International Journal of Thermophysics, Vol. 27, No. 3, May 2006 (© 2006)
DOI: 10.1007/s10765-006-0049-y

Effect of Fly Ashes on the Rheological Properties of Fresh Cement Mortars[1]

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Rheological measurements of a concentrated suspension can be used to describe the flow of concrete. The rheological constants (yield value and plastic viscosity) of the mortar can be determined with a co-axial viscosimeter, and this technique is applied in this study. If the efficiencies of the mortar phase with respect to the cohesion, fluidity, bleeding and the friction of the concrete with the pipe are taken into consideration, this approach can be recognized as beneficial and helpful. Rheological tests on mortars were carried out with a Mettler RM 180 Rheomat co-axial viscosimeter. The angular deformation rate ($\dot{\gamma}$) and shearing stresses (τ) were determined, and $\dot{\gamma}$-τ diagrams were drawn. All the mortars showed a tixotropic behavior conforming to the Bingham model. A linear regression of these parameters gave the yield value (τ_o) and the plastic viscosity (η_{pl}) of the mortars.

KEY WORDS: Bingham model; co-axial viscosimeter; fly ash; plastic viscosity; pumping concrete; superplasticizer; workability; yield value.

1. INTRODUCTION

Concrete is an important construction material, and the transport of fresh concrete by pumping is an important process and widely used in concrete technology. This process has been applied since the beginning of the twentieth century. Developments of pumping equipment and new findings in mineral and chemical admixtures over recent decades motivated

[1] Paper presented at the Fifteenth Symposium on Thermophysical Properties, June 22-27, 2003, Boulder, Colorado, U.S.A.

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concrete technologists to undertake more sophisticated research on pumping concretes, concrete types, and production methods [1, 2].

It is obvious that concretes pumped in the solid state should have sufficient mechanical strength and good durability as compared with normal concretes. Pumped concretes differ from normal ones only in the fresh state, and this difference affects their mix composition and procedure. Fresh concrete has to be produced according to international standards and structural requirements. There are many recommendations for the composition of pumping concretes. They are not based on standard specifications, but are very useful in various applications. In this research, recommendations of the American Concrete Institute ACI-304.2R are used to determine the gradation of the aggregates and the mix proportions, volume and kind of the aggregates, and the absolute volume of the mortar phase [3–5]. For these reasons, we need to understand and develop fresh mortar and concrete properties and test methods. Workability is the most important property of the fresh concrete. Workability is actually determined by standard workability tests such as the slump test, K-slump test, flow table, Kajima box, box test, J-ring, L-box, compacting factor, workability meter, and plasticity meter. Not all of the standard test methods are applicable to all consistency levels of fresh concrete. Some of the above mentioned test methods are applicable to the dry consistency level; others are valid for plastic and flowable consistency levels [6, 7].

All test equipment can be used for different consistency levels, and these test results are taken at only a single point. The workability of the fresh concrete has complex properties. We note these complex properties as follows: the cohesion of the concrete should be high to avoid segregation, but the concrete should also be flowing to prevent head loss along the pipe and the bleeding of the concrete should have an optimum value; too little bleeding increases the friction between concrete and pipe, and too large bleeding causes blockage of the pipe [8–10]. So, we must use different test methods than those mentioned above for fresh concrete tests, which are inadequate. It is evident that those tests cannot give sufficient information about the specific complex properties. We must search for more types of tests that can give more information about concrete [2, 9, 11, 12].

2. RHEOLOGICAL PROPERTIES

In the construction field, terms like workability, flowability, and cohesion are used, some times interchangeably, to describe the behavior of concrete under flow. The definitions of these terms are very subjective. Therefore, there is a need for more fundamental and quantitative descriptions of concrete flow. Rheological measurements of concentrated suspensions can be used to describe the flow of concrete. Numerous researchers have successfully used the Bingham equation. Two parameters define the flow: yield stress and plastic viscosity. Yield stress is related to slump, but plastic viscosity may be related to properties such as stickiness, placeability, pumpability, and finishability. In addition, segregation can be defined as the ability of the aggregate to migrate in the cement paste. This phenomenon is linked to the viscosity of the cement paste and the concrete mix design. Therefore, methods to predict concrete workability need to take into account more than just the yield stress [7, 13].

The "two-point workability test apparatus" which helps to obtain the yield value and the plastic viscosity of the concrete may give more detailed and necessary information for the workability of the pumping concrete. Also, the rheology of fresh mortar is important in understanding the behavior of fresh concrete and predicting the flow properties of fresh concrete. In this work, the effects of the mixing procedure, the testing procedure, and relative proportions of constituent materials on the rheology of fresh mortar as measured by the co-axial viscosimeter have been studied. The rheological constants (yield value and plastic viscosity) of the mortar can be determined with a co-axial viscosimeter, and this process is applied in this study. If the efficiencies of the mortar phase with respect to cohesion, fluidity, bleeding, and the friction with the pipe of the concrete are taken into consideration, this approach can be seen to be beneficial and helpful [4, 11, 12, 14, 15].

3. STATE OF CONCRETE FLOW

Another important subject is the theoretical investigation of the hydrodynamic behavior of pumping concrete in a pipe. An understanding of this behavior is very difficult. The concrete mass, which gains velocity under a pressure gradient, is a viscous suspension containing coarse solid particles of nonuniform size. The motion of this suspension in the pipe should be uniform and laminar without exceeding the limit of turbulence; this is necessary for preventing segregation. On the other hand, transport must be achieved with low pressure and energy losses. The factor the results in increases in the pressure and energy is the friction between the concrete and pipe wall. If the pressure of the pump is increased to overcome this friction, another danger may appear, i.e., exceeding the limit of the segregation pressure at which point the mortar can separate from the mass and the aggregate particles block the pipe [5, 12, 16, 17].

Mortar plays a primary role in all of these phenomena. The gradation and fineness of the sand, cement, and admixtures content and the water/cementitious materials ratio of the mortar are the composition parameters that affect the behavior of the concrete in the pipe. The mortar can provide cohesion of the concrete, but should be fluid enough for seeping through the concrete and forming a gliding layer on the pipe wall. The combined use of a superplasticizer and fly ash is an optimum solution to satisfy pumping requirements of concrete. Admixtures mainly affect the flow behavior of the cement paste of concrete [2, 12, 19–21].

4. EFFECTS OF ADDITIVES ON WORKABILITY AND STRENGTH

Mortar can provide cohesion of the concrete, but should be fluid enough for seeping through the concrete and forming a gliding layer on the pipe wall. Mortar possessing these properties has a low yield value and moderately high plastic viscosity. The cohesion of the mortar may be increased by adding some fine mineral additive such as fly ash, and the fluidity may be improved by adding a plasticizer or superplasticizer. It is assumed that the plasticizers decrease the yield value without diminishing significantly the plastic viscosity. Therefore, the combined use of a superplasticizer and fly ash is an optimum solution. This method is applied in this work [18–20, 22].

It is usually reported that, if the volume concentration of a solid is held constant, the addition of mineral admixtures improves concrete performance but reduces workability. The most common reason for poor workability is that the addition of a fine powder will increase the water demand due to the increase in surface area. This problem can be solved by using chemical admixtures. However, in certain cases, it is reported in the literature that the use of fine material admixtures can reduce the water demand or increase the slump. A popular hypothesis proposed to explain the workability enhancement due to the use of certain fine mineral admixtures, especially fly ash (FA) or silica fume (SF), is that the spherical particles easily roll over one another, reducing interparticle friction [6, 7, 13].

The use of fly ash in concrete technology has assumed an important role in recent years. The increase of the number of power plants working with coal or lignite in the world began to cause ecological pollution problems due to the by-production of fly ash. This pozzolanic material is no longer considered as a dangerous waste material, but as a necessary mineral additive for manufacturing an economical, durable, and workable concrete. Countless studies are carried out on fly ash concretes. Fly ashes of lignites are classified as C Class fly ash by ASTM. They contain more CaO than do F class fly ashes; the latter ones are rich in SiO_2 and Al_2O_3, giving them higher pozzolanic activity. Turkey has many beds of lignite and uses them in power plants. For this reason, the majority of Turkish fly ashes are C class fly ash. Another type of fly ash is sulfo–calcic fly ash, which also contains $CaSO_4$; it is not cited in an ASTM specification. The high content of free lime and sulfate in C class fly ash and especially in sulfo-calcic fly ash may disturb the durability of the concrete. Positive progress has been obtained to improve their quality and to use them successfully in dam construction [23–28].

The use of fly ash in ready mixed concrete is necessary, even compulsory, for obtaining a pumpable, durable, and economically viable concrete. Pumped concrete has two essential properties: fluidity and cohesion. Cohesion provides the stability of the mix and prevents segregation of coarse aggregates in pipes. It is obtained by adding fine particles or by increasing the quantity of the sand and cement. Fly ash particles finer than cement particles improve the gradation without impairing the fluidity due to their spherical form. Fly ash addition also improves the impermeability of the concrete to water and chloride ions. The chloride diffusion is the main cause of the embedded steel corrosion in reinforced concretes; the chloride ions suppress the beneficial effect of alkaline passivation due to the presence of $Ca(OH)_2$ in the hydrated cement. Minimum cement content is also needed for obtaining the pozzolanic efficiency of the fly ash. Replacement of the cement by fly ash decreases the compressive strength of the concrete. To compensate for this loss, the absolute volume of the fly ash should exceed the replaced cement volume, i.e., the total quantity of the binder (cement + fly ash) will be greater than the initial cement content. The problem is determination of the fly ash quantity for obtaining the required compressive strength. This estimation is possible if the binding capacity of the fly ash is known in comparison to that of the cement. The ratio of binding capacity of the fly ash to that of cement is called the “efficiency factor” (E). In previous studies, the values of the efficiency factor for different Turkish C class fly ashes have been determined. Properties and efficiencies for Turkish C class fly ashes are shown in Table I. Oxide and physical compositions of fly ash and PC 42.5 are shown in Table II [4, 8, 10, 12, 29].

5. EXPERIMENTAL

Rheological tests on mortars were carried out with a Mettler RM 180 Rheomat co-axial viscosimeter (Fig. 1). The mortars were placed in a viscosimeter tube after 8, 18, and 28 minutes from the beginning of their mixing with water. A program of eight steps was performed, and the rotation rates and torques were measured in each step. Based on these results, the angular deformation rate ($\dot{\gamma}$) and shearing stresses (τ) were computed, and $\dot{\gamma}$-τ diagrams were plotted. All the mortars showed tixotropic behavior

Table I. Properties of Fly Ashes

	FA1 Orhaneli	FA2 Cayirhan	FA3 Seyit Omer
10 to 40 μm fraction (%)	42.6	28.3	43.9
D_{median} (μm)	29	33	23
Blaine Fineness Modulus ($m^2 \cdot kg^{-1}$)	303	350	402
Specific gravity ($kg \cdot m^{-3}$)	2400	2300	2100
Efficiency factor, E (for $C = 350\,kg \cdot m^{-3}$)	0.43	0.37	0.61

Table II. Oxide and Physical Compositions for Fly Ash and PC 42.5

	(mass %)			
Oxide parameters	FA1 Orhaneli	FA2 Cayirhan	FA3 Seyit Omer	PC 42.5
SiO_2	34.8	43.4	46.7	23.0
CaO	26.3	14.2	12.4	63.3
MgO	1.7	4.6	4.6	0.9
Fe_2O_3	3.9	8.4	9.8	4.0
Al_2O_3	19.4	14.2	16.8	4.5
Na_2O	2.7	4.4	2.8	–
K_2O	1.9	2.2	2.7	0.5
SO_3	6.3	5.8	2.9	2.3

conformable to a Bingham model. The linear regression on the linear parts of these curves gave the yield value (τ_o) and the plastic viscosity (η_{pl}) of the mortars. The rheological behavior of a fluid such as cement paste, mortar, or concrete is most often characterized by at least two parameters, the yield value (τ_o) and the plastic viscosity (η_{pl}) as defined by the following equation:

$$\tau = \tau_o + \eta_{pl}\dot{\gamma} \tag{1}$$

A linear regression on these parameters gave the yield value and the plastic viscosity of the mortars [2, 6–7, 13, 30–33]. All the measured flow curves could be very well described by Eq. (1). Some examples are shown in Fig. 2. The sand, cement, and fly ash (maximum grain size is two mm) were first mixed in the dry state and then for 2 minutes; they were mixed with water with an 800 rpm mixer. The maximum effective diameter of the samples is 2.38 mm. The superplasticizers were added after 2 minutes, and the mortar was mixed for 5 minutes. Some criteria are proposed and applied on the choice of materials and the determination of ingredients:

Fig. 1. Mettler RM 180 Rheomat (co-axial viscosimeter).

- The natural stock of ASTM-F type fly ash is limited in Turkey; the use of ASTM-C class fly ash in the research would be more sensible for the Turkish concrete industry. To realize this aim, after three kinds of fly ashes were examined from the point of view of water and superplasticizer requirements to obtain the prerequisite high strength concretes, the most convenient was used in the main research. Test results of Orhaneli fly ash are more sensible than the other fly ashes. All applied mortar rheological tests are presented in this work [24, 34].
- The fly ash content must be determined by applying the partial replacement method. Thus, a preliminary investigation was undertaken to find out the efficiency factors of the fly ashes and these factors are used to estimate the quantity of fly ash content. The ACI-304.2R recommendations are applied for the aggregate gradation and mix design. Therefore, the aggregate absolute volume is taken as $0.55\,m^3/m^3$. In that case the volume of the mortar phase was approximately $0.45\,m^3/m^3$in all the series. The maximum effective diameter of the sand is 2.38 mm [24,29].

PC-42.5 Portland cement corresponding to ASTM Type III cement and naphthalene sulfanate formaldehyde condensate superplasticizer were used. Oxide compositions of PC-42.5 Portland cement are shown in Table III.
Based on the preliminary test results on the fly ashes, the most suitable one, Orhaneli fly ash, was identified. Seyit Omer fly ash was too fine (Blaine $402\,m^2 \cdot kg^{-1}$) and Cayirhan fly ash contained fewer particles between 10

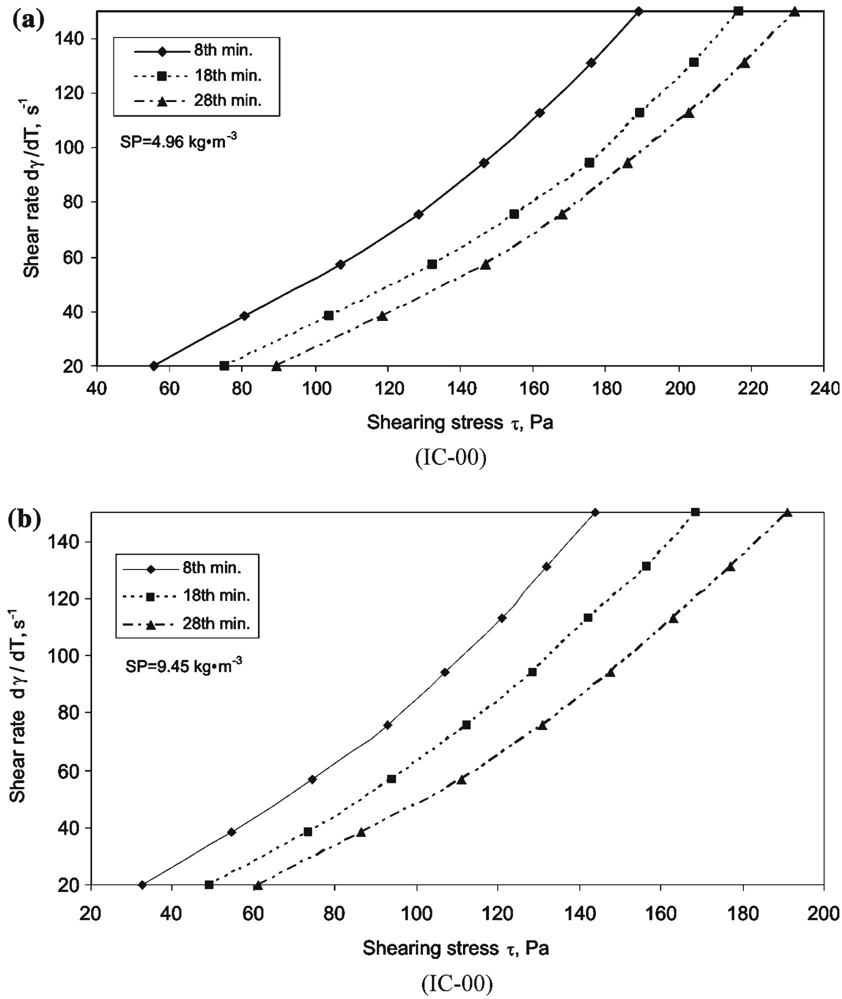
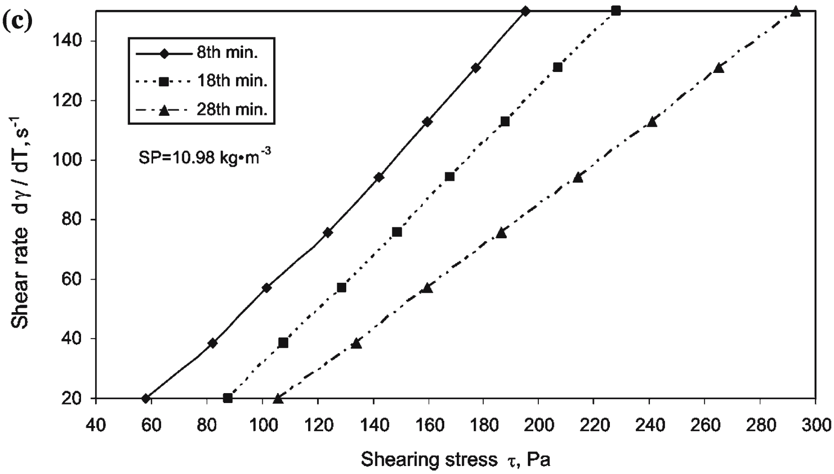


Fig. 2. Flow curves for mortar phase: (a) $SP = 4.96\,kg \cdot m^{-3}$, (b) $SP = 9.45\,kg \cdot m^{-3}$, (c) $SP = 10.98\,kg \cdot m^{-3}$, and (d) $SP = 21.96\,kg \cdot m^{-3}$.

and 40 μm size (28.3%). Seyit Omer fly ash required a large quantity of water and superplasticizer. A main objective in the tests was to maintain the volume of the mortar phase while changing its quality. This change was realized by choosing two different initial cement contents, by replacing cement by different amounts of fly ash, and by adjusting the superplasticizer addition with different quantities. The initial cements in these studies were fixed

(c)



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(d)

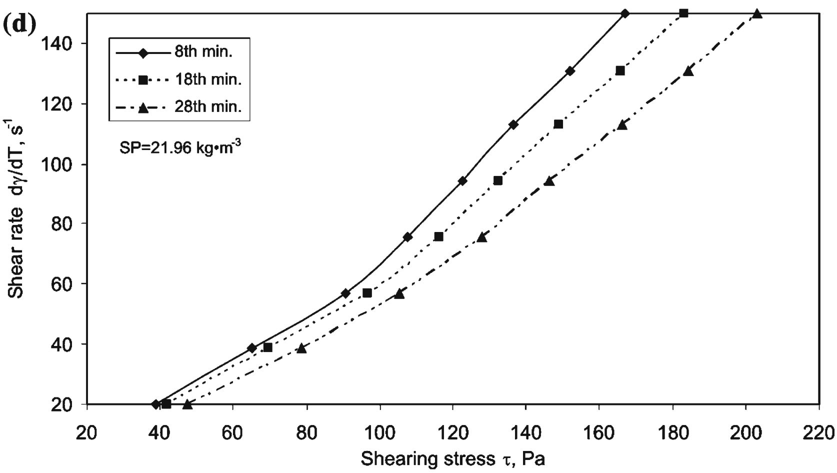

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Fig. 2. Continued

as 300 and 400 $kg \cdot m^{-3}$. The water contents were kept constant, but the superplasticizer additions increased significantly.

It will be more convenient to summarize the conclusions of this research in two different rubrics: modifications that occurred in the rheological behavior of the mortar phase and the influences of the rheological constants of the mortar on the concrete pumpabilities.

Table III. Oxide Compositions of Cement

	PC 42.5
	(mass%)
C_3S	51.7
C_2S	22.8
C_3A	8.6
C_4AF	9.4
SO_3	2.7
Fineness Modulus ($m^2 \cdot kg^{-1}$)	347

As mentioned above for good pumpability, the yield value (τ_0) should be low and the plastic viscosity (η_{pl}) should not significantly decrease. The additional superplasticizer to the mortar decreased τ_0 by 78% and η_{pl} by only 35%. This result is inconsistent with the proposed goal. The addition of a fly ash to a superplasticized mortar increased the values of τ_0 and η_{pl} in the same manner, but this increase is not too significant. It is interesting to note that this increase is continuous in τ_0 for all the fly ash addition ratios, but if the addition of the fly ash exceeds 40 to 50% of the cement content (15 to 25% in partial replacement), η_{pl} begins to decrease. According to these experimental results and economic considerations, it can be suggested that the selection of a superplasticizer/cementitious materials ratio between 2 and 2.5% (as a solid material), a cement content of $400\,kg \cdot m^{-3}$, and the addition of fly ash between 25 to 35% may give the proper result. In that case, τ_0 has a value between 38 and 48 Pa, and η_{pl} between 0.8 and 1.0 Pa·s. Rheological constants are given in Tables IV to VI for each of the mortar mixes. The addition of a superplasticizer to the mortar mixes increased the consistencies as expected. If a higher initial cement content is chosen and it a quantity of fly ash less than 15% replaces partially the cement, the solution is economically viable. It was possible to establish a linear relation between the cohesion of the concrete and the rheological constants of the mortar phase. In general, increases of τ_0 and η_{pl} result in an increase of the concrete cohesiveness. In the case of lean concretes containing a high proportion of fly ash, the rate of cohesion increase with τ_0 is significantly high [16, 17, 29].

Table IV. Components, Rates, and Rheological Constants of Mortar Phases with Orhaneli Fly Ash

Code	C	FA	$\frac{C}{FA+C}$	$\frac{FA}{FA+C}$	$\frac{W}{FA+C}$	$\frac{SP}{FA+C}$	τ_o (Pa)			η_{pl} (Pa·s)		
	(kg·m^{-3})						8th	18th	28th	8th	18th	28th
							(min.)					
IC - 00	738	0	1	0	0.376	0.007	68.8	95.7	104	0.812	0.820	0.863
					0.377	0.008	63.2	81.1	92.9	0.729	0.810	0.826
					0.380	0.013	42.1	56.4	70.9	0.685	0.755	0.807
IC - 15	599	259	0.7	0.3	0.309	0.013	52.2	67.9	78.5	0.952	1.064	1.635
					0.313	0.019	46.8	56.6	60.5	0.842	0.957	1.209
					0.316	0.026	45.9	47.9	47.8	0.814	0.900	1.036
IC - 25	497	516	0.49	0.51	0.264	0.032	83.0	86.6	94.5	0.766	0.928	1.058
					0.267	0.038	76.3	80.3	81.8	0.675	0.877	0.988
					0.271	0.045	72.8	78.6	79.8	0.657	0.831	0.974
IC - 35	390	866	0.31	0.69	0.232	0.090	118.3	137.7	127.8	0.534	0.588	0.604
					0.244	0.110	113.8	116.3	117.0	0.527	0.539	0.536
IIC - 00	606	0	1	0	0.380	0.038	56.5	60.9	64.1	0.639	0.662	0.707
					0.387	0.051	54.3	56.7	59.1	0.513	0.575	0.621
					0.394	0.064	51.4	54.3	56.0	0.473	0.529	0.602
IIC - 15	475	357	0.57	0.43	0.271	0.050	36.3	46.8	53.0	0.928	0.955	1.085
					0.279	0.064	35.8	45.6	48.9	0.799	0.868	0.939
					0.284	0.074	34.7	44.4	45.6	0.783	0.822	0.842
IIC - 25	384	694	0.36	0.64	0.214	0.074	50.4	54.1	56.4	0.621	0.690	0.739
					0.225	0.093	46.6	50.2	51.9	0.547	0.593	0.669

Table V. Components, Rates and Rheological Constants of Mortar Phases with Cayirhan Fly Ash

Code	C	FA	$\frac{C}{FA+C}$	$\frac{FA}{FA+C}$	$\frac{W}{FA+C}$	$\frac{SP}{FA+C}$	τ_o (Pa)			η_{pl} (Pa·s)		
	($kg \cdot m^{-3}$)						8^{th}	18^{th}	28^{th}	8^{th}	18^{th}	28^{th}
							(min.)					
IC - 00	738	-	1	0	0.376	0.007	68.8	95.7	104	0.812	0.820	0.863
					0.377	0.008	63.2	81.1	92.9	0.729	0.810	0.826
					0.380	0.013	42.1	56.4	70.9	0.685	0.755	0.807
IC - 15	590	293	0.67	0.33	0.301	0.013	46.5	58.1	73.4	0.592	0.694	1.082
					0.304	0.019	40.5	45.4	59.5	0.503	0.650	0.855
					0.308	0.026	33.4	42.1	39.2	0.448	0.527	0.635
IC - 25	487	560	0.47	0.53	0.250	0.032	75.3	82	85.2	0.502	0.616	0.751
					0.255	0.038	66.2	71.2	79.8	0.437	0.596	0.708
					0.259	0.045	58.6	66.3	69.3	0.381	0.590	0.690
IC - 35	383	887	0.3	0.7	0.227	0.090	95.5	112.9	120	0.417	0.468	0.543
					0.239	0.111	91.3	99.5	115.2	0.342	0.418	0.493
IIC - 00	606	-	1	0	0.380	0.038	56.5	60.9	64.1	0.639	0.662	0.707
					0.387	0.051	54.3	56.7	59.1	0.513	0.575	0.621
					0.394	0.064	51.4	54.3	56.0	0.473	0.529	0.602
IIC - 15	471	369	0.56	0.44	0.267	0.050	34.6	40.1	47.4	0.519	0.561	0.650
					0.275	0.064	34.4	43.4	46.5	0.428	0.489	0.559
					0.281	0.074	31.3	43.3	42.9	0.425	0.476	0.517
IIC - 25	380	688	0.36	0.64	0.214	0.074	47.9	51.9	56.1	0.375	0.392	0.418
					0.225	0.093	44.6	49.0	54.0	0.310	0.346	0.382

Table VI. Components, Rates and Rheological Constants of Mortar Phases with Seyit Omer Fly Ash

Code	C	FA	$\frac{C}{FA+C}$	$\frac{FA}{FA+C}$	$\frac{W}{FA+C}$	$\frac{SP}{FA+C}$	τ_o (Pa)			η_{pl} (Pa·s)		
	(kg·m^{-3})						8th	18th	28th	8th	18th	28th
							(min.)					
IC - 00	738	-	1	0	0.376	0.007	68.8	95.7	104	0.812	0.820	0.863
					0.377	0.008	63.2	81.1	92.9	0.729	0.810	0.826
					0.380	0.013	42.1	56.4	70.9	0.685	0.755	0.807
IC - 15	607	182	0.77	0.23	0.345	0.013	93.9	113.7	141.4	1.334	1.459	1.771
					0.348	0.019	75.9	88.9	120.2	1.236	1.387	1.711
					0.352	0.026	63.4	85.2	89.0	1.128	1.154	1.325
IC - 25	514	352	0.59	0.41	0.315	0.032	144.3	154.4	176.9	1.176	1.355	1.554
					0.318	0.038	119.4	131.8	167.4	1.165	1.399	1.474
					0.322	0.045	115.5	137.9	142.9	0.886	1.208	1.451
IC - 35	418	576	0.42	0.58	0.294	0.090	182.7	213.2	238.7	0.994	1.220	1.348
					0.306	0.111	177.3	193.6	228.2	0.896	1.182	1.284
IIC - 00	606	-	1	0	0.380	0.038	56.5	60.9	64.1	0.639	0.662	0.707
					0.387	0.051	54.3	56.7	59.1	0.513	0.575	0.621
					0.394	0.064	51.4	54.3	56.0	0.473	0.529	0.602
IIC - 15	489	226	0.68	0.32	0.318	0.050	74.7	92.6	115.2	1.138	1.377	1.463
					0.326	0.064	73.2	91.7	106.1	1.032	1.241	1.423
					0.332	0.074	70.3	89.1	93.4	0.983	1.214	1.419
IIC - 25	404	434	0.48	0.52	0.276	0.074	106.6	115.1	117.8	0.967	0.994	1.246
					0.287	0.093	99.1	111.9	119.4	0.945	0.875	1.058

6. CONCLUSION

Investigations have been made on methods of measuring viscosities of fresh mortar, and the flow of mortar though a pipe as a fundamental study for a rational understanding of fresh concrete behavior. The rheological constants of mortar and concrete of relatively wet consistency can be measured reasonably with the double-cylinder rotation viscometer (co-axial viscometer). The measuring system conforms to DIN 53019 with an uncertainty of ±0.5% of the actual value. The flow curves of the mortar conform to the Bingham model. The effects of different relative proportions of constituent materials and the influences of admixtures and fly ash on the yield value and plastic viscosity are similar to those observed with fresh concrete. This suggests that tests on mortars in the RM 180 Rheomat co-axial viscosimeter might be useful in predicting the behavior of fresh concrete. Experiments to show the correlations between mortars and concretes were, of course, needed to confirm this. The RM 180 Rheomat co-axial viscosimeter is capable of measuring the rheological parameters of mortar, paste, and fine grained materials. Mortar and concrete workability can be characterized in terms of the rheological parameters in the Bingham equation. The flow of granular material such as mortar and concrete needs to be defined by at least two parameters, for instance, the yield value and plastic viscosity, as defined by the Bingham equation [9,11–13, 29].

As a final conclusion, one may assume that the determination and improvement of the rheological constants of the mortar phase are necessary and sufficient for obtaining a pumpable concrete. With regard to economy, strength, and durability, the most convenient solution to obtain a good pumpable concrete is to keep the nominal cement content at the level of $400\,\mathrm{kg{\cdot}m^{-3}}$, to replace 15 to 20% of this cement content by fly ash, and to add a sufficient quantity of superplasticizer for the fluidity required [16, 17, 29, 34, 35].

NOMENCLATURE

C	cement
FA	fly ash
W	water
E	efficiency factor
SP	superplasticizer
FA+C	total quantity of binder or cementitious materials
$\frac{C}{FA+C}$	cement/cementitious materials ratio by mass of mortar

$\frac{FA}{FA+C}$	fly ash/cementitious materials ratio by mass of mortar
$\frac{W}{FA+C}$	water/cementitious materials ratio by mass of mortar
$\frac{SP}{FA+C}$	superplasticizer/cementitious materials ratio by mass of mortar
τ_o	yield value
η_{pl}	plastic viscosity
I	nominal cement content, $400\,kg \cdot m^{-3}$
II	nominal cement content, $300\,kg \cdot m^{-3}$
Sample for IC-00	Nominal cement content, $400\,kg \cdot m^{-3}$and no fly ash content
Sample for IC-15	Nominal cement content, $400\,kg \cdot m^{-3}$and fly ash content, 15%
Sample for IC-25	Nominal cement content, $400\,kg \cdot m^{-3}$and fly ash content, 25%
Sample for IC-35	Nominal cement content, $400\,kg \cdot m^{-3}$and fly ash content, 35%
Sample for IIC-00	Nominal cement content, $300\,kg \cdot m^{-3}$and no fly ash content
Sample for IIC-15	Nominal cement content, $300\,kg \cdot m^{-3}$and fly ash content, 15%
Sample for IIC-25	Nominal cement content, $300\,kg \cdot m^{-3}$and fly ash content, 25%

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