The Development of a Hand-Held Rheology Tool for characterising the Rheological Properties of Fresh Concrete

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ABSTRACT

The use of the two-point workability test to describe the rheological properties of fresh concrete has been long established. This paper outlines the issues involved with the development of a hand-held version of the "Two-Point" test that will have the capacity to measure the fresh properties of concrete on the construction site.

INTRODUCTION

It has been recognised for some time that traditional methods for measuring the rheological properties of concrete as specified in the British and European Codes of practice are not sufficiently accurate for characterising fresh concrete on the construction site. The measurement of the fresh properties of concrete has changed little over the last century; when fresh concrete arrives on site normally a slump test is conducted on the concrete before the concrete is placed. Although there is a correlation between the slump of a concrete and the yield stress, which was observed by Tattersall and Banfill[1], there is no correlation between the slump and the plastic viscosity of the fresh concrete. So, effectively, two concretes may have the same slump value but in reality they may behave very differently under flow conditions[2]. These current testing methods are dated and are no longer sufficiently accurate for characterising fresh concrete on site.

The placing, pumping, compaction and finishing of fresh concrete are all closely related to the fresh properties of concrete. With all the advancements in concrete technology and research that has taken place in rheology of fresh concrete in recent years it is now possible to accurately predict the fresh properties and design concrete mixes accordingly[3]. The science behind the designing of tailored concrete mixes to suit particular applications has moved forward with the help of rheology. However, when the concrete arrives on the construction site, there is normally no readily available test that can solely determine the rheological properties of fresh concrete[4]. This gives rise to the clear need for a more universal scientific and accurate means of testing of fresh concrete on arrival to the construction site.

Presently in the construction industry, an ever-increasing proportion of concrete is pumped throughout the site and the flow properties determine how efficiently this concrete can be pumped. It is only a matter of time before self-compacting concrete (SCC) will become as widespread in the European market as it has in Japan; the introduction of a quick and simple test to determine the flow properties of this type of concrete is vital for consumer confidence and quality assurance of the product. The introduction of a hand-held rheological tool that is robust, lightweight, portable and that has the capabilities of accurately and quickly determining the rheological properties of fresh concrete on site will inevitably help in the quality control of concrete and will have the capability of diagnosing problematic concrete before it is poured. This would eliminate any unnecessary delays in construction with the potential for costly and time-consuming investigation into problematic concrete. The authors are now at the stage of developing a pre-commercial prototype rheology tool, combining the experience with the technologies that have been gained over the past 10 years at Trinity College. This tool is described in the paper.

RHEOLOGY OF FRESH CONCRETE

Rheology, the science of deformation of flow of matter, can be used to characterise the flow behaviour of fresh concrete. The ease of placement, durability, strength and appearance are all related to the fresh properties of concrete[3]. With the more widespread use of more complex forms of concrete in the industry, such as Rheodynamic Concretes and SCC, more precise methods of testing need to be introduced into regular concrete production. These advanced concretes lie outside the validity of the slump test and are currently tested by a combination of simple tests which assess three areas of the concrete's performance; its filling ability, its passing ability and its stability. However, there is no test that can measure all three properties and, furthermore, there is no clear correlation between test results and performance on site[4]. It is strongly believed that a rheological test is more appropriate in these cases; however, there are no favourable alternatives to these quick and simple tests (L-Box, Slump Flow, J Ring) and it is their simple and robust nature that makes them so popular[5].

In 1976 Professor G. H. Tattersall[2] adapted a Hobart food mixer and used it to measure the torque required to turn an impeller immersed in fresh concrete at a constant speed. By running the device at several speed settings, Tattersall observed that there was a linear relationship between torque and angular velocity of the impeller, which was found not to pass through the origin. Tattersall recognised that fresh concrete behaves, as a Bingham material (see Fig. 1) This indicates that the shear-stress (τ in MPa) shear-rate (γ in s^{-1}) relationship of the concrete approximates closely to linearity, with a positive intercept on the stress axis, where the yield value τ_0 (MPa) and plastic viscosity μ (Ns/m^2) can be related mathematically by Eq. 1.

$$\tau = \tau_0 + \mu.\gamma \qquad (1)$$

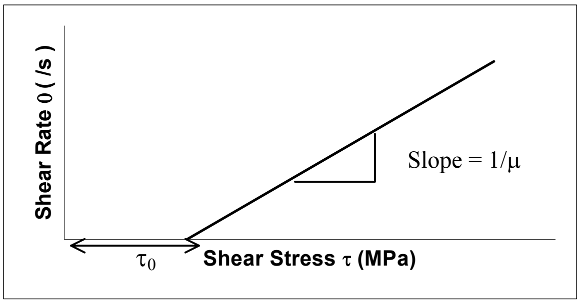

Figure 1. Flow line for a Bingham fluid.

TWO POINT WORKABILITY TEST

It is well known that in 1983 Tattersall and Banfill[1] designed a more suitable test for measuring the rheological properties of fresh concrete, which involved rotating a specially designed impeller at several different speed settings in a bowl of fresh concrete. According to Tattersall's earlier findings[2] a minimum of two points are needed to characterise the flow properties of fresh concrete hence, the test became known as the "Two Point Workability Test". Figure 2 is a graph of a typical flow line for concrete and can be described mathematically by Eq. (2)

$$T = g + h.N \qquad (2)$$

where T is the torque (Nm) required to rotate the impeller immersed in the concrete, N is the angular velocity (revs/min), g is the intercept with the torque axis and h is the reciprocal of the slope of the line. Equations 1 and 2 can be related to each other by calibrating the device with oils of known viscosities and yield stresses.

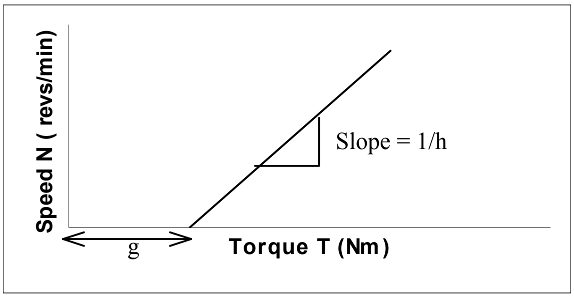

Figure 2. Typical flow line obtained from rotating an impeller in fresh concrete.

Domone et al.[6] have further developed the "Two Point" test and a computer assisted model is commercially available[7].

CONCRETE RHEOMETERS

A study was carried out at the LCPC in Nantes, (2000)[8] sponsored by the American Concrete Institute (ACI) which involved the comparison of concrete rheometers which were developed in different countries to see whether the results from each apparatus could be correlated. The rheometers included the BML[9], IBB[10], Two-Point[6], the BTRHEOM[11], and the CEMAGREF-IMG[12] rheometers. The conclusions from the study showed that although there was considerable variance in the yield stress and plastic viscosity measurements between the different rheometers, each rheometer characterised the concrete as a Bingham material and out of the 12 concrete mixes tested, each rheometer ranked the mixes in the same order for both yield stress and plastic viscosity. Considering the variety of rheometers used (coaxial cylinders, parallel plates, and interrupted helix) the agreement and predictability of results from one apparatus to another was found to be compelling.

All the rheometers that were used in the study at Nantes were primarily designed for use in laboratory conditions to assist in the designing of concrete mixes and for research purposes. Rheometers of this nature are unsuitable for use on the construction site due to their limitations in their portability due to their size, weight, the need for electricity and computers to analyse results.

RHEOLOGY TESTING AT TCD

TCD has been actively researching in the area of rheology of fresh concrete for over a decade and has developed two prototypes for measuring the flow properties of fresh concrete, and a third prototype[13] is currently nearing completion.

TCD Prototype No.1

The first of these prototypes was developed in 1992 by O'Leary[14] (see Fig. 3) and was based on Tattersall's second Two Point Workability Apparatus (1983). The main differences between Tattersall's device and the TCD device were; torque measurement was measured by means of a current transducer measuring the current requirement of a DC-motor, and angular velocity was measured with an optical tachometer. Both signals from the optical tachometer and the current transducer were sampled with a PC and the results were analysed with statistical software. The TCD prototype was found to produce more accurate and reliable results than Tattersall's second device with all acceptable values of coefficient correlation exceeding 0.995. The TCD apparatus has been used as a research tool to investigate, amongst other parameters, the effect of normal constituents, vibration and steel fibres on the rheology of fresh concrete.

Although both the TCD and Tattersall device can accurately and repeatably characterise the rheological properties of fresh concrete, they have their drawbacks, principally both apparatuses are very limited in their portability. They are large and are more suited to measuring the rheology of fresh concrete in laboratory conditions. Both apparatuses run at a number of discrete speed settings and both require two sets of readings, "No Load and Load", which means that a single test can take up to 10 minutes to complete.

Figure 3. The TCD two point workability apparatus[14].

A revised edition of Tattersall's device developed by Domone et al.[6] has succeeded Tattersall's second edition. The revised edition speeds up the testing procedure with the eradication of the different speed settings, and records the torque and speed data on an accompanying PC. However, the issues regarding the size and portability of the apparatus remain.

TCD Prototype No. 2 – Hand-held

In 2002 it was proposed to develop a second prototype rheology tool[15], with a view to investigating whether it would be possible to construct a mobile hand-held rheology device that would be capable of accurately and repeatably characterising the rheological properties of fresh concrete on site. With improvements in data sampling technologies, it was decided to have a continually varying rotational speed, with a data logger continuously monitoring changes in RPM and torque of the impeller rotating in the fresh concrete in a similar fashion to that implemented by Domone et al.[6]. This has reduced the testing time.

Prototype No. 2 (see Fig. 4) comprises of a modified hand drill utilising current as a measure of torque and an optical tachometer as a measure of angular velocity. Both current and velocity data are logged and analysed on a data logger alongside the drill.

Figure 4 Prototype hand-held rheology tool[15]

Before a suitable system for logging the current and angular velocity data was implemented, a system of five speed settings was used similar to that used on the TCD prototype No. 1. Figure 5 shows a typical plot of results from this setup with error bars in place representing the fluctuations in the measured current due to the inability of the operator to provide sufficient torsional restraint for the device. Figure 6 shows a typical plot of results after the data logging system had been implemented.

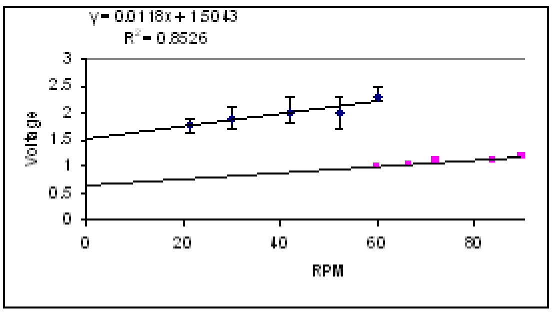

Figure 5. Initial testing using five different speed settings with the hand held prototype.

Prototype No. 2 has displayed positive initial results regarding its ability to detect small changes in the concrete's yield stress and plastic viscosity[15] when testing normal concrete mixes.

Prototype No. 2 was also used in a study of the rheology of SCC[16], where results displayed positive trends (see Fig. 6). Six SCC mixes of a similar composition were made and were tested using the slump flow test[4] and the hand-held device.

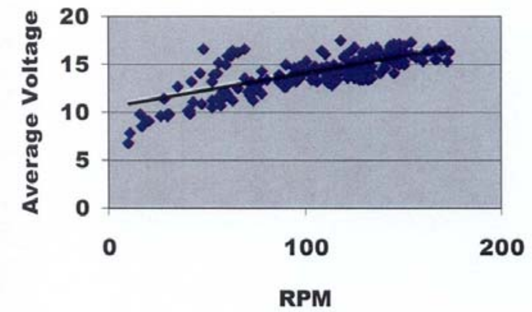

Figure 6. Results of SCC using varying angular velocity

There was found to be variation in the yield stress values obtained, however this variation was found to have a correlation with the measured slump flow tests. As slump flow values increased there was a decrease in the measured yield stress values. As might be expected, similar trends were not noticed regarding the plastic viscosity of the SCC mixes.

There are a number of contributing factors that affect the sensitivity of the device including errors involved with the measurement of the current and speed data, one of them being the operator's inability to provide sufficient torsional restraint while the impeller is rotating in the concrete. The modified drill which was used as the basis of prototype No. 2 was found to be ergonomically unsuitable in its design. With only one handle, the device placed large stresses on the operator's wrist as the impeller struck pockets of grout and aggregates. This made it difficult to provide sufficient restraint and was found to be uncomfortable and potentially dangerous. Thus the inability to provide sufficient restraint for the device has a detrimental effect on the quality of the recorded data and subsequent results. Insufficient restraint has a damping effect on the torque measurement and, due to the absorption effect caused by the lack of rigid restraint, the measured values are not found to be a true representation of the actual torque experienced at the impeller.

Other difficulties encountered with prototype No. 2 included the ability to accurately measure low torque and angular velocity data while the device was operating at low angular velocities, typically less than 25rev/min. With the inability to accurately measure low values of torque and angular velocity, this meant that higher velocities were measured so that a good spread of results could be measured for analysis. However, although the results were useful in the development of the device, the lack of lower values made it very difficult to accurately describe the rheological properties of concretes, especially SCC due to it's more complex rheology.

It was decided that further exploration was required to investigate whether it is possible to develop a hand-held rheology tool that can accurately determine the rheological properties of fresh concrete. This is the driving force behind the development of the third prototype.

<u>Key issues related to developing a hand-held version of the Two-Point Workability Test</u>

While developing a hand-held version of the two-point test, a number of issues arose that did not cause any problems with the existing laboratory apparatuses. Testing of fresh concrete using existing laboratory apparatuses is done in a controlled environment and each test is conducted in an identical manner. The aim of developing a hand-held test is to create a portable test which will provide a universal test for the rheological properties of fresh concrete at the construction site.

Power supply and requirements of existing concrete rheometers are in the region of 110V-240V which, for testing in laboratory conditions is acceptable, but is not always acceptable for site conditions due to safety constraints. To create a device that is truly portable then, the portability cannot be restricted by the location of a suitable power supply. However, the introduction of battery power as a replacement for traditional power supply introduces more issues in the development of a portable device. The size and power requirements of the motor to be used in the rheometer have to be considered, along with all other electrical and electronic equipment that will be present that require power in the device when selecting an appropriate voltage, capacity and composition of battery. Problems associated with battery selection include the compromise that has to be made between the maximum allowable weight that can be allocated to the battery and to the minimum amount of battery capacity that is required. Either a number of battery packs that are continually changed throughout the days testing, or a single battery pack that will have the power requirements to last the full day could be used depending on whether a battery can be sourced that meets both the capacity and weight requirements. It is imperative that the device has the capacity of completing a full day's testing without the interruption of having to recharge the battery during the day.

Existing concrete rheometers are all similar in design in one aspect; they are all based on a rigid platform design. Both the TCD No. 1 prototype and the "Two-Point" apparatuses are built around a structure that provides torsional restraint for the rheometer while the impeller is being rotated though the concrete mix. In the development of a portable version of a concrete rheometer, the idea is that the human frame will act as the structure that will provide the torsional restraint for the rheometer as the impeller rotates in the concrete mix, and that the operator will be responsible for the movement of the impeller through the mix. However, it is unknown at this stage whether the operator will be able to provide sufficient torsional restraint. It was found that in the testing of the TCD prototype No. 2 insufficient torsional restraint could be provided by the operator of the device. It is thought that if the device was to be designed to take full advantage of the most efficient and comfortable operating position to provide maximum torsional restraint for the rheometer, the issue could be overcome[13].

The accurate measurement of torque and angular velocity of the impeller at low angular velocities was found to be problematic with the methods used in prototype No. 2. For a successful hand-held device to be developed, it is imperative that a system of accurately measuring the torque and angular velocity be implemented, it is these lower values that are of most importance in describing the flow of fresh concrete and in the prediction of how the concrete will behave when being placed.

Creating a test that is universal and complete is essential. Some of the existing apparatuses utilise a computer to analyse and compute the rheological properties of the concrete. If the need for a computer to analyse the results can be eliminated then the device becomes more portable.

FINAL PROTOTYPE

The TCD prototype No.3 is to be the final prototype for a hand-held rheology tool which is nearing its completion. The third prototype has been designed to overcome all the issues that have been previously discussed, both for conventional desk based and hand-held tools. The success of the prototype will not be known until testing has taken place. The development of the third prototype can be divided in to two categories, electronic, and ergonomic, both of which features will be discussed.

Electronic

The third prototype is being developed around an embedded microprocessor. A simple menu system has been developed for the operation of the tool which uses a small liquid crystal display (LCD) and a 12 button alphanumeric keypad for user interface with the device. The microprocessor controls every aspect of the device from maximum rotational speeds of the impeller, duration of the test, recording of torque and rotational velocity data, processing and reduction of recorded data, displaying rheological results of the test along with the coefficient of correlation for the reduced data. The device has the capability of saving each test result along with time and date of test plus a 20 character string that can be inputted via the keypad. The embedded system can transfer all saved data from the device to a PC for further analysis if necessary and for saving as a permanent record.

The main difficulties have been concerned with the interfacing of the electronic components, which include a motor controller circuit, keypad, LCD, safety systems and a novel torque/angular velocity measurement system which has the capabilities of accurately measuring low values of torque and angular velocity.

Ergonomics

The ergonomics of the hand-held device plays a vital role in the development of a successful prototype. As previously described when testing Prototype No. 2, the inability of the operator to provide sufficient torsional restraint for the device has a negative effect on the quality of the results obtained. A design was developed with the aid of a dummy model to assist in the ergonomic design process (see Fig. 7). It was decided that in order to provide a stable and rigid platform for the device, two handles placed at waist height of the operator and at an angle of 120^0 to each other, accompanied with an adjustable underarm brace and a guide that rests on the operators leg just above the knee would be the most comfortable for the operator. This type of design makes efficient use of the human body to resist torsional forces and makes it relatively easy for the operator to guide the impeller through the concrete mix.

Other ergonomic considerations include keeping the overall weight of the device to a minimum to assist in the ease of use and to improve the operator's comfort.

Figure 7. Non working prototype developed to assist in the ergonomic design process.

The device also includes certain safety features which will help reduce the likelihood of the operator from causing themselves injury. Sensors are located on each of the two handles, such that for the operator to conduct a test, both hands must be in place on the handles. Should one of the hands be removed during a test, then the test will automatically be aborted. This feature has been introduced to compensate for the unlikelihood of the impeller becoming stuck during a test whereupon the operator can let go of one hand to abort the test procedure and prevent any unnecessary injury to the operator and damage to the device.

CONCLUSIONS

It is expected that the difficulties associated with conventional concrete rheometers will be overcome and that a universal hand-held rheology device will be developed. It is anticipated that the introduction of such a device will emerge as a practical tool in the testing of fresh concrete on site.

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