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Rheological Behaviour of Cement Paste with Fly Ash in the Formulation of Self-Compacting Concrete (SCC)

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Abstract: The use of Self-Compacting Concrete (SCC) is growing rapidly due to its ability to compact solely under its own weight. But, due to the unavailability of a universally approved mix design procedure, the industry uses trial and error methods to proportion mixes leading to high material and time wastage.
Unlike traditional concrete, SCC possesses a very high workability. Thus, it is worthwhile to be evaluated through a rheological point of view. But, to facilitate high workability, SCC requires a sufficient amount of paste to fill the voids and confine its aggregates. However, if the binder or the cement content is raised to achieve this purpose, it will result in many negative structural and non-structural impacts. It will not only increase the cost, but will also lead to cracks due to the increased heat of hydration. It will also harm the environment through excessive use of resources, while contributing to the emission of large amounts of carbon dioxide, a greenhouse gas. Therefore, Supplementary Cementitious Material (SCM) such as fly ash could be identified as a better supplement to overcome these problems.
This study focuses on determining the yield shear stress and plastic viscosity (Bingham constants) of paste having varying constituent proportions, by using coaxial type rheometer. Both individual and combined effect of water/cement (w/c) ratio and fly ash content on the rheological behaviour is observed and analysed to determine the optimum SCM composition for a mix for two common w/c ratios. The results for optimum material quantities could be used as a guide for initial trial mixes, minimizing the time and material wastage.

Keywords: Rheology, Self-Compacting Concrete, Bingham model, coaxial concentric rheometer, Fly Ash

1. Introduction

Self-Compacting Concrete (SCC) was first developed in Japan in 1988 to overcome inefficiencies in the traditional concreting procedure. Insufficient compaction leads to increase the presence of air voids and a reduction in both strength and durability, whereas, too much compaction leads to segregation, creating non-homogeneous products. Therefore, SCC has been identified as a valuable substitute in structures where complex shapes and congested reinforcements are involved.

1.1 Criteria for Self-Compactability

For a concrete to be categorized as self-compacting, the following criteria should be fulfilled [1].

Filling ability: Ability to flow freely, both in the horizontal and the vertical directions and fill the formwork completely under its own weight without any other form of external compactive effort.

Passing ability: Should not cause any type of blockage when passing through a narrow gap

Stability: Should not segregate during mixing, placement and after casting. Otherwise, it may lead to a non-homogeneous mix.

The above criteria are mainly associated with the flowability of SCC. Therefore, SCC is much suitable to be evaluated in a rheological perspective. Bingham model, which depicts a linear relationship between shear stress and shearing rate, is useful in this regard.

1.2 Rheology

Rheology is the science dealing with flow and deformability of material. Even though, slump flow is the most common method to assess SCC, the flow values may differ with differences in the formwork geometry and reinforcement. Therefore, studies based on rheology are much more important to evaluate the functionality of SCC [2].

1.3 Bingham model

There are many models, such as, Bingham model, Herschel Bulkley model, and modified Bingham model developed to characterize the rheological properties of thick suspensions. The latter two are nonlinear models, whereas the former is the simplest, which depicts a linear relationship between shear stress and shearing rate. However, there are some evidences where the yield shear stress has given very small negative values probably because, SCC has a yield shear stress which is closer to zero [1],[3].

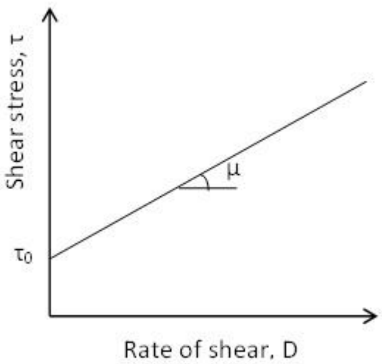


Figure 1: Bingham model

Figure 1 elaborates the Bingham model, which gives the simplest relationship of all. Rheological properties of a paste could be simply defined using the Bingham constants; Yield shear stress and Plastic viscosity, which are defined as follows:

- Yield shear stress: The critical shear stress at which a thick suspension (e.g., concrete) initiates its flow (different to Newtonian fluids). It is given by the intercept of the line (τ_0)

- Plastic Viscosity: Rate of increase of the resistance to flow with the increase in shearing rate, once the flow has initiated. It is represented by the gradient of the line (μ)

To satisfy the filling ability criterion, it is necessary to incorporate a high capacity of deformation. Thus, a low yield shear stress is required. To ensure a uniform suspension without segregation of aggregates and mortar, the SCC must have a moderate viscosity. Therefore, it is necessary for a concrete to have a low yield shear stress and a moderate plastic viscosity, to be categorized as a self-compacting concrete. Nevertheless, there are interdependencies between these two parameters. For example, increasing the water content to reduce the yield stress would also reduce the plastic viscosity, and it may lead to segregation of particles. If the cement content is kept constant this would result in a decrease of strength as well. Therefore, the use of high range water reducing admixtures (HRWRA)/ superplasticizers are necessary to support high water reduction without compromising the workability. However, it should be noted that the effect of superplasticizer diminishes with time [1]. Performance of superplasticizer mainly depends on the inherent properties of the product and will not be discussed in this paper. Nevertheless, it is necessary to consider its effect as well in the formation of SCC.

1.4 Paste and the rheology

The paste volume must be sufficient to fill the voids and to create an enveloping layer around aggregates to lubricate the relative movement between particles [4]. This could be accompanied by increasing the cement content, which may result in high costs. Furthermore, it will contribute to release large amounts of heat of hydration, resulting in cracks, which raises concern on serviceability and durability of the structure. In addition, it contributes to environmental issues such as greenhouse effect, with the release of carbon dioxide to the atmosphere. To overcome such problems, substitutes should be identified, which could replace the cement partially. Fly ash is one of such material which will help to reduce the above mentioned problems.

1.5 Objectives and scope

Despite the wide use of SCC in the construction industry, there is no universally accepted mix design methodology to formulate concrete with target self-compactable properties. Therefore, SCC is formed based on trial and error methods, leading to a large amount of material and time wastage. This could be avoided if the characteristics of the self-compacting concrete are to be adjusted at the earliest possible point in the mixing process. Therefore, linking the rheological properties of the paste to that of the final SCC mix is of great importance. To do so, the behaviour of the mix with the addition of each material should be studied thoroughly.

This study focuses on identifying the rheological behaviour of paste when fly ash is added to paste comprising cement and water. The relationships are determined in terms of Bingham constants, yield shear stress and plastic viscosity. The study is based on two common w/c ratios that are used in the industry, and the experiment is carried out using a coaxial type rheometer. However, testing the time-dependent rheological properties and the hardened concrete properties of the SCC are left outside the scope of this study.

2. Literature Review

There has been extensive research on the formation of self-compacting concrete. But, only a handful of research concentrates on the rheological characteristics.

SCC can be treated as a two-phase material, composed of coarse aggregate and suspending mortar. Similarly, mortar is a two phase material composed of fine aggregate and paste. Therefore, the workability of the mortar must be dependent upon the physical properties and the quantity of fine aggregates, as well as the rheological characteristics of paste [5].

2.1 Excess thickness theory

Experimental studies have shown that the fluid mortar volume must be sufficient to fill voids between coarse aggregate particles and also to create an enveloping layer to lubricate the relative movement of coarse aggregates [3].This layer is known as the mortar film and its thickness is half of the spacing between aggregate particles. Similarly, excess paste thickness is referred to as the thickness of the film layer which is in excess of the paste, after the paste fills the void spaces in between fine aggregate particles [4].

Paste film thickness relates the combined effect of the content and the physical properties of the fine aggregate. In a similar manner, mortar film thickness account for the content and the physical properties of the coarse aggregate. When the mortar film thickness is kept constant, the rheology of SCC can be determined by the rheological characteristics of the mortar. Similarly, when the paste film thickness is kept constant there will be such relationship between the paste and the mortar as well. Thus, when both paste film thickness and mortar film thickness are kept constant, the rheology of SCC could be directly related to the rheology of paste. Experimental studies have been carried out to directly relate the paste to SCC by means of Bingham constants. Thus, SCC mix could be altered at the earliest possible point to avoid unnecessary wastage of material and time, using a simple mini slump cone test. However, this concept has been evaluated only by varying the superplasticizer dosage and the water/cement ratio (w/c). It has also been assumed that the mortar film thickness around gravel particles are same for all gravel sizes, particles are spherical and the equivalent diameter can be obtained through sieve analysis. However, future research has been proposed on the investigation of mortar film thickness and the paste film thickness [5].

2.3 w/p ratio and SCC

Water-cement ratio is the most significant single parameter that governs the strength of concrete while, w/p (water/powder) ratio governs the workability of the concrete. The term "powder" is defined as a material of particle size less than 0.125 mm [6]. This includes cement, supplementary cementitious material, and even non-cementitious material falling in to that size. In traditional concrete, the w/c ratio is altered and through that, the required strength is achieved. In contrast, design of SCC concentrate more on the workability and thus, the governing factor would be w/p ratio, and the paste content. Extensive research has been carried out to link the variation of w/p to SCC properties (i.e. by varying water, cement, filler and the superplasticizer dosage). One method of carrying out mix design for SCC has been identified as to keep the fine and coarse aggregate contents constant and to vary the powder characteristics to achieve self-compatibility [7]. However, neither single method nor combination of methods has been approved universally as a mix design method for SCC.

2.4 Supplementary Cementitious material (SCM)

As mentioned previously, in order to achieve adequate self-compatible properties, it is always necessary to achieve a moderate viscosity in the SCC mix. So, it is necessary to obtain a low w/p compared to the traditional concrete, and in order to do this, the finer material content has to be increased [1],[8],[9].This helps to enhance the cohesion and ultimately result in good segregation resistance between the binder phase and the aggregate particles. However, if the binder or the cement content is increased it will increase the cost, increase the heat of hydration and lead to cracks, while contributing to the emission of a large amount of carbon dioxide, a greenhouse gas, to the environment. Therefore, SCM could be identified as a better replacement to overcome these problems.

There has been investigations on how the rheological properties of SCC varies with the addition of various SCMs such as; Silica Fume (SF), Metakaolin (MK), Ground Granulated Blast furnace slag (GGBS), Siliceous Fly ash (class F fly ash - FAF) and Calcareous fly ash (class C fly ash -FAC) [9]. The summary of the outcomes are listed below.

- SF and MK : reduce workability, plastic viscosity and permeability of SCC; gives a high early strength; increase HRWRA demand & yield shear stress.
- GGBS: improve workability; reduce early strength, HRWRA demand and plastic viscosity
- FAC: higher HRWRA demand than the FAF, increase plastic viscosity
- FAF: reduce HRWRA demand, reduce (maintain somewhat constant) plastic viscosity
- Water/binder ratio: reduce HRWRA demand, reduce plastic viscosity
- Viscosity Modifying Admixture (VMA): enhance plastic viscosity

Among these SCMs, class F fly ash is the most commonly found material which could be used to enhance the properties of the SCC. Class F fly ash meets pozzolanic properties while class C fly ash meets latent hydraulic properties (cementitious properties), in addition to weaker pozzolanic properties. Both Fly ash types may contain carbon in significant amounts, which in turn reduce the strength of concrete and reduce the efficiency of air entrainment. However, out of these two categories class F fly ash has a spherical morphology and a smooth surface texture of grains, leading to a higher ball bearing effect to reduce inter-particle friction. Therefore, it reduces the plastic viscosity and enhances the workability. Other than that, low porosity of particles and a lower fineness has contributed to the low HRWRA demand. In contrast, class C fly ash contains irregular grain shapes reducing some of these benefits [9].

2.5 Typical ranges of proportions for SCC to achieve self-compatibility

Following guidelines are stated in literature as the most appropriate proportions in the formation of SCC [6].

- Water/ Powder ratio by volume : 0.8-1.1
- Total powder content : 160 - 240 L/m^3 (400-600 kg/m^3)
- Water content, typically less than 200 L/m^3

2.6 Testing

Some of the most common tests used to evaluate the characteristics of SCC are: slump flow test, V-funnel test, J-ring test, L-box test, U-box test and sieve segregation test. In the laboratory, the most commonly used type of tests applied on cement paste are the mini slump cone test, Marsh cone test, and the coaxial rheometer test. Out of these three, the most convenient and simple test is the mini slump cone test which is an indirect test used to estimate the yield shear stress and plastic viscosity of flowable paste. However, the geometry of the cone largely affects the test results [10]. Equations have been identified to link the plastic viscosity and yield shear stress to the slump flow and flow time.

The other common apparatus used is the coaxial type rheometer, which is a direct method of measurement. However, the results depend highly on the accuracy of measurement and the geometry of the cylinder. There, are several equations obtained to relate the Bingham constants with the rheometer readings (torque and rotational velocity). There have also been attempts to relate the mini slump cone test results with the rheometer test results [10].

3. Methodology

3.1 Material

Material required for the experiment are defined according to the ASTM standard as in Table1.

Table 1: Properties of ingredients

Material	Description	
Cement	Type	ASTM Type 1 OPC
	Specific gravity	3.15
	Blaine fineness	326m^2/kg
Fly ash	Type	ASTM C618 Class F fly ash
	Specific Gravity	2.15
	Blaine fineness	438m^2/kg
	Particle size	Passing 75 μm sieve

3.2 Procedure

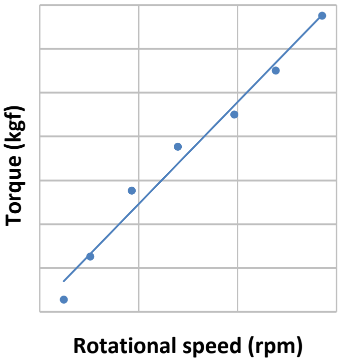
The results of the experimental program was analysed using the Bingham model. Each specimen was tested with coaxial type rheometer as stated in ASTM guidelines [11]. The equations to convert experimental data to yield shear stress and plastic viscosity are stated in a later section.

The effect of fly ash on cement paste mix was observed, for w/c ratios of 0.50 and 0.55. The fly ash content by mass of cement was varied as 0%, 6%, 12%, 18%, 24%, 30%, and 36% for each w/c ratio. It was expected that only a certain amount of fly ash to contribute to the hydration reaction. The rest was expected to stay in the matrix as an inert compound contributing to the powder, enhancing the workability.

3.3 Apparatus, tests and mixing procedures

The Bingham constants were evaluated using a coaxial type rheometer as indicated in Figure 2 (a). This is a direct test method of obtaining yield shear stress and plastic viscosity. The test was performed according to the guidelines given in ASTM C1749-12: "Standard Guide for the measurement of rheological properties of a hydraulic cementitious paste using a rotational rheometer". For the apparatus to be categorized as a narrow gap concentric cylinder, it had to satisfy the following requirement as per the guideline, where R_1 and $R_2$is the radius (m) of the inner stationary cylinder and the outer rotating cylinder respectively.

$$\frac{R_1}{R_2} \geq 0.92$$



(a) (b)

Figure 2 : (a) Concentric cylindrical rheometer , (b) Rheometer observations and trend line

The available rheometer satisfied the above requirement and was categorized as a narrow gap concentric cylinder. The following equations were used in the determination of shear stress and shearing rate from the torque and rotational speed respectively.

$$\text{Shear stress} = \frac{T}{2\Omega R_1^2 L}$$

$$\text{Shearing rate} = \frac{\Omega i.\ R_2}{R_2 - R_1}$$

Ω_i - rotational speed of the outrer cylinder (r/s)
T - torque (N·m)
L - cylinder length (m)

In the coaxial type cylindrical rheometer (Figure 2(a)), the outer cylinder is rotated, while the inner cylinder is kept stationary. Thus, to prevent slip through the development of a liquid layer on the wall of the rotating cylinder, the cylinder surfaces are made rough.

The initial torque reading had to be obtained 20s after continuous rotation at the lowest speed. All the readings were first taken in the ascending order and then, in the descending order. The torque and the rotation was recorded at each stage and it was converted to shear stress and shearing rate values as stated in the ASTM standard specification. The expected variation of torque with the rotational velocity is indicated in the Figure 2(b).

In the presence of only cement, water and fly ash, the approach to mixing is different than the concrete, due to the absence of aggregates. The ASTM C1738/C1738M-14 [12], provides the guidelines to carry out the tests. As stated in the standard, the method has been useful in testing the rheology of the paste because it gives similar results to those obtained in a concrete mix where the aggregates have been removed. Mixing of paste does not falls under ASTM C305,since, it should not be thoroughly mixed due to the absence of sand. This practice is known as high shear mixing, because, it imparts a significantly higher amount of shear than in ASTM C305 [13].

4. Results and Discussion

4.1 Influence of fly ash content on yield shear stress of paste

The fly ash content of the paste was varied from 0% to 36% by mass of cement at w/c 0.5 and w/c 0.55. The only constituents in the paste while carrying out this experiment was cement, water and fly ash. The extracted results for the yield shear stress of those samples are shown in the Table 2.

Figure 3 is the graphical representation of variation of yield shear stress with the fly ash content by the mass of cement. As shown, the yield shear stress of the paste has increased, approximately following a polynomial function with the addition of fly ash. It further shows a significant change after 18% of fly ash by mass of cement. Even though, fly ash could be used to reduce the heat of hydration as a partial substitute for cement, adding excessive amounts would increase the yield shear stress creating a high resistance to initiate flow. Thus, it is better to keep the maximum substitution level of fly ash for cement, below 18% as indicated.

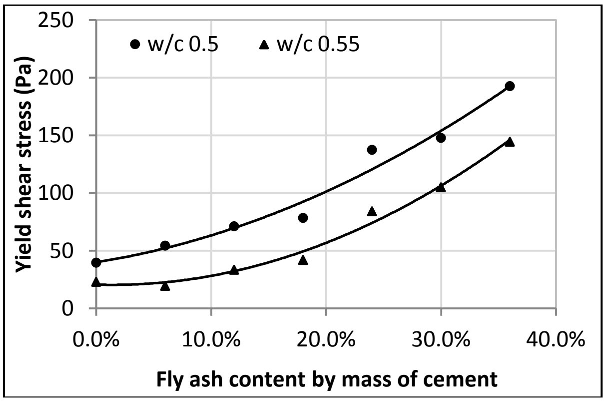


Figure 3: Variation of yield shear stress with fly ash content from (0 to 36%)

It also shows a reduction in yield shear stress with the addition of water (higher w/c ratio). However, near zero fly ash content, the two trend lines converges to closer values. The increase of yield shear stress with the addition of fly ash is more significant at w/c 0.50 compared to w/c 0.55. Table 3 indicates results in detail. The two equations given by the two polynomial trend lines are as indicated in Table 4.

Table 3: Yield shear stress result for different fly ash contents (*FA : Fly Ash)

Sample	w/c	Fly ash	Abs vol of *FA/ total vol	Yield shear stress (Pa)
LFA(0)	0.50	0	2.00	40
LFA(0.06)	0.50	0.06	1.45	54
LFA(0.12)	0.50	0.12	1.34	71
LFA(0.18)	0.50	0.18	1.25	78
LFA(0.24)	0.50	0.24	1.17	137
LFA(0.30)	0.50	0.30	1.09	148
LFA(0.36)	0.50	0.36	1.03	193
HFA(0)	0.55	0	1.82	23
HFA(0.06)	0.55	0.06	1.59	19
HFA(0.12)	0.55	0.12	1.47	33
HFA(0.18)	0.55	0.18	1.37	42
HFA(0.24)	0.55	0.24	1.28	85
HFA(0.30)	0.55	0.30	1.20	105
HFA(0.36)	0.55	0.36	1.13	144

Table 4: Functions for yield shear stress variation with fly ash by mass of cement (FA)

w/c	Yield shear stress (τ)	R^2
0.50	$734.5(FA)^2 + 159.8(FA) + 39.86$	0.972
0.55	$1047.(FA)^2 - 28.12(FA) + 20.46$	0.986

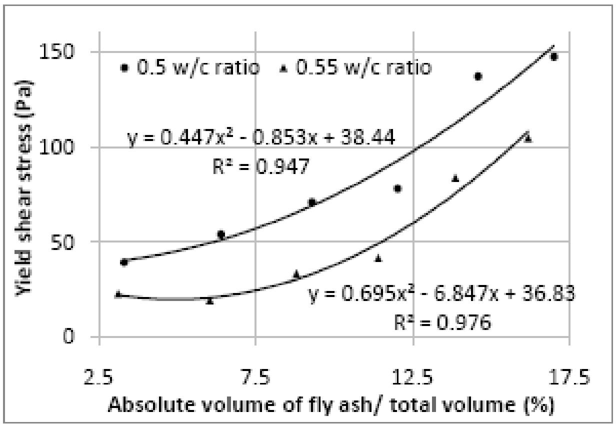


Figure 4: Variation of yield shear stress with the ratio between absolute volume of particles to total volume

The variation of the yield shear stress with the absolute volume of fly ash as percentage of the total volume of paste is indicated in Figure 4. Here, the absolute volume is the mass divided by specific gravity of each material. The total volume is the addition of absolute volumes of water, cement and fly ash. After 12% of absolute fly ash volume with respect to the total volume, the yield shear stress of the mix has increased dramatically.

4.2 Influence of fly ash on plastic viscosity of paste

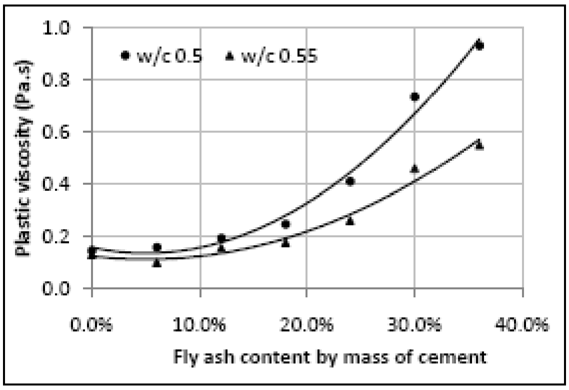


Figure 5: Variation of plastic viscosity with fly ash content from (0 to 36%)

The details of the variation of plastic viscosity with the fly ash content is given in the Table 5. Figure 5 indicates that in general, the plastic viscosity increase with the fly ash content for the two different w/c ratios. However, the polynomial functions vary and the lower w/c ratio (0.5 w/c) shows a higher plastic viscosity value compared to the one with the higher w/c ratio as expected. Nevertheless, in both cases, the rate of variation has differed after 18% fly ash by mass of cement. After this point there is an increase in the rate of change of plastic viscosity. More detailed results are shown in the Table 5. The functions of the two trend lines are given in the Table 6, which indicates a quadratic relationship between the two parameters.

Table 5: Plastic viscosity result for different fly ash contents (*FA : Fly Ash)

Sample	w/c	Fly Ash	Abs vol of *FA/ total vol	Plastic viscosity (Pa.s)
LFA(0)	0.50	0	2.00	0.147
LFA(0.06)	0.50	0.06	1.45	0.160
LFA(0.12)	0.50	0.12	1.34	0.195
LFA(0.18)	0.50	0.18	1.25	0.249
LFA(0.24)	0.50	0.24	1.17	0.411
LFA(0.30)	0.50	0.30	1.09	0.735
LFA(0.36)	0.50	0.36	1.03	0.931
HFA(0)	0.55	0	1.82	0.132
HFA(0.06)	0.55	0.06	1.59	0.101
HFA(0.12)	0.55	0.12	1.47	0.157
HFA(0.18)	0.55	0.18	1.37	0.177
HFA(0.24)	0.55	0.24	1.28	0.262
HFA(0.30)	0.55	0.30	1.20	0.460
HFA(0.36)	0.55	0.36	1.13	0.549

Table 6 : Functions for plastic viscosity variation with the fly ash content for different w/c ratios

w/c	Plastic viscosity	R^2
0.50	8.520(FA)2 - 0.855(FA) + 0.159	0.986
0.55	4.762(FA)2 - 0.478(FA) + 0.125	0.976

For convenience, the results have been presented as the absolute volume of fly ash as a percentage of total volume of the paste, as indicated in Figure 6. A similar, trend exist here as well, where there is a significant variation in the rate of change of plastic viscosity after 12% of absolute fly ash volume with respect to the total volume of the mix.

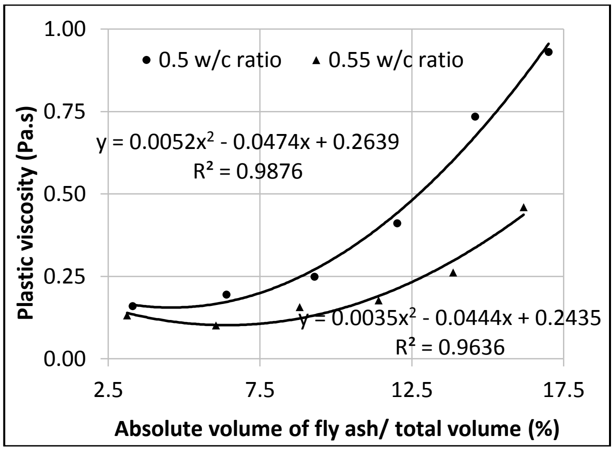


Figure 6: Variation of yield shear stress with the ratio between absolute volume of particles to total volume of paste

4. Conclusions and Recommendations

With the addition of fly ash to a paste the yield shear stress and the plastic viscosity of the mix increases according to a polynomial function. Both parameters shows significant rises in their values after 18% of fly ash by mass of cement. Even though fly ash is a good SCM which partially substitute cement, adding excessive amounts would increase both yield shear stress and plastic viscosity creating a high resistance to flow. The diminished self-compactibility will compromise the benefits from reduction of cement. Thus, 18% can be used as the optimum level of fly ash to proportion initial trial mixes.

If the optimum value is to be represented as a ratio between absolute fly ash volume to total volume, it would fall around 12%. This representation is more convenient in terms of proportioning.

Nevertheless, the hardened properties of the concrete, has not been linked to the rheology of the fresh mix within the scope of this publication.

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