Influence of Chemical Admixtures on Workability of Lightweight Aggregate Concrete

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ABSTRACT

Effects of superplasticizer and air entrainment on rheological parameters and slump of fresh lightweight aggregate concrete (LWAC) were studied. Results showed that increasing superplasticizer content in non-air entrained LWAC decreased the yield stress but did not have significant effect on the plastic viscosity. The yield stress and plastic viscosity of air entrained concrete were lower than those of non-air entrained concrete. As entrained air content increased, the plastic viscosity decreased whereas the yield stress remained relatively unchanged. Comparing concrete with or without entrained air at similar yield stress, the slump of the air entrained concrete was higher due to its lower plastic viscosity. At similar slump, the air entrained concrete had higher yield stress and lower plastic viscosity compared with non-air entrained concrete, implying that higher shear stress is needed to initiate flow of air entrained concrete but its flow resistance would be lower. In summary, superplasticizer and air entraining admixture improve the workability differently from rheology perspective.

Keywords: air entrainment, lightweight aggregate, plastic viscosity, rheology, superplasticizer, workability, yield stress

1. INTRODUCTION

The workability of fresh concrete is related to its flow behaviour that can be reasonably represented by Bingham model [1-2]. The model is a linear relationship between the shear stress and shear rate. Yield stress and plastic viscosity are two rheological parameters from the Bingham model that can be used to describe the flow behaviour of fresh concrete. The yield stress is the minimum shear stress that must be exceeded in order for the material to flow. Once the flow has started, the plastic viscosity of concrete determines its flow rate.

One of the most commonly used chemical admixtures is the superplasticizer. Superplasticizers are used extensively to improve fluidity and homogeneity of fresh concrete and to produce high performance concretes. With increasing superplasticizer content, both the yield stress and plastic viscosity of cement paste are observed to decrease [3]. Although the rheological behaviour of cement paste is useful to describe the behaviour of concrete, the behaviour of the latter is not always the same as the former. Superplasticizer also reduces the yield stress of fresh concrete, but either reduces or increases the plastic viscosity, depending on the mixture proportion [1-2]. In general, the effect of increasing the dosage of superplasticizer in concrete reduces its yield stress but does not affect the plastic viscosity significantly [1 -2, 4]. Chia and Zhang [5] investigated the effect of a naphthalene sulphonate formaldehyde-based superplasticizer on rheological parameters of lightweight aggregate concrete (LWAC), and found its effect on the yield stress and plastic viscosity to be similar with that of the normalweight concrete.

Air entrainment is a process whereby many small air bubbles are incorporated into the cement paste matrix that binds aggregate together in hardened concrete. Air entrainment has been used to protect hardened concrete from damage due to repeated freezing and thawing cycles. The entrained air bubbles are produced through agitation of the concrete during the mixing process and stabilized due to reduction of surface tension of water by adsorption of surfactants from the AEAs onto the bubbles' surfaces. Air entrainment is known to alter the properties of fresh concrete. This includes the improvement of workability by increasing slump [6]. Comparatively, the air entrained concrete is well known to be more cohesive than non-air entrained concrete and has a lower tendency to segregate by bleeding of water or separation of aggregate from the mortar matrix [7-8].

Struble and Jiang [9] investigated the effect of air entrainment on cement paste, and reported that yield stress of cement paste increases with increasing air entrainment, with or without the use of a naphthalene sulphonate formaldehyde-based superplasticizer. This result is consistent with the finding by Kreijger [10]. The same study [9] also shows that the plastic viscosity increases with air entrainment in cement paste with the superplasticizer, but decreases with air entrainment in cement paste without the superplasticizer.

Chia and Zhang [5] investigated the effect of air entrainment on the rheological parameters of LWAC, and found that the plastic viscosity of concrete with similar yield stress is reduced with increasing air entrainment. However, the yield stress is only reduced when the AEA is first introduced into the superplasticized concrete, and any further increase in entrained air content does not have significant effect on the yield stress. In general, increasing air entrainment is known to decrease the plastic viscosity of concrete while its yield stress is relatively unaffected [11].

In this paper, the effect of the chemical admixtures on the workability of the LWAC in relation to the rheological parameters and the slump of the concrete is presented. The effect of the chemical admixtures on LWAC is discussed from rheology perspective with explanations using quantitative experimental results.

2. EXPERIMENTAL DETAILS

2.1 Materials

In the study, ordinary Portland cement and a naphthalene sulphonate formaldehyde-based superplasticizer (SP)[1] were used for all the concretes. An air-entraining admixture (AEA)[2] of a blend of anionic surfactants and foam stabilizers was used for some concrete mixtures. Details of the materials can be found in reference [5].

Lightweight aggregates[3] (LWA) used in this study was expanded clay type with dry particle density and bulk density of 1100 and 650 kg/m^3, respectively. The LWA particle size ranged from 4 to 8 mm with 1, 2 and 24-hour water absorptions of 8.7, 10.2 and 13.7% by oven-dried mass according to ASTM C127-88, respectively. More than 60% of the 24-hour absorption took place within the first hour, and only less than 10% was absorbed in the second hour. Based on this, all the LWA was pre-soaked for 1 hour before mixing in the concrete. This will prevent rapid loss of workability during the tests to ensure the consistency of results.

Two natural sands with a specific gravity of 2.65 and different particle size distributions were used as fine aggregates. The reason for using a different grading of sand was due to unavailable supply after the old stock was used up when the experiment of Series I concrete was completed. The sands were tested according to ASTM C136-96a and complied with the requirements of ASTM C33-99a. The sand with a fineness modulus of 2.43 was used in Series I of the concrete mixtures, while the sand with a fineness modulus of 2.86 was used to prepare Series II concrete mixtures. Sieve analyses of the LWA and sands are given in Table 1.

2.2 Mixture proportions and preparation of concrete

In this study, there were two series of concrete mixtures. The mixture proportion of the concretes was similar with a w/c of 0.35, except for a different fineness of sand used. The mixture proportion of water, cement, fine sand and LWA by mass per cubic meter of concrete was 152 : 435 : 845 : 390 (kg/m^3). In addition, where AEA was added for air entrainment, the material proportion of the concrete was kept constant as entrained air content varied. This implied that the volume of the mortar fraction increased as air entrainment increased, resulting in a lower LWA volume in the concrete. The moisture states of the sand and LWA in the given

[1] W R Grace & Co. Super 20
[2] W R Grace & Co. Darex AE4
[3] Liapor GmbH & Co. (Hallerndorf-Pautzfeld) Liapor 6.5

mixture proportions were saturated surface dry and oven dry, respectively. The water content in the mixture proportion was the effective amount of water in the concrete during mixing and excluded the water absorbed by the LWA.

In the experiment, the sand and LWA were oven-dried before mixing to achieve good moisture control in the concrete, which is an important factor for repeatability in the test results. Before concrete mixing, the oven-dried LWA was pre-soaked in water for 1 hour. Water in excess of the amount required for the aggregate absorption and concrete mixing was used in order to ensure that all the aggregate particles were fully submerged during soaking. After 1 hour the excess water was removed and the mass added into the mixer included that of oven-dried aggregate, water absorbed by the aggregate in 1 hour, and mixing water based on concrete mix design. In this way, water absorption by the LWA would be consistent for the same given period. The mixing procedure can be found in reference [5]. The total time lapse between the addition of mixing water and the beginning of testing was kept constant at 7 $\pm$ 1 minutes.

2.3 Test methods

Slump test was performed for all the concrete according to ASTM C143, and density was determined according to ASTM C138. The air content of the LWAC was determined using the volumetric method in accordance with ASTM C173.

The yield stress and plastic viscosity[*] of concrete in the study were measured using a coaxial-cylinders BML rheometer[4], where the torque of an inner cylinder was measured as an outer cylinder rotates at variable angular velocities. Each concrete mixture was tested at about 15 minutes after the mixing water was first added, and the test lasted for about 45 seconds. The outer cylinder started rotating at 21 rpm (0.35 rps) while the inner cylinder was lowered. The first torque reading was made when the inner cylinder was fully immersed in fresh concrete and a maximum rotating speed of 26 rpm (0.43 rps) was attained. A total of 10 data points were collected at various step-down rotational speeds decreasing from 26 to 4 rpm (0.43 to 0.07 rps). At each speed, the transition time was 3 seconds after which 50 torque measurements were taken during a 1-second interval. Then the average of the 10 lowest measurements was

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[*] The BML rheometer requires equipment calibration with oil and separate input of calibration constants in the computer software. The data for the yield stress and rotational speed in reference [5] were based on calibration constants that were lower than the true values. This affected the values of the yield stress and the rotational speed. These constants are now corrected and the revised values of the yield stress and rotational speed are presented in this paper. The revisions do not affect the observed trends in reference [5].

[4] ConTec BML Viscometer 3 (http://www.contec.is/index.htm)

taken as a point on the graph of torque T versus rotational speed N. The setting of 'average 10 lowest measurements' was chosen to minimise any possible effect due to bridging of the coarse aggregates that might cause an abnormally high torque to be registered during the shearing of the concrete. At the end of each test, the computer software that was linked to the BML rheometer computed the yield stress and the plastic viscosity of the fresh concrete.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Influence of a naphthalene-based superplasticizer

Figure 1 shows the effect of SP dosage on the yield stress of concrete with different sand size distributions. In general, an increase in SP dosage reduced the yield stress. This means that the fresh LWAC had greater ease in initiating flow with the increase in SP dosage. This was the result of deflocculating of cement particles due to adsorption of the superplasticizer molecules onto the surface of cement particles, which leads to release of water originally trapped within cement agglomerates [1-2]. The difference of the sand size distributions did not seem to affect the yield stress of the concrete at given mixture proportion significantly (Fig.1).

The origin of the yield stress may be contributed by three primary sources [12]. One source is the mechanical interlocking between aggregates that give rise to internal friction [13]. The second source may be attributed to the attractive forces between the cement and other submicron particles [14]. The third source is a colloidal gel of calcium silicate hydrates that form around the cement particles as a result of cement hydration [15]. The final source is not expected to influence the yield stress significantly in the current study as the duration for cement hydration was less than 20 minutes at the time of the test. Thus, the reason for the reduction of the yield stress in this case was two-fold. The first was electrostatic repulsion between oppositely-charged cement particles due to adsorption of superplasticizer molecules, while the second was reduction of internal friction between the aggregates due to the release of entrapped water from the cement agglomerates.

Figure 2 shows that the concrete in Series I made with finer sand (Fineness modulus 2.43) had higher average plastic viscosity than the corresponding concrete with coarser sand in Series II (Fineness modulus 2.86) at similar SP dosage. This was probably due to a larger specific surface area of the former. Furthermore, it was observed that the plastic viscosity of the concrete in Series II decreased as SP dosage increased beyond 7.31 kg/m^3.

The slight reduction of the plastic viscosity in the concrete at higher dosage of SP may be due to the decrease of plastic viscosity of the cement paste in the concrete with high sand-aggregate ratio (S/A). The S/A for all the concrete in this study was 0.47. Tattersall [2] presented data showing that the addition of a superplasticizer resulted in a decrease in plastic viscosity in a concrete with a high sand content (S/A = 0.45), while the plastic viscosity was increased in a concrete with a low sand content (S/A = 0.35). The effect of the SP on the yield stress was approximately the same regardless of the S/A. Tattersall and Banfill [1] suggested that in concrete with high sand content, the sand fills the space between coarse aggregate particles. As a result, a reduction in plastic viscosity of the cement paste results in a reduction in the plastic viscosity of the concrete because the coarse particles do not move sufficiently closer together. On the other hand, in concrete with low sand content, the flocculated cement paste separates coarse particles, and when the cement is deflocculated due to the addition of SP, the coarse particles come closer together and generate greater resistance to flow. The result is an increase in the plastic viscosity of the concrete in spite of the decrease in viscosity of the cement paste.

Although some of the concrete mixtures showed a decreasing plastic viscosity as SP dosage increased, the effect is not as significant as compared to the decrease in the yield stress. In summary, increasing the SP dosage reduced the yield stress but did not have a significant effect on the plastic viscosity of the LWAC, which is consistent with that for NWAC [1-2, 4]. On the other hand, using coarser sands would lead to a lower plastic viscosity although the yield stress was not affected.

3.2 Effect of air entraining admixture

In Series I, the non-air entrained LWAC had air content of about 4.5% whereas the air content of the air entrained LWAC mixtures was varied from 6 to 17% using different dosages of AEA. The SP dosage was kept constant at 5.22 kg/m^3. The air entrained concrete had the same material proportion as the non-air entrained concrete except for different air contents. Due to increased air content from 6 to 17%, the fresh concrete density of the air entrained concrete in Series I decreased from about 1860 to 1535 kg/m^3, and the mortar density was reduced from 2135 to 1775 kg/m^3.

The effect of entrained air content on the yield stress of the fresh LWAC is presented in Fig.3. The figure shows that the yield stress of the air entrained concrete was relatively unaffected by the increase in entrained air content and was averaged at about 720 Pa (standard deviation 130 Pa). Comparing the results with those of the non-air entrained concrete made with the same aggregate and with the same SP dosage, the yield stress had reduced by ~50% with the introduction of entrained air (Fig.3).

Figure 4 shows the effect of entrained air content on the plastic viscosity of the fresh LWAC compared with that of the non-air entrained LWAC at similar yield stress. For the concretes of similar yield stress, their plastic viscosity decreased with an increase in the entrained air content. While the non-air entrained concretes had a mean plastic viscosity of 58 Pa·s, the plastic viscosity of the air entrained concrete was reduced from about 50 to 15 Pa·s as entrained air content increased from 6 to 17%.

3.2.1 Effect of air entrainment in concrete – The decrease in the yield stress from the non-air to air entrained concrete (i.e. from ~4.5 to 6% air) may be due to a drastic change in the size and distribution of air bubbles in the mortar matrix. The entrapped air bubbles are of random sizes and spacing. The entrained air bubbles are much smaller and more uniform in size than the entrapped air bubbles as they are stabilized by the anionic surfactants from the AEA, and well distributed throughout the mortar matrix during mixing. Due to these differences, the entrained air bubbles were able to act effectively as deformable and elastic ball bearings, reducing the mechanical interlocking and internal friction in the fresh concrete. On the other hand, the orientation of the anionic surfactants from the AEA on the surfaces of the air bubbles caused them to possess negative charges. Edmeades and Hewlett [7] suggested that superplasticizer adsorbed on cement surfaces may attract cations from solution to produce a positively charged surface. Thus, there would be electrostatic attraction between the oppositely charged air bubbles and cement particles [8-9], and this may increase the yield stress. In fact, this has been believed to be the reason for the increase of the yield stress in air-entrained cement paste [9, 10].

According to the discussion on the origin of yield stress from the previous section, the initial reduction of the yield stress in this case, as the concrete changed from non-air to air entrained, was likely to be dominated by the reduction of the mechanical interlocking, although the electrostatic forces of attraction was expected to increase. This explains the decrease of the yield stress, compared with the non-air entrained concrete although the change in total air content from non-air entrained to air entrained was small from about 4.5 to 6%.

Besides the reduction of the yield stress, the overall shear resistance of the concrete was reduced as the entrained air bubbles collapsed and deformed easily under shear forces, resulting in the decrease of the plastic viscosity as well.

3.2.2 Effect of increasing air entrainment in air entrained concrete – With increase in the entrained air content from 6 to 17%, the yield stress was relatively unaffected (Fig.3) while the plastic viscosity was decreased

(Fig.4). As the entrained air content increased, the volume ratio of the mortar fraction was also increased, causing the volume of LWA particles to decrease in the air entrained concrete. This resulted in greater distances between the LWA particles and further reduced inter-particle friction and interactions. These explain why the plastic viscosity was decreased. On the other hand, the increase in the entrained air content would also lead to greater electrostatic attraction between the air bubbles and the cement particles, leading to increase in the yield stress. However, this effect might be offset by the reduction of the internal friction due to the ball bearing effect of the entrained air bubbles and less LWA particles. As mentioned previously, the yield stress in concrete is partly due to the mechanical interlocking between aggregates and the electrostatic attraction between the cement and other submicron particles. As entrained air content increased, the effect of further increase in the electrostatic attraction might be offset by greater reduction of the mechanical interlocking such that the yield stress remained relatively unchanged as shown in Fig.3.

3.3 Comparison on workability of non-air and air entrained LWAC

Figure 5 shows the relationship between the yield stress and the slump of the concrete with and without air entrainment. The average plastic viscosity of the air entrained concrete was 19 Pa·s, while that of the non-air entrained concrete was 53 Pa·s.

From the figure, it appears that at similar slump the air entrained concrete had higher yield stress than the non-air entrained concrete. However, the air entrained concrete had lower plastic viscosity than the non-air entrained concrete. Hence, the flow behavior between the air entrained and non-air entrained concrete of the same slump may be different. The higher yield stress means that a higher shear stress is required to initiate flow of the air entrained concrete. However, once the flow has been initiated, the flow rate of the air entrained concrete will be higher than the non-air entrained concrete due to its lower plastic viscosity.

Comparing concrete of similar yield stress from Fig.5, it can be seen that the slump of the air entrained concrete is higher than that of the non-air entrained one. This is despite of the fact that the air entrained concrete had lower SP dosage, as compared with the non-air entrained concrete. The higher slump may be due to the fact that the air entrained concrete had lower plastic viscosity than the non-air entrained one.

4. SUMMARY AND CONCLUSIONS

Superplasticizer and AEA improve the workability differently from rheology perspective. A small dosage of AEA would be useful to improve the workability of fresh concrete as both the yield stress and plastic viscosity would be reduced. This is in contrast to the use of SP to improve workability as the SP reduces the yield stress but does not have significant effect on the plastic viscosity.

Based on the experimental results and discussion, the following conclusions maybe drawn:

1. As superplasticizer content was increased, the yield stress was reduced whereas the plastic viscosity was not affected significantly. At higher dosage, the plastic viscosity was reduced slightly due to reduction in plastic viscosity of the cement paste in concrete with high sand-to-aggregate ratio.
2. With given SP dosage, the yield stress and plastic viscosity of the lightweight aggregate concrete were reduced with air entrainment so that the air entrained concrete had lower yield stress and plastic viscosity than the non-air entrained concrete. As the air entrainment was increased, the plastic viscosity of the air entrained concrete was decreased, whereas the yield stress remained relatively unchanged.
3. At similar slump, the air entrained concrete had higher yield stress and lower plastic viscosity compared with the non-air entrained concrete. This implied that higher shear stress is required to initiate flow in the air entrained concrete, but the flow resistance of the air entrained concrete would be lower than the non-air entrained concrete. In order to obtain concrete with similar slump, less SP is required in air entrained concrete.
4. At a similar yield stress, the air entrained concrete had higher slump than the non-air entrained concrete. The higher slump of the air entrained concrete was probably due to the lower plastic viscosity by air entrainment.
5. Increasing fineness modulus of the aggregate led to lower plastic viscosity due to lower specific surface area of the aggregate. The yield stress, however, was not significantly affected.

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Table 1– Sieve analysis (cumulative retained) of coarse LWA and normal weight sand

D (mm)	9.5	4.75	2.36	1.18	0.60	0.30	0.15	pan	FM
LWA F6.5	0	80	100						5.80
Sand (Series I)	--	0	2	20	46	79	95	100	2.43
Sand (Series II)	--	1	8	30	63	86	98	100	2.86

D – Diameter; FM – Fineness modulus

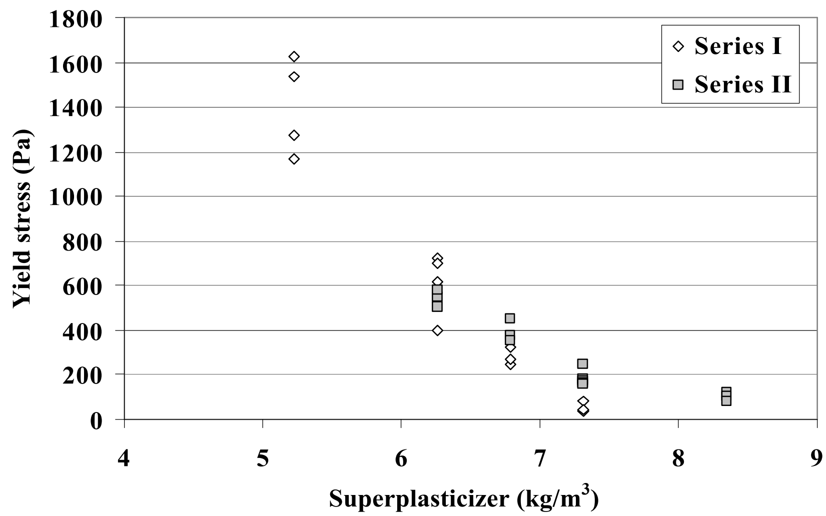

Fig.1 – Effect of a naphthalene-based superplasticizer on the yield stress of fresh LWAC with different sand size distributions

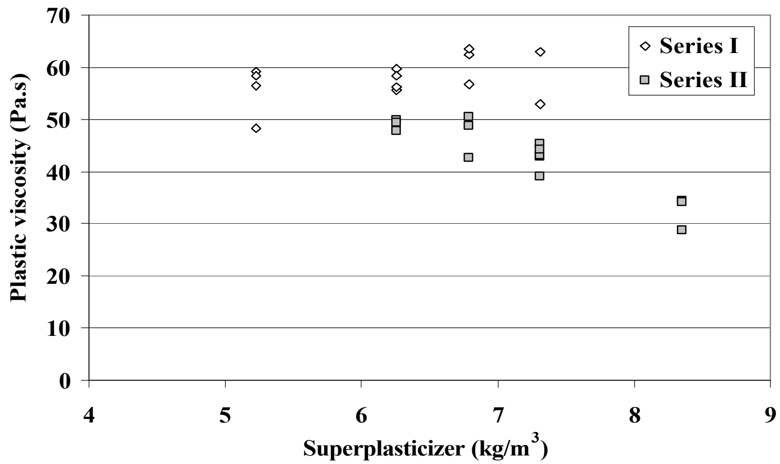

Fig.2 – Effect of a naphthalene-based superplasticizer on the plastic viscosity of fresh LWAC in Series I and II with different sand size distributions

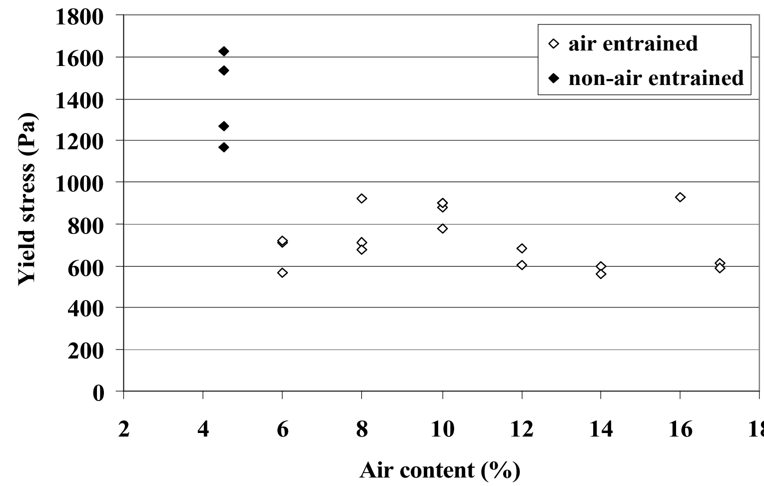

Fig.3 – Effect of air entrainment on the yield stress of concrete with F6.5 aggregate in Series I (The concretes had the same SP dosage)

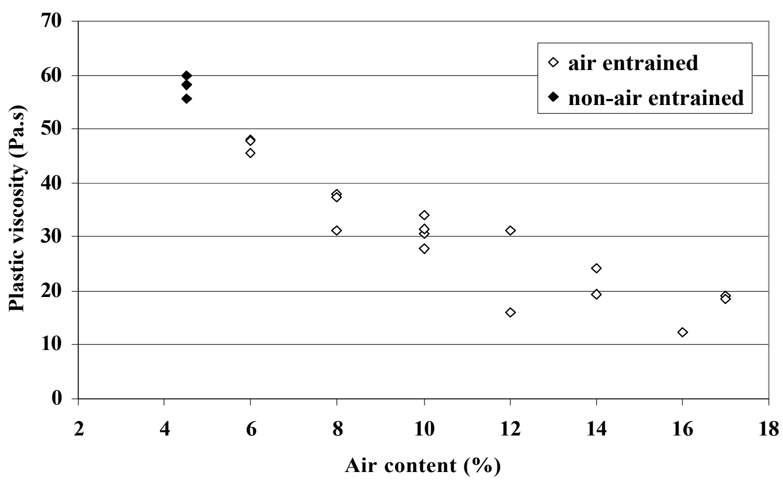

Fig.4 – Effect of air entrainment on the plastic viscosity of concrete with F6.5 aggregate in Series I (The concretes had similar yield stress)

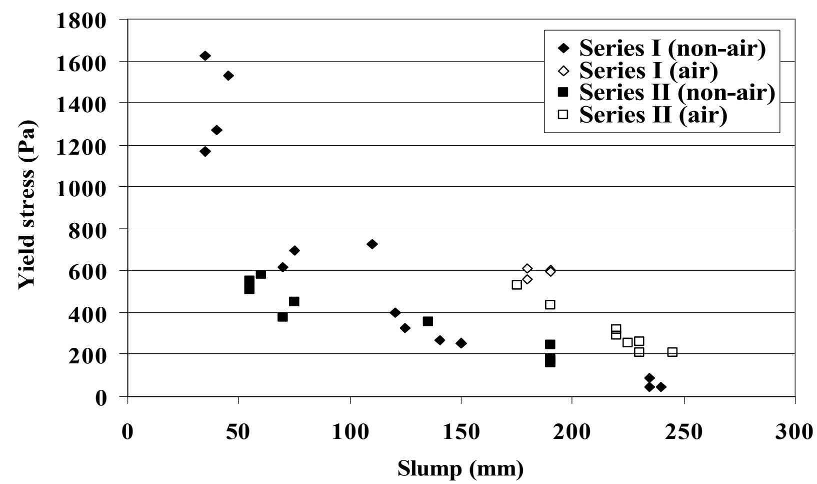

Fig.5 – Slump of air entrained (plastic viscosity was about 19 Pa s) and non-air entrained (plastic viscosity was about 53 Pa s) concrete against yield stress.