.

1. Introduction

1.1. Rheological terminologies

Since civilizations first started to build, the human race has sought materials that bind stones into solid formed mass. After the discovery of Portland cement in 1824 (year of patent), concrete has become the most commonly used structural material in modern civilizations. The quality of the concrete structure is of course dependent on the quality of each constituent used in the concrete mix. However, this is not the only controlling factor. The quality also depends very much on the rheological properties of the fresh concrete during placement into the formwork [1]. That is, the concrete must be able to properly flow into all corners of the mold or formwork to fill it completely, with or without external consolidation (depending on workability class). This is a process that might be hampered by the presence of awkward sections or congested reinforcement [1]. Tragic events may sometimes be traced back to concrete of unsuitable consistency resulting in, for example, coldjoint and honeycombing. Therefore, one of the primary criteria for a good concrete structure is that the fresh concrete has satisfactory rheological properties during casting.

Older terms like workability, consistency, flowability, mobility and pumpability have been used to describe the rheological behavior of the fresh concrete. It is well-known that these terms rather reflect personal beliefs than scientific precision [1,2]. For example, an interesting discussion about the subjectiveness of the term "workability" is given in a textbook by Tattersall and Banfill [1]. Other similar terms are also discussed there. The primary problem is that there is no guarantee that such terminology means the same thing to different people. In fact, there has been a disagreement between different workers about the exact meaning of the term "workability" [3].

1.2. Empirical test methods

During the course of time, empirical test methods of different types and quality have been developed and used to give some kind of rheological description (or indication) of the fresh concrete. The most famous, oldest and currently most used empirical test is the so-called slump test. It gives only a single value, namely the slump value *S*. The test was developed in the USA about one century ago, or around 1910 [4]. The test apparatus is generally associated with Abrams [4,5] and it is believed that its use was first reported by Chapman [6]. After this, other different empirical rheological tests have been developed like the flow/spread table test, which was developed in Germany in 1933 by Graf [7]. Other empirical test methods, like the L-box and the V-funnel (which are intended for highly flowable concrete), have followed since then.

In Refs. [1,8,9] it is stated that the empirical tests are very often operator-sensitive, in the sense that minor variations in the execution of the test, gives a different result. The same literature discusses the need for describing the rheological properties of fresh concrete in terms of fundamental physical quantities, not depending on the details of the apparatus with which they are measured. For this purpose a different class of test apparatus named *viscometers* has been developed in the community of concrete science.

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0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2011.01.009

Viscometers and advanced rheometers are usually designed to be operatively insensitive, meaning that variations in the technique of carrying out the test, does not affect the results. In addition to this, viscometers are designed to retrieve the material parameters in terms of fundamental physical quantities, not depending on the details of the apparatus with which they are measured. An example of such viscometer is the coaxial cylinders viscometer.

1.3. Search for fundamental physical quantities

The use of coaxial cylinders geometry for fresh concrete dates back to 1941 with the use of the Plastometer developed by Powers and Wiler [10,11]. A closed inner cylinder is suspended in the center of a larger bucket containing the fresh concrete. The bucket (i.e. the outer cylinder) rotates back and forth by a small angle, while torque is registered at the inner cylinder. The obtained data consisted of stress–strain curves. By the use of smooth surface for both cylinders, slippage could occur and thus the angle of oscillation had to be small. Eriksson [12] reported the use of the same type of device in 1949, in which the cylinders consisted of protruding blades or vanes, to avoid possible slippage.

According to Tattersall and Banfill [1], a fully rotational coaxial cylinders viscometer was not used for concrete until after about 1970. Motivated by the fact that such instrument had already been used for mortar and cement paste for quite a while before this, Tattersall made an attempt to apply a coaxial cylinders geometry to measure the rheological properties of fresh concrete [1]. Unfortunately, he was not successful. After this, in 1973, he introduced the use of a modified food mixer [1,8,13] to extract the Bingham parameters, namely the plastic viscosity μ and the yield stress τ_0 (these two terms are explained in Section 2.1). This configuration is known as the Mk I. A further development of the Mk I resulted in the famous Mk II and Mk III devices [1]. The Mk II is intended for highly workable concrete while the Mk III is intended for lower workability concrete. These devices measure certain empirical values, designated as *g*- and *h*-values. Through a special calibration technique [1], *g* and *h* can be converted into fundamental physical quantities, namely the yield stress τ_0 and the plastic viscosity μ. The Mk systems are still being used and are continuously going through some improvements as reported in different papers [9,14]. The Mk systems are also known simply as the “two-point” apparatus and have been commercially available. It should be noted that the Tattersall impeller currently used in the Mk systems, is also used in other commercially available measuring devices.

In the beginning of the 1970s, trials were made by others [15,16] using the coaxial cylinders system, which were reported to be somewhat more successful than the work by Tattersall. To avoid slippage, the inner and outer cylinders consisted of serrated surfaces. In the late 1980s, a further improvement of the coaxial cylinders geometry was made in Norway [17,18] which among other things was altered so that the bottom part of the inner cylinder did not measure torque. This was done to avoid the effect of shear stress τ generated from the lower part of the geometrical system used. This approach was further validated in Refs. [19,20] by numerical simulations. This viscometer is named the BML viscometer. Ever since its first introduction, this viscometer has been continuously going through improvements, in terms of more accurate instrumentation and enhanced software, FreshWin, for controlling the viscometer. The successor of this viscometer is the ConTec BML Viscometer 3 and thereafter the ConTec Viscometer 5. The latter is commercially available. In 1996 a viscometer for fresh concrete, using parallel plates, was developed in France [21] and is also commercially available. This viscometer is designated as BTRHEOM. Results of numerical flow simulations for the BTRHEOM are available in Ref. [19]. The research on parallel plate based type geometry for the ConTec viscometer is reported in Ref. [22].

The Tattersall Mk system, ConTec BML Viscometer 3 and the BTRHEOM all measure the rheological properties of fresh concrete in terms of fundamental physical quantities, namely in yield stress τ_0 and plastic viscosity μ (see Section 2.1 about τ_0 and μ). A comparison of these (and other) devices was made in France in October 2000, where the same concrete batch was simultaneously tested [23]. Ideally, one should expect that the same set of rheological values (τ_0,μ) should be measured by all devices, whereas in reality this was not so. Fig. 1 compares the Mk system, ConTec BML Viscometer 3 and the BTRHEOM (the figure is reproduced from Ref. [19], in which the original data is attained from Ref. [23]). Although the same changes in rheological behavior are roughly measured from batch to batch, the absolute values of τ_0 and μ differ somewhat; however, with a good agreement between the Mk system and the ConTec BML Viscometer 3.

The results presented in this article are based on the data attained from the Mk II system, the ConTec BML Viscometer 3 and the newer ConTec viscometers. Thus, when absolute values are presented (for example in Fig. 6), these are acronym “Mk/CT/BML-values” (here, the term CT is an acronym for ConTec). However based on Fig. 1, the same result of rheological behavior should be registered by the BTRHEOM viscometer. That is, although the absolute values in yield stress τ_0 and plastic viscosity μ are prone to be somewhat higher (c.f. Fig. 1), principal illustration like for example the one shown in Fig. 5 should be more or less valid for all devices.

1.4. Rheology of suspensions

In terms of rheology, it is natural to consider fresh concrete, mortar and cement paste as different types of suspensions. Other examples of suspensions are paint, printing inks, coal slurries and drilling mud [24]. Traditionally, a particle suspension consists of two phases, namely the suspended particles and the matrix. As is generally known, fresh concrete consists of particles with a broad range of mass, dimension, shape and surface texture, suspended in a matrix. The distinction between matrix and suspended particles is a matter of choice, in contrast to the more traditional suspension of spheres submerged in a Newtonian liquid. For example in Ref. [19], the matrix has been defined as the 0–2 mm mortar inside the concrete by pure convenience. Another but otherwise equivalent choice for the definition of the matrix is the 0–0.125 mm filler modified cement paste [25].

The term Rheology was coined by Professor Bingham of Lafayette College, Indiana [24]. The term means “*the study of the deformation and flow of matter*”, which was accepted by the American Society of Rheology when founded in 1929 [24]. This science is in one sense very old. An example of this is the famous dictum “*panta rhei*” (everything flows), which is attributed to the Greek philosopher Heraclitus (540–475 BC). It has been taken as a motto of the American Society of Rheology [26]. Rheology is essential for scientists employed in many industries, including those involving plastics, paint, printing inks, detergents, oils, etc. [24].

From the above text, it is clear that rheology is the logical tool to characterize and describe the flow-behavior, thickening, workability loss, stability and even compactability of a fresh cement based particle suspension such as cement paste, mortar and concrete. To apply this tool, one has to be able to evaluate and choose the material parameters of importance (for example yield stress τ_0 and plastic viscosity μ) and to be able to obtain information about them, for example through testing. A great deal of effort has been spent on obtaining accurate and repeatable data on the rheological material parameters. Although the same trend and behavior is generally attained by different types of devices, the absolute value can however differ somewhat.

2. Basic rheology

2.1. Generalized Newtonian model

When a shear stress τ is applied to a fluid element (also known as *fluid particle* [27]), a deformation will result as shown in Fig. 2. The

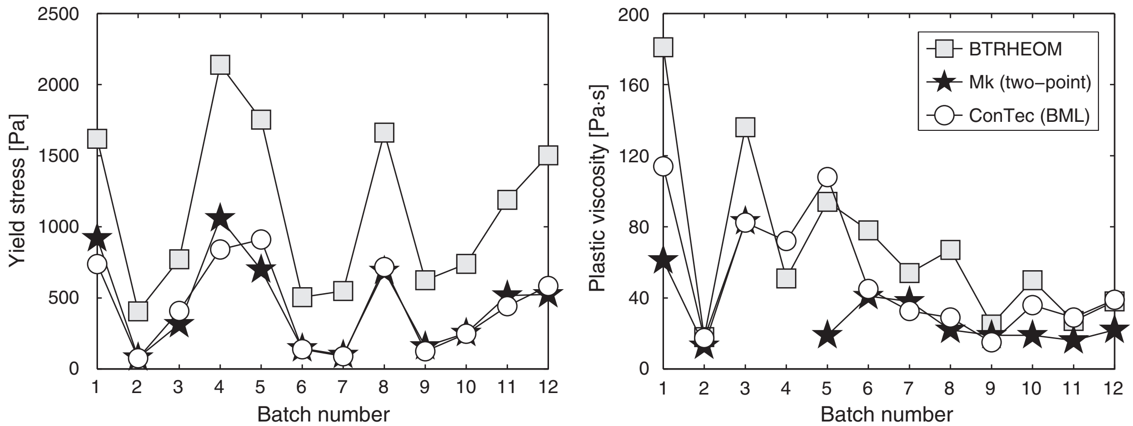

Fig. 1. Comparison of results obtained for different concrete batches by the Mk II system, ConTec BML Viscometer 3 and the BTRHEOM.

rate of deformation is usually designated as *shear rate* or *rate of shear* and represented with the symbol $\dot{\gamma}$. The relationship between the shear stress τ that is applied on a fluid element and its resulting shear rate $\dot{\gamma}$ is named *apparent viscosity* η [24]. The term η is also designated as shear viscosity, to better distinguish it from other viscosity types like the bulk viscosity κ. The latter is fundamentally different from the former (see for example Ref. [28] about the bulk viscosity).

When the relationship between the shear stress τ and the shear rate $\dot{\gamma}$ is a constant, the material constitutes a so-called Newtonian fluid.

$$\tau = [\text{constant}]\,\dot{\gamma} = \eta\dot{\gamma} \tag{1}$$

However, for fluids in general, the apparent viscosity is not a constant, but rather depends on the shear rate $\dot{\gamma}$. When this is the case, the fluid is designated as non-Newtonian and the shear stress is given by Eq. (2).

$$\tau = \eta(\dot{\gamma})\,\dot{\gamma} \tag{2}$$

In tensorial form, Eq. (2) is called the Generalized Newtonian Model (GNM) [24,26]. The GNM is a simplified version of the Reiner–Rivlin model [24]. In the literature, the latter model is sometimes incorrectly confused with the Reiner–Riwlin equation (see for example Ref. [19] about the difference).

Within the range of non-Newtonian fluids, there is a class of materials that are viscoplastic. Such materials are characterized by a yield stress (or equally, yield value; c.f. British Standard BS 5168:1975) that must be exceeded before significant deformation can occur. Such materials typically sustain an applied stress at rest.

One of the simplest types of viscoplastic materials is the so-called Bingham fluid and constitutes an important class of viscoplastic material. It is named after E.C. Bingham, who first described paint in this way in 1919 [29]. Paint, slurries, pastes, and food substances like margarine, mayonnaise and ketchup are good examples of Bingham fluids [29].

It is commonly agreed that fresh concrete can, with good accuracy, be considered as a Bingham fluid [1,8,9,14]. As for viscoplastic materials in general, it has to overcome a certain yield stress τ_0 in order to initialize flow. However, after the initialization, there is a linear relation between the shear stress τ and the shear rate $\dot{\gamma}$, named plastic viscosity. It is usually represented by the Greek letter μ. The flow behavior of Bingham material is often described with the following pair of equations:

$$\eta(\dot{\gamma}) = \mu + \tau_0 / \dot{\gamma},\ \tau \geq \tau_0 \tag{3}$$

$$\dot{\gamma} = 0,\ \tau < \tau_0. \tag{4}$$

A more common representation of the Bingham fluid is attained by combining Eqs. (3) and (2), which gives (with changed order of terms):

$$\tau = \tau_0 + \mu\dot{\gamma},\ \tau \geq \tau_0. \tag{5}$$

Eq. (4) remains unchanged in this process.

A *flow curve* is defined as a plot of shear stress τ versus shear rate $\dot{\gamma}$ [24]. Such a plot for Newtonian and Bingham fluids is shown in Fig. 3. In addition to the Bingham equation there exist numerous other material equations, for example of the power-law type that describes the so-called pseudoplastic (shear thinning) and rheoplex (shear thickening) behaviors.

In the science of fresh concrete, mortar and cement paste, the power-law behavior combined with a yield stress is sometimes applied to fit experimental data. Eq. (6) shows such type of behavior, which is the Herschel–Bulkley equation [30].

$$\tau = \tau_0 + k\dot{\gamma}^n,\ \tau \geq \tau_0 \tag{6}$$

$$\dot{\gamma} = 0,\ \tau < \tau_0 \tag{7}$$

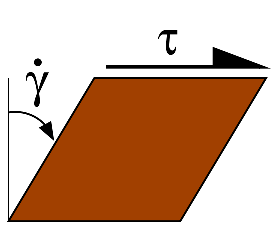

Fig. 2. Deformation of a fluid element.

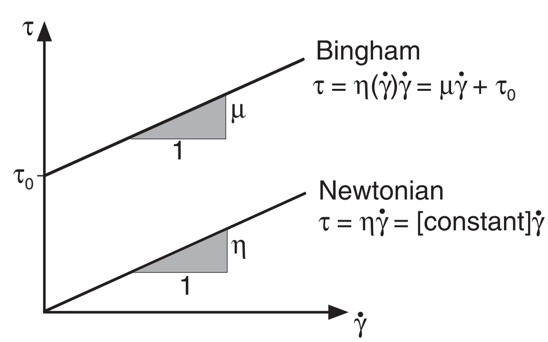

Fig. 3. Flow curve for Newtonian and Bingham fluids.

The terms k and n are sometimes referred to as consistency (or flow coefficient) and power law exponent, respectively. These terms describe the shear rate dependency of the test material. When $n>1$, the equation signifies a shear thickening behavior and with $n<1$, a shear thinning behavior, while a Bingham behavior for $n=1$. Fig. 4 shows the flow curve for the Herschel–Bulkley fluid relative to the Bingham fluid.

Although valid in most cases, fresh concrete cannot always be considered as a Bingham fluid. In some cases, for example in Belgium [31] and surrounding countries, self-compacting concrete (SCC) demonstrates often a nonlinear behavior. In such cases, it is often more suitable to describe the rheological behavior of SCC with the Herschel–Bulkley model. One of the benefits using this model is that a negative yield stress is less likely encountered, as unfortunately sometimes occurs when applying the Bingham model to such cases.

2.2. Rheograph

As mentioned in Section 2.1, a good first approximation of the fundamental rheological quantities for cement based material can be obtained in terms of yield stress τ_0 and plastic viscosity μ. In this context a *rheograph* is defined here as a plot of changes in the relation between yield stress τ_0 (the y-axis) and the plastic viscosity μ (the x-axis) as a function of material properties, time, additives, etc. That is, the rheograph is a plastic viscosity μ–yield stress τ_0 diagram established in order to reveal in a systematical way the effects of diverse changes on the rheological behavior of the cement based suspension (e.g. concrete, mortar and cement paste). As will be explained in this article, the rheograph is thus a convenient and essential tool to compare different concrete batches and examine the behavior relative to changed constituents, quantities of constituents, and/or relative to different times from water addition (and so forth). On a historical note, the term *rheograph* has been previously used in 1970 then by Bombled [32]. It was however done so in a context different from that above, namely in relation to penetration of a cylindrical needle into cement paste.

A very systematic and comprehensive use of rheograph was not made until in 1983 by Wallevik, using the Mk II [33] (see Section 1.3 about the Mk devices). His investigation was in particular to examine the effect of added water (Water), air entrainer (Air), superplasticizers (SP) and silica fume (SF) in a concrete mix [33]. A general representation of the results of his research is shown in Fig. 5. This figure consists of six illustrations. The two illustrations to the left and the two to the right are *flow curves*. The results of these four flow curves are combined into a single *rheograph* shown with the main center illustration of Fig. 5. The center top illustration explains how different *rheograph directions* will change the concrete, i.e. to stiff, wet or viscous. All changes in Fig. 5 are relative to a reference mix. The added SF is on replacement basis, meaning that the mass ratio of water to cement + SF is constant (meaning, $w/(c+\mathrm{SF})=$ constant). The increased water content is made at constant cement content.

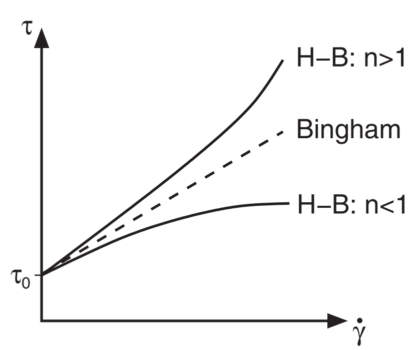

Fig. 4. Flow curve for Herschel–Bulkley ($n\neq1$) and Bingham ($n=1$) fluids.

As clearly shown with the rheograph in Fig. 5, each constituent has a significantly different influence on the flow behavior of fresh concrete. In the same year as Wallevik [33] made these findings, or in 1983, Tattersall and Banfill [1] used also such graph to re-plot results made by Scullion [34] to show the effect of changed w/c-ratio and fines content on rheological behavior. Few years earlier, or in 1979, Bloomer also used such graph to show that changed workability was due to increased water content of site concrete [35].

As mentioned above, Fig. 5 was generated with the Mk II system in 1983. About two decades later, some of the results were reproduced with mortar, using the ConTec BML viscometer. The results are shown in Fig. 6 and are based on 22 mortar mixes. The sand to cement ratio for all mixes is 2 and the maximum particle size is 8 mm. The plasticizer used was melamine based and the dosages are shown in terms of dry polymer weight per unit weight of cement (i.e. solids by weight of cement). As shown, the values are given as percentage. Other trends shown in Fig. 5 have also been reproduced in various projects using ConTec viscometers for both fresh concrete and mortar.

Although the results shown in Figs. 5 and 6 are generally valid for mortar and concrete, the situation is not so simple for cement paste. This is due to the fact that thixotropic behavior as well as structural breakdown behavior is more pronounced for cement paste relative to concrete and mortar. The rheological behavior of cement paste in terms of the two different phenomena, thixotropy and structural breakdown is well treated in Ref. [36]. The effect of the kinetics of dispersion and coagulation for the cement particles, in addition to the process of breaking of early chemical products (i.e. early C–S–H, syngenite, ettringite and so forth) is more prominent in cement paste because of the absence of aggregates, which act as a very effective grinder and/or dispersant. In addition to this, a separately mixed cement paste has a much lower solid concentration relative to concrete and mortar (the volume of water in cement paste is typically about 50% or more). For example when superplasticizer (SP) is added to concrete (Ref.-mix), the plastic viscosity μ will remain relatively unaffected, while as for cement paste, SP could reduce the plastic viscosity in a similar way as when water is added. A principal illustration of this is shown in Fig. 7.

It is difficult to provide a complete description of the effects of the aggregates, due to how other different parameters simultaneously change in the process. However as shown in Fig. 8, some general trends can be depicted in a rheograph. In general, by increasing the sand fraction in a reference mix containing crushed coarse aggregates (however, keeping the total aggregate content fixed), the yield stress τ_0 will increase and the plastic viscosity μ will significantly decrease. The opposite effect is obtained when the sand fraction is reduced. By replacing the crushed coarse aggregates by rounded ones, the yield stress τ_0 will reduce to some extent and the plastic viscosity μ will be significantly reduced. The opposite effect is attained when flaky aggregates are introduced instead of the rounded ones.

3. Workability boxes and rheographs

3.1. Workability boxes in general

In Section 2.2, a short historical background of the rheograph and its key benefits has been presented. In this section, another important concept is defined and described, named here the *workability box*. A workability box consists of an area within a rheograph. More precisely, such a box consists of a certain domain of yield stress τ_0 and plastic viscosity μ. A single workability box is associated with a particular concrete type. Thus, several workability boxes can be represented in a single rheograph. It should be clear that a workability box does not have to consist of a perfect square. It can also consist of a two-dimensional polygon, or pointed regions without an exact and clear boundary. Examples are given shortly. Thus, the term “box” is just used here as a loose description of the domains and boundaries

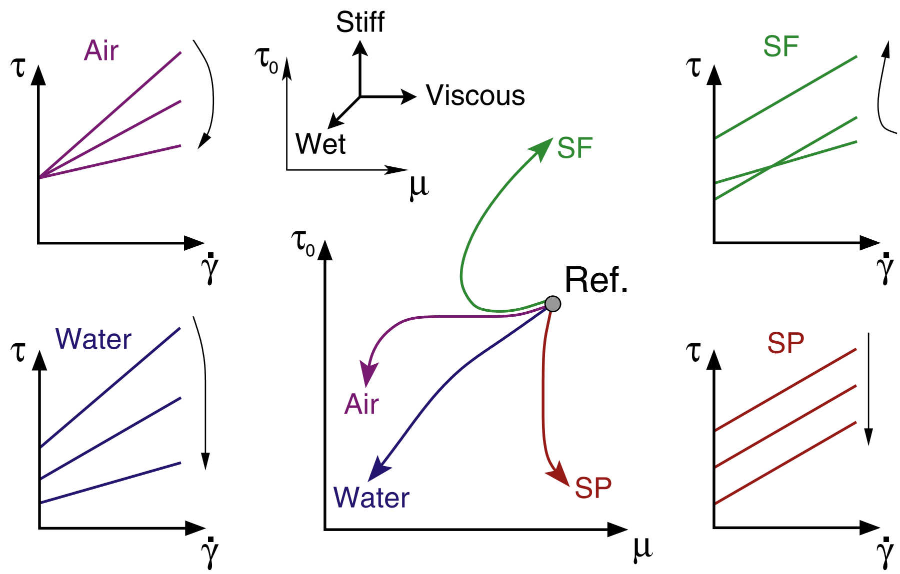

Fig. 5. Rheograph; principal illustrations showing the effect of adding different constituents to a reference mix (reproduced from Ref. [33]).

discussed. On a historical note, Tattersall and Banfill [1] defined in 1983 a certain "suitability band" on a *g*–*h* diagram (see Section 1.3 about the *g* and *h* values). The objective with the suitability band is similar to that mentioned above, namely to describe suitable workability for concrete mixes. In addition to this, others [37–40] have attempted to identify areas for ideal workability in a similar manner.

As previously mentioned, a single workability box is associated with particular concrete type (like Conventional Vibrated Concrete, CVC) and its corresponding job application. For example, the CVC is often of a relatively stiff consistency (slump <170 mm), which corresponds to yield stress τ_0 in the higher range, say above 300 Pa [41]. To maintain a workable CVC, the plastic viscosity μ is usually in the lower range, or say at and below 40 Pa · s. This is often the case at job sites for example in Iceland, Norway and Denmark. The point is that one can define a recommended workability box for CVC as the area consisting of $\tau_0 > 300$ Pa and $\mu < 40$ Pa · s. A CVC that is located outside this box, could indicate a risk of failure at the job site due to unsuitable consistency. A skilled technician would appreciate the importance in keeping the particular mixture close to or in the area defined by a certain workability box of relevance. When the concrete is outside the particular box, a rheograph (for example Fig. 8) can aid the technician in putting it back into an optimum state (i.e. back to the workability box of the best choice, defined by the application in question).

For some cases, the plastic viscosity of a CVC can be much higher than 40 Pa · s, meaning that the particular batch is outside the above mentioned workability box. This is often observed for example in Japan, where its value can easily reach 100 Pa · s. To maintain a workable concrete for such cases, the main interest becomes to reduce the plastic viscosity μ, and thus bringing the corresponding batch closer to the defined workability box. In this manner, the workability box (along with results like those shown in Fig. 5) can be considered as a practical tool at mixing plant to evaluate the necessary steps to produce a successful batch, reduce cost and increase productivity.

Fig. 9 shows rheographs with several different workability boxes. No values are shown for μ and τ_0 on the corresponding axes as the figure is only to show relative arrangements of workability boxes for different concrete types. Later, for example in Figs. 10 and 11, actual values are shown for some specific cases (i.e. Mk/CT/BML-values, c.f. the last paragraph in Section 1.3). Below are some few explanations about the workability boxes shown in Fig. 9.

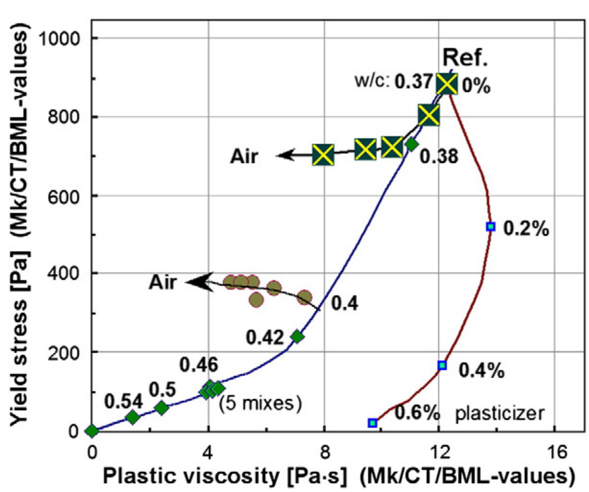

Fig. 6. Effect of water, air and plasticizer on the yield stress and the plastic viscosity for mortar (8 mm).

3.1.1. Uphill casting

As mentioned in Section 2.1, the yield stress τ_0 describes the shear stress required to initialize flow. Hence, during an uphill casting, the fresh concrete is often required to retain sufficiently high yield stress τ_0 to prevent it from downhill flow (i.e. preventing the fresh concrete from sliding down the formwork).

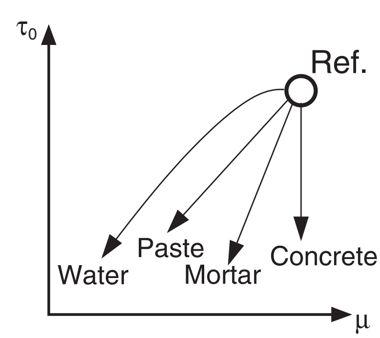

Fig. 7. Principal illustration of difference in behavior between cement paste, mortar and concrete with increased addition of SP.

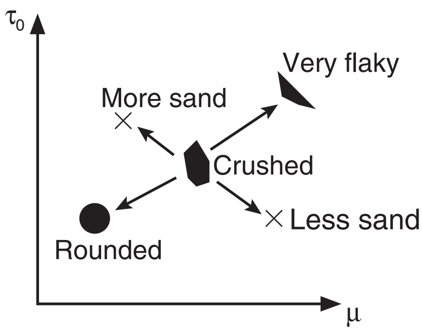

Fig. 8. Effect of aggregate shape and sand content shown in a rheograph.

The arrow shown in Fig. 9 demonstrates the direction needed to go if the uphill slope is increased. With a steeper slope, the gravitational effect becomes stronger in pulling the concrete out of the formwork. To compensate for this, the yield stress τ_0 must be increased to make it that harder to initialize flow by gravity. However, in taking this step, the plastic viscosity μ must be reduced to maintain a workable batch. That is, it is necessary to combine a high yield stress τ_0 with a low plastic viscosity μ to ensure workability.

Here, the workability box only constitutes a direction (i.e. of an arrow), which serves as a guideline to improvements when the uphill slope is increased. More such "workability boxes" (or rather *workability arrows*) will follow below.

3.1.2. Pumping of CVC and SCC

To successfully pump a CVC, experience has shown that the yield stress τ_0 has to exceed roughly around 150 Pa to maintain a sufficient degree of stability and homogeneity of the fresh concrete. Thus, the concrete will be present as an "*undisturbed*" plug in the pipe. Then the shearing of the CVC will mostly occur in the slippage layer at the pipe wall. This layer is largely maintained by pressurized bleeding from the concrete and to some degree by dilatancy effects.

The SCC has much lower yield stress than CVC, normally below 50 Pa. Therefore, there will be much less plug and thus more shearing throughout the concrete sample in the pipe. Of course, there will be some slippage between the SCC and the pipe wall, generated for example by shear induced particle migration. Because there is more pipe cross-sectional shearing $\dot{\gamma}$ throughout the SCC sample (meaning more viscous shear stresses $\tau_v = \mu\dot{\gamma}$ involved, relative to CVC; c.f. Bingham: $\tau = \tau_v + \tau_0 = \mu\dot{\gamma} + \tau_0$), it is expected that the plastic viscosity μ will contribute much more to the overall flow resistance and therefore to the pump pressure.

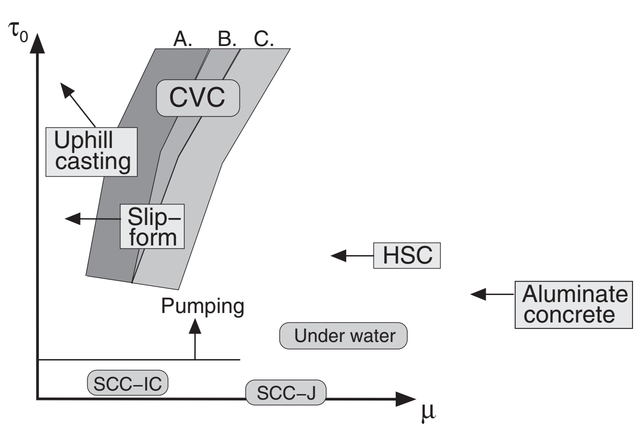

Fig. 9. A rheograph for different construction applications (reproduced from Ref. [42]).

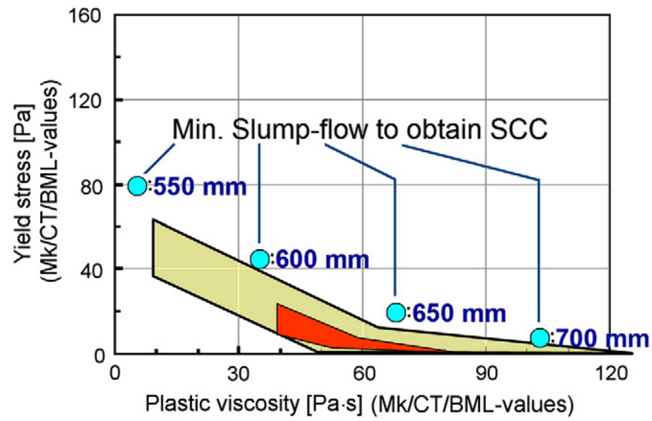

Fig. 10. Proposed rheograph for SCC (reproduced from Ref. [50]).

The SCC has usually much larger paste volume relative to CVC, which reduces any potential dilatancy effects. This effect can be a major segregation factor for a CVC during pumping.

3.1.3. HSC

Usually, because of low water content and high content of powder (in terms of cement and other constituents like silica fume, SF), the plastic viscosity μ of high strength concrete (HSC) has a tendency to become exceptionally high as indicated in Fig. 9. Thus, one of the major concerns when mixture proportioning a HSC is the reduction of the plastic viscosity μ in order to make it workable. With a successful reduction, one can start to further reduce the volume of water (or w/c-ratio) in the mixture. More to the point, to be able to attain the maximum strength of HSC (by reduced w/c-ratio, and thus increased powder content), some techniques must be applied to reduce or control the plastic viscosity μ. "*The art of making HSC is the ability to reduce the plastic viscosity*".

3.1.4. CAC

The same concern applies to calcium aluminate concrete (CAC) as for HSC. The CACs are notorious for exhibiting an extremely high plastic viscosity μ, even at w/c-ratio as high as 0.5. Since it is often required that $w/c < 0.4$ for CAC, a measure must be taken to sufficiently reduce the plastic viscosity μ by, for example the use of rounded aggregates (see Fig. 8). Another and straightforward approach is to increase the water content (c.f. Fig. 5) at constant w/c-ratio. Such formulation would however lead to higher cement content and thus a less economical mixture, as well as other drawbacks like shrinkage. The third possibility to reduce the plastic viscosity is to add silica fume, SF (see Fig. 5). In this case, the SF would be used as a viscosity reducing admixture and *not* as a strength/durability enhancement admixture.

3.1.5. UWC

The underwater concrete (UWC) must be constituted with high plastic viscosity μ. Otherwise, the shearing (flowing and deformation) can be excessive resulting in an undue washout of the cement paste, which will deteriorate the concrete. Also, higher plastic viscosity μ will generally increase the cohesiveness of the fresh concrete. It is recommended that the yield stress τ_0 should be lower than about 150 Pa to obtain the necessary consolidation of the concrete in water. Note that in this respect, the difference between SCC and UWC can be very small and even nonexistent in some cases (see Section 3.2).

3.1.6. CVC

Conventional Vibrated Concrete (CVC) is the most common type of concrete produced in the world. The consistency of this type calls for

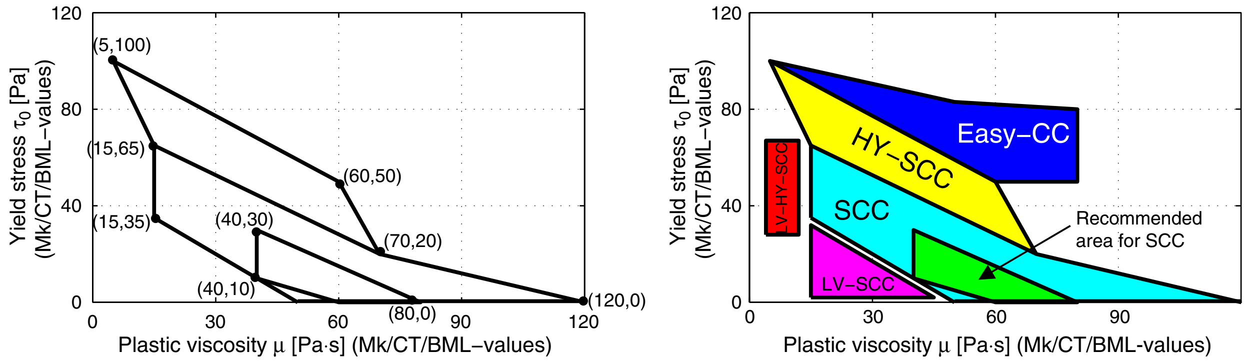

Fig. 11. The new proposed area in rheograph for SCC, to replace Fig. 10.

vibration to properly consolidate it into a formwork or mold. The strength class of this type typically ranges from low strength to medium strength (the high strength concrete, HSC, constitutes a different class already mentioned in Section 3.1.3).

In Fig. 9, three workability boxes are shown for CVC. They are labeled A, B and C. Region A represents what typically applies in Scandinavia, while region labeled B is what typically applies for mainland Europe. Region C represents the CVC that commonly applies in Asia. For region A in Fig. 9, it could be considered preferable to use dispersing admixture that can increase the plastic viscosity, like polycarboxylate based superplasticizer with relatively long backbone.

One of the possible reasons for that a particular concrete resides in region C, is due to the use of high quantity of very angular crushed aggregates. In this case, the challenge will be primarily to reduce the plastic viscosity μ, for example by use of low viscosity polycarboxylate based superplasticizer (i.e. SP that can actually reduce the plastic viscosity μ).

3.1.7. Slipform concrete

The direction (or arrow) labeled "Slipform" in Fig. 9, points towards reduced plastic viscosity μ, while maintaining a necessary yield stress τ_0 to attain sufficient stability (i.e. prevent segregation). In other words, the major emphasis with a slipform concrete is to reduce the plastic viscosity to allow for particle migration away from the interface boundary (i.e. generation of liquid in the shearing zone). With such reduction in plastic viscosity, a slip layer is more easily formed and maintained between the slipform and the concrete. This is of paramount importance in reducing adhesion and shear stresses (friction) in the interface zone (between the concrete and the slipform). Thus, the understanding of behavior for particle migration is very important, when considering possible concrete damage during lifting operations of the slipform. Of course, other effects are also of importance in reducing such damage, but such discussion is outside the scope of the current article (see rather Ref. [43]).

3.1.8. SCC-IC and SCC-J

The workability box designated "SCC-IC" in Fig. 9 represents the domain of plastic viscosity μ and yield stress τ_0 that are typical for Icelandic SCC. It is characterized by relatively low plastic viscosity, while the yield stress is slightly elevated. In contrast, the Japanese SCC (the box designated "SCC-J") has a much higher plastic viscosity and a very low yield stress (close to or at zero). The typical numerical values in terms of μ and τ_0 for Icelandic and Japanese SCCs are indicated in Fig. 12.

3.2. Workability boxes for SCC

Self-compacting concrete (SCC) is a type of concrete that can fill all corners of formwork or mold without the use of a vibrator. When discussing satisfactory rheological properties of SCC, terms like filling ability, passing ability and resistance to segregation have become the most predominated ones [44]. With optimum values of plastic viscosity μ and yield stress τ_0, the anticipations for these three properties are likely to be fulfilled. However, optimum values do not guarantee this.

The interest for self-compacting concrete (SCC) has increased rapidly worldwide following the pioneering work done in Japan, where it was first defined in 1988 [45]. SCC is considered by many experts to be the greatest breakthrough in concrete technology for many decades due to the improved performance and working environment. It all started around 1988 at Tokyo University with Prof. Okamura and his students, among others Ozawa and Maekawa, as they established the basic description of SCC. Before that, several cases of application were known in which the concrete did not need external consolidation to obtain necessary compaction and could therefore be considered as SCC, but were not defined as such [46]. For example, concrete that requires little vibration or compaction has been used in Europe since the early 1970s [47,48].

The early studies of SCC in Japan were followed by several spectacular uses [49]. The concept then spread rapidly to many other countries. In Europe, it was probably first used in civil works for transportation networks in Sweden in the mid 1990s [47].

The proposed area for SCC in a rheograph is shown in Fig. 10 (first presented at the SCC conference in Kochi, Japan, 1998). The small red area (i.e. the red workability box) shows the most recommended values for SCC, while the larger yellow area shows generally

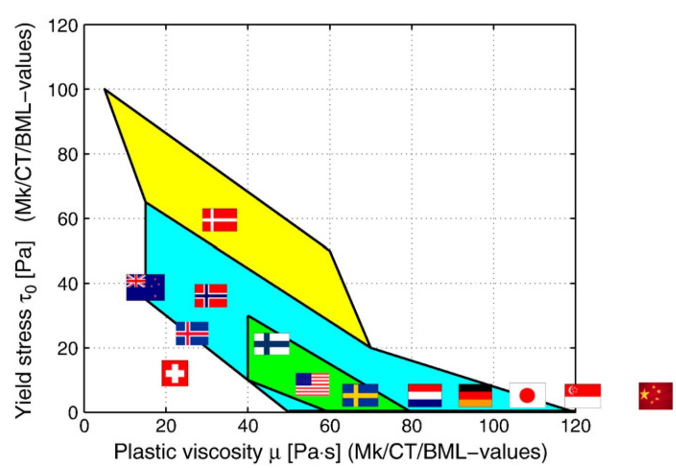

Fig. 12. General impression by the first author, after making SCC in the countries indicated.

recommended values. The figure also shows the necessary slump-flow, depending on plastic viscosity, to obtain SCC.

A further development of Fig. 10 is proposed in Fig. 11, based on data from almost 100 different ConTec devices around the world. In this new proposal in Fig. 11, are areas (i.e. workability boxes) shown for different types of SCCs. These are high yield SCC ("HY-SCC"), also known as semi-flow self-compacting concrete (SF-SCC), low viscous-high yield SCC ("LV-HY-SCC") and low viscous SCC ("LV-SCC"). In this context, the term *high yield* (HY) means high yield stress τ_0 (relatively speaking). Likewise, *low viscous* (LV) means low plastic viscosity μ.

The area designated as "Recommended area for SCC" (green) in Fig. 11, shows the most recommended values for SCC, while the larger surrounding area, designated as "SCC" (light blue), shows generally recommended values. Also shown in this figure is a so-called Easy compacting concrete ("Easy-CC"), which is outside the domain for SCC.

As shown in Figs. 10–11 (and also in Fig. 12), if the plastic viscosity μ is low, i.e. below some 40 Pa · s, the SCC should have a relatively high yield stress τ_0, to maintain stability. On the other hand if the SCC is highly viscous i.e. with plastic viscosity over 80 Pa · s, the yield stress should be in the lower range, say below 15 Pa, to maintain flowability relevant for SCC. For very high viscous SCC (μ>100 Pa · s), the yield stress has to be almost zero to keep sufficient flowability.

The generally recommended SCC area (designated with "SCC" or light blue), the most recommended SCC area ("recommended area for SCC" or green) and the high yield SCC ("HY-SCC" or yellow) shown in Fig. 11, are replotted in Fig. 12. The last mentioned figure shows indication of typical rheological values for SCC in different countries, based on experience. The applied plastic viscosity can differ considerably among SCCs and the authors have experienced plastic viscosity in the range of 7 to 200 Pa · s and even higher than this when using an excessive amount of structural steel fibers. In the pioneering countries (like in Japan, Sweden and Netherlands), the SCC generally displays a very high plastic viscosity due to the high amount of powder used in the concrete mixture. The yield stress in these countries is normally negligible or close to zero. In Norway, Iceland and Switzerland (where often very good aggregates are available and used) very low plastic viscosity SCCs are usually applied, while maintaining a relatively high yield stress (typically between 20 to 40 Pa).

In Denmark, the HY-SCC is typically proportioned with yield stress around 60 Pa (slump-flow around 550 mm). What is noteworthy in this case, is that the greatest success in applying SCC in ready mix plants so far is in Denmark. This success consists of that about 1/3 of the total annual ready mix concrete production is in fact SCC (i.e. HY-SCC).

4. Discussion

4.1. Application of workability boxes and rheographs

There are many ways to apply rheology in concrete technology. One can use it as a guide during mixture proportioning (mix designing), for raw material evaluation or for quality control at building site.

In many countries the plastic viscosity μ of conventional vibrated concrete (CVC) (having slump value between 50 and 170 mm) is relatively low or between 20 to 40 Pa · s. In this case the empirical slump test might be an adequate way to evaluate the workability of the fresh concrete. But with higher plastic viscosity values, more information is in most cases needed, available by other and more sophisticated measuring devices like the Mk system, ConTec-, or the BTRHEOM viscometer [23]. Then it is important to retrieve the rheological properties in terms of fundamental physical quantity to evaluate the workability.

Plastic viscosity μ of CVC higher than 50 Pa · s, will start to exert a negative impact on the workability due to reduced flowability. To reduce the plastic viscosity in such cases, one could for example use the rheograph of Fig. 5 as a guideline. Use of silica fume (SF) could help, but only up to a certain dosage (say, up to 5%). Another method to reduce the plastic viscosity appears from the rheograph in Fig. 8 and consist of using rounded aggregates and/or reduce the content of coarse aggregates.

As the concrete becomes more fluid, meaning that the yield stress falls below about 300 Pa (i.e. slump value greater than about 170 mm [41]), the plastic viscosity starts to play a more important role in characterizing the overall concrete consistency. In this respect, one can consider the ratio of plastic viscosity μ to yield stress τ_0 as the value of major interest. When μ/τ_0 exceeds say 10, the empirical test methods like the slump test (see Section 1.2) may become inadequate in describing the overall workability. If the volume of water is low (less than 170 kg/m^3), aggregates are flaky and the volume fraction of stone is high, this ratio can easily reach 100, which calls for a more sophisticated measuring apparatus (see Section 1.3).

Another important use of rheology is the evaluation of diverse constituents (i.e. ingredients) and their impact on the concrete like:

I. Cement: fluctuation in properties among different cement deliveries (production dates) and in particular in the presence of dispersing admixture, *a cement–admixture interaction* [51].

II. Water content: in mixture proportioning, it is important to check the plastic viscosity μ if the volume of water or the water/cement-ratio (w/c) is low. Increased water is a major factor in reducing the plastic viscosity, as shown in Fig. 5. Thus a (prescribed) low water content and accordingly, high plastic viscosity, may call for other measures to ensure sufficient workability.

III. Aggregates: information on the influence of aggregate particle shape on the plastic viscosity may be gained through rheological tests, as well as the effect of means to reduce it, e.g. by changing the composition of total grading curve. Analogously, the effect of the grading of aggregates on the yield stress can be evaluated, as has been shown with the rheograph in Fig. 8.

IV. Chemical admixtures: the effectiveness of chemical admixtures with a given cement type may be hard to predict without thorough evaluation. To give an example, an admixture that works very well with cement from, for example, Denmark may not be suitable with Icelandic cement. Such evaluation as well as doing it in a combination with workability loss investigation, highlights the importance of rheology. Also, selection of suitable dispersion admixture to reduce plastic viscosity is greatly facilitated by the use of rheology.

4.2. Use of rheographs in designing SCC—vectorized-rheograph approach

A good quality viscometer/rheometer is an essential aid in proportioning a good SCC in respect of flowability, stability and finding a robust as well as an economical solution. It tells (scientifically) where one is sited regarding the properties of a particular fresh concrete, where to go to optimize it and how to get there. Some SCCs should be very viscous (i.e. display high plastic viscosity μ) while others not so. But, this ultimately depends on the application at jobsite. If a mix displays a low plastic viscosity (like 25 Pa · s) it must have sufficient yield stress (say, τ_0>30Pa) to maintain stability in respect to segregation. If the SCC is very viscous (μ>80 Pa · s) the yield stress has to be close to zero (say, τ_0<10 Pa) to be able to move easily. The point is that both values, the yield stress τ_0 and the plastic viscosity μ, are needed to properly make a decision about the next optimization step, both in respect to flowability as well as stability. Unfortunately, empirical test methods like the slump-flow, T_{50} and V-funnel can only give an indication of the plastic viscosity μ, and probably only so when the yield stress τ_0 is close to zero.

There are several methods to alter the plastic viscosity μ of the SCC. The three simplest steps are to add water, increase air content or add silica fume (SF) on replacement base of cement. This is shown on the rheograph in Fig. 13 (see also Fig. 5). The first two steps (increase in water and air content) will reduce strength as the third one, the SF addition, will however increase it.

As shown in Fig. 13, water will reduce yield stress τ_0 whereas air will have little influence on it. By addition of SF (on cement replacement basis) however, the yield stress can in fact increase, in particular if the dosage is higher than 5%. Thus, there are different ways to change and control the rheological behavior of fresh concrete. What is specifically important to note in this respect is that these steps can (in principle) be combined to attain the desired results. An example of this is shown in Fig. 13, where the aim is to reduce the plastic viscosity. In this case, this is done by combining a certain type of stabilizer [52] (to increase the yield stress), with water addition (to decrease both the plastic viscosity and the yield stress), with the overall result that mostly the plastic viscosity is reduced (going from the "Ref."-point to the large circle, in Fig. 13). This type of combination could be called *vectorized-rheograph approach*, as the vector addition (the arrows in Fig. 13) of each step gives the final result. Other vector steps can be combined with this as well. For example, the yield stress can easily be regulated with dosages of superplasticizer (SP). Additionally, in some cases different types of coarse aggregates are available. As previously mentioned, the use of crushed and flaky aggregates will lead to high plastic viscosity, while rounded aggregates will result in low plastic viscosity (see also Fig. 8). These constituents can be used in part to further change the rheological properties of the fresh concrete. In case of flaky aggregates, a small fraction of mid-size rounded aggregates can reduce significantly the plastic viscosity. In addition to the above steps, emulsion-containing polymer (PCC) [53] can be added to significantly reduce the plastic viscosity. The point is that various constituents (and combinations of them) not mentioned in this article can be used in rheographs in the manner as explained above.

4.3. Effect of mixers on the plastic viscosity μ

The mixer type and size can have a large influence on the rheology behavior of fresh concrete. In Fig. 14 are shown rheological results of 3 different SCC mixes, designated as MC05, MC06 and MC19, when mixed in three different types of mixers. The mixers are the typical drum mixer, the Maschinenfabrik Gustav Eirich 50 l mixer as well as the Maschinenfabrik Gustav Eirich 150 l mixer. Roughly 25 l of concrete was mixed in the drum mixer each time, while about 40 l in the Gustav Eirich 50 l mixer, and about 100 l in the Gustav Eirich

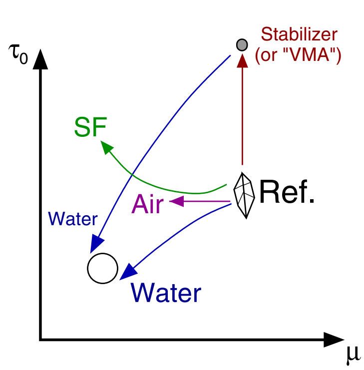

Fig. 13. Some measures to reduce the plastic viscosity.

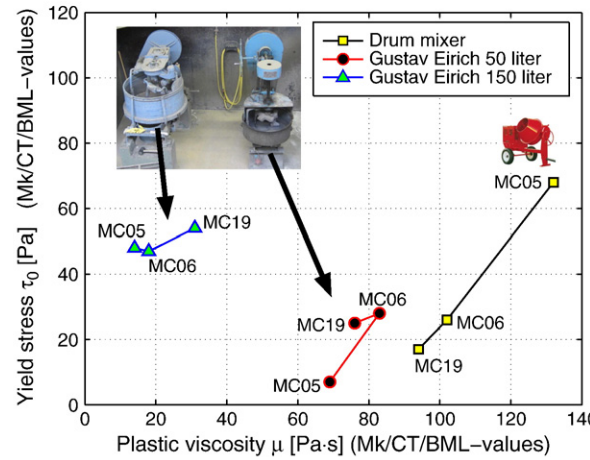

Fig. 14. Effect of mixer type on the rheology behavior of fresh concrete (Eco-SCC).

150 l mixer (it should be noted that the rotational speed applied during mixing, is larger for the 150 l mixer, relative to the 50 l mixer).

The proportions and type of each constituent (cement, water, sand, and etc.) in the MC05 mix is the same when mixed in the Gustav Eirich 50- and 150 l mixers. However, when mixed in the drum mixer, the dosage of superplasticizer (SP) had to be doubled to maintain SCC properties. That is, without this step, the drum mixed concrete would have been too stiff. The same issue as for MC05, applies for the MC06 and MC19 mixes. More precisely, the drum mixes MC05, MC06 and MC19 shown in Fig. 14 contain double SP content, relative to the mixes MC05, MC06 and MC19 of the Gustav Eirich mixers (50 and 150 l). The particular SCC used in this test is a so-called *Eco-SCC*, which is a very economical and environmental friendly type of SCC [54–56].

As is clear from the rheograph in Fig. 14, the 150 l Gustav Eirich mixer gives far the lowest plastic viscosity μ of all mixes, which demonstrates its effect. That is, as the size of the mixer increases, the plastic viscosity μ gets reduced.

The overall results shown in Fig. 14, give a good example of how rheographs can be used to quantify not only the fresh concrete rheological behavior, but also the effect of the mechanical instruments being used in relation to fresh concrete (i.e. the effect of mixers in this case).

5. Concluding remarks

Rheology can supply valuable information regarding the properties of fresh concrete, how to obtain an optimization of the product and how to attain it by the use of a rheograph. Otherwise, the optimization is largely based on feeling. Even if experienced technologists can achieve very passable results based on feeling, it will give (contrary to rheological measurements) little quantifiable data for eventual comparison to other mix solutions or for later reference. Normally, an empirical test method only tells *if* the material flows but not *how*.

One can develop high performance concrete like SCC without the use of rheology, but then a lot is based on impression and feeling. The point is that rheology is crucial for effective development of SCC. It should be used in all phases from selecting materials to mix designing (mixture proportioning) and production.

The effects of many admixtures as well as the basic constituents of fresh concrete in a rheograph have been revealed. Although these are the general trends, one can in most cases add the effects of two or three constituents to estimate the combined effect. This approach constitutes a so-called vectorized-rheograph approach.

Finally, *a rheograph can help to find out where one is, where to go and how to get there.*

Acknowledgements

The authors would like to thank the Icelandic Research Fund (Rannis), The Icelandic Road Administration (ICERA), The Housing Financing Fund (ILS) and Landsvirkjun (LV) for their financial support of the research. The colleagues at ICI Rheocenter (former IBRI) are thanked for their assistance, in particular Asbjorn Johannesson. Also those who have made a scientific contribution at the institute in rheological research; Indridi Nielsson, Thordur I. Kristjansson, Halldor Svavarsson, Hreinn Jonsson, Bjorn Hjartarson, Stefan Kubens, Guido Krage, Sonja Oesterheld, Florian Mueller, Sunna O. Wallevik and Kristjan Alexandersson.

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