Scientific Research and Essays Vol. 5(10), pp. 1111-1121, 18 May, 2010
Available online at http://www.academicjournals.org/SRE
ISSN 1992-2248 © 2010 Academic Journals

Full Length Research Paper

Application of numerical analysis for investigation of relationship between slump values and other rheological properties of fresh concrete

Ahmet Bilgil[1], Baki Öztürk[1] and Ayhan Şamandar[2*]

[1]Department of Civil Engineering, Faculty of Engineering, Nigde University, 51100, Nigde, Turkey.
[2]Düzce Vocational School, Düzce University, 81620 Düzce, Turkey.

Accepted 15 April, 2010

The main concern in working with fresh concrete is the workability during filling of formwork. In this study, the mechanism of segregation during the filling of fresh concrete into formwork is numerically investigated considering the rheological properties of fresh concrete. A mathematical model, which considers fresh concrete as a non-Newtonian fluid that, is used for the investigation of relationship between slump values and rheological properties of fresh concrete. The aggregates are considered as Lagrangian particles whose trajectories determine segregation. This study will provide an insight to the relationships between workability and various rheological parameters of fresh concrete that is, yield stress, segregation, viscosity during filling of fresh concrete into formwork. The relationships between workability and rheological properties during the fill of fresh concrete for both concrete mixtures with no admixtures (MC) and concrete mixtures with admixtures (MCS) are investigated. MCS concrete mixture includes super-plasticizers for the same composition of MC. Cylindrical formworks for three different heights of 50, 100 and 150 cm are employed. It is observed that MCS mixtures have higher slump values and less aggregate segregation (%) compared to MC mixtures for the same compositions of fresh concrete. It is found that, slump values decrease as yield stress increases for both MC and MCS fresh concrete mixtures. When MCS mixtures are used, there is a significant reduction in yield stress compared to MC mixtures.

Key words: Non-Newtonian fluid, workability, slump values, aggregate segregation, fresh concrete rheology.

INTRODUCTION

Fresh concrete is mainly used in reinforced concrete structures. It should be composed of a viscous compound where it can be poured easily at highly reinforced parts of the formwork with minimum consolidation and without segregation. The aggregate segregation during filling of formwork is the main problem in working with fresh concrete (Arslan et al., 2005). The fresh concrete is usually considered as a Non-Newtonian fluid since; it is a mixture of aggregate, cement and water. The flow behaviour of the fresh concrete (that is, viscosity) plays a crucial role in the quality of the high performance concretes. Aggregates in fresh concrete usually cause segregation in the final product depending on the flow condition. It is known that segregation is strongly related to composition of fresh concrete. Fluid concrete can be poured in formwork without excessive leakage, settlement and segregation. According to Soshiroda (1981), a minimum slump value of 190 mm's should be satisfied. The use of this type of concrete at congested or restricted regions of formwork to ease pouring of concrete may cause the formation of cement mortar and aggregate segregation. As a result; the risk of significant reduction in the workability of concrete occurs. Among the most important properties of fresh concrete is "workability". It refers to the consistency, flowability, pumpability, compactability, and harshness of a concrete mixture. Quality of fresh concrete refers mainly to its

*Corresponding author. E-mail: ayhansamandar@gmail.com. Tel: +90-380-5240099. Fax: +90-380-5240097.

workability and flowability. The workability of fluid concrete is strongly related to its rheological properties. In addition, it depends on the composition of concrete. Workability is defined either qualitatively as the ease of placement or quantitatively by rheological parameters (Ferraris, 1999). Iwasaki (1983) listed some of the major definitions of workability given by professional societies. Tattersall (1976a) interpreted workability as “the ability of concrete to flow in mould or formwork perhaps through congested reinforcement, the ability to be compacted to a minimum volume, perhaps the ability perform satisfactorily in some transporting operation or forming process and may be in the other requirements as well”. Tattersall (1976a) stated that the most common rheological parameters of the flow concrete, used to qualify workability, are the yield stress and plastic viscosity as defined by the Bingham equation. There has been considerable effort on the development of the application of standard rheological principles to the measure of workability of concrete (Tattersall, 1991; Tattersall and Banfill, 1983). Furthermore, Tattersall and Banfill (1983) analyzed the state of the art for workability of concrete test methods.

De Larrard et al. (1998) found that, in some cases the Herschel-Bulkley equation is suited better to describe the concrete flow. The Herschel-Bulkley equation contains three parameters, one of which does not represent a physical entity. De Larrard et al. (1998) showed that in certain concretes, such as self-consolidating concretes, it is the equation that best describes the concrete behaviour. Both Bingham fluid and Herschel-Bulkley fluid exhibits non-Newtonian flows with similar behaviours. The Bingham equation is commonly employed in practice since the parameters used in the equation are independently measurable quantities. Tattersall (1976a) showed that, the flow of real concrete seems to follow this equation fairly well in most cases. In addition, it has been shown that, a simple analysis based on the Bingham model correlates slump data for a wide variety of materials including concrete (Schowalter, 1998). Workability term can be used as a general description of the nature of fresh concrete, whose more specific properties include fluidity, mobility, and compactability. Fresh concrete are closely approximates to the Bingham model. There is increasing pressure on engineers to ensure high workability while at the same time to maintain the structural properties necessary to meet the design specifications. Workability should be defined in terms of established measurable rheological parameters such as yield stress and viscosity. Accordingly, investigation of slump and yield stress relationship has been one of the main factors being investigated in the numerical study presented in this paper.

The slump test is the most common method for assessing the flow properties of fresh concrete. It provides a qualitative measure of workability. Scullion concluded that, slump has a negative power law dependence on yield stress and is largely independent on viscosity using the “two-point” method developed by Tattersall (1976b). Dzuy and Boger (1985) used the Vane method for direct yield stress measurement and showed that, it is a simple but accurate method for direct yield stress measurement. Pashias and Boger (1996) stated that the slump test offers a robust and inexpensive method of directly measuring the yield stress and found good agreement between the slump measurements and theoretical prediction devised by Murata (1984). Morinaga found an inverse relationship between slump and yield stress using a concentric cylinder concrete rheometer (Morinaga, 1973). Using normal and lightweight concrete, Murata confirmed the results of Morinaga. Murata suggested that slump is not influenced by viscosity and related slump is to yield stress based on a simple force balance method (Murata, 1984). Saak et al. (2004) developed a dimensionless model relating slump to yield stress and they suggested that a fundamental relationship exists between yield stress and slump that is, independent of the material under investigation. As a contribution, in the study presented in this paper, the slump – yield stress relation is investigated using Computational Methods and Numerical Analysis techniques provided by Phoenics (Rosten and Spalding, 1986). Recently, further research has been conducted both analitically and experimentally (Li, 2007; Leeman and Winnefeld, 2007; Wallevik, 2006; Safawi et al., 2004).

In this study, a numerical investigation is applied using slump values and rheological properties of concrete during the workability of fluid concrete. The correlations between workability (slump values) and various rheological parameters of concrete, that is, yield stress, segregation, viscosity, are investigated. The main concern is to investigate the relationship between workability and aggregate segregation. Aggregate segregation is highly important especially in term of building frame. The *scenario* is that normal performance flow concrete with different slump values is filled from bottom of formwork at the different inlet velocity. The fresh concrete is assumed to behave as non-Newtonian fluid. A group of particles are introduced at the formwork inlet and segregation is studied through the trajectories of these particles. The particles are allowed to change momentum with the continuous phase. The rheological properties of the fresh concrete are obtained from Ferraris and de Larrard (1998). The results of this study will provide information in order to define the relation of workability and aggregate segregation during the fill of fresh concrete into formwork. As a result of computational and numerical approach, this study will also provide information on definition of relationship between slump values and yield stresses developed in the concrete mixtures. In addition, it will help to understand application

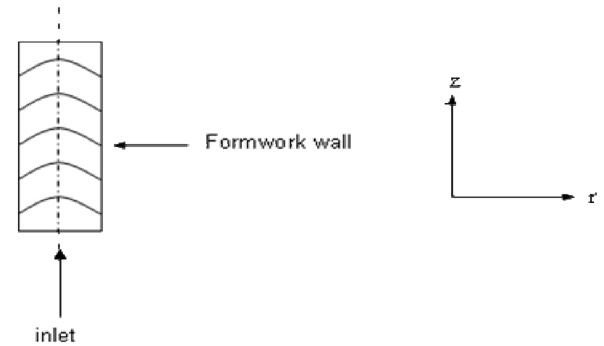

Figure 1. Schematic drawing of test configuration (Cylindrical formwork).

of retrofitting of structural elements and construction practices at seismically active regions.

MATERIALS AND METHODS

Significance of study

Concrete is a composite material with aggregates, cement and water as the main components. When it solidifies, this mixture has to have high compaction level and a homogenous distribution. It is vital that fluid concrete provide adequate stability in order to reduce the structural imperfections. This study will provide information to determine the relationship of workability and aggregate segregation during fill of fresh concrete. In the mean time, it will provide an insight to the definition of relationship between yield stress and slump values. In literature, a similar numerical study has not been done previously. Concrete mixture data related to the rheological properties of fresh concrete is presented. In this study, slump – viscosity and slump – segregation relationships are also investigated. This will be helpful to provide stable concrete with minimum segregation, high compaction and homogeneity during its pumping and pouring. In order to optimize the stability of concrete, which can be used to retrofit the damaged structural systems during an earthquake, it has been suggested to fill in fluid concrete beneath the formwork.

Problem considered

The sketch of the test configuration is shown in Figure 1. It consists of a formwork-filling system. The cylindrical formwork has a uniform internal section. Concrete enters from the bottom of formwork and progressively rises the forming of a free surface. Three different heights for the formworks are used as 50, 100, and 150 cm, and diameter of the formworks is 30 cm. The compositions of fresh concrete mixtures are given in kg/m^3 (Table 2).

Formulation

A mathematical representation of the formwork filling process requires solution of the equations governing the conservation of mass and momentum along with constitutive equations representing the slurry behaviour and particle dynamics. A group of particles is introduced at the inlet of formwork and these particles are allowed to exchange momentum with a continuous phase.The governing equations for a formwork filling of a plastic form system can be expressed in cylindrical co-ordinates as:

Continuity equation

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r \upsilon_r)+\frac{\partial}{\partial z}(\rho \upsilon_z)=0 \quad (1)$$

Axial momentum

$$\rho\left(\frac{\partial \upsilon_z}{\partial t}+\upsilon_r\frac{\partial \upsilon_z}{\partial r}+\upsilon_z\frac{\partial \upsilon_z}{\partial z}\right)=\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \upsilon_z}{\partial r}\right)+\frac{\partial^2 \upsilon_z}{\partial z^2}\right]-\frac{\partial p}{\partial z}+\rho g_z \quad (2)$$

Radial momentum

$$\rho\left(\frac{\partial \upsilon_r}{\partial t}+\upsilon_r\frac{\partial \upsilon_r}{\partial r}+\upsilon_z\frac{\partial \upsilon_r}{\partial z}\right)=\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\upsilon_r)\right)+\frac{\partial^2 \upsilon_r}{\partial z^2}\right]-\frac{\partial p}{\partial r}+\rho g_r \quad (3)$$

where, u is the velocity vector; and v and w are the radial and axial velocities respectively, p is the static, and τ is the shear stress tensor. De Larrard et al. (1998) suggested to employ Herschel-Bulkley equation in order to represent the rheological properties of fresh concrete due to its non-Newtonian behaviour. This relates shear stress to shear strain rate based on a power function expressed as;

$$\tau=\tau_0^{'}+a\gamma^b \quad (4)$$

where, τ is the shear stress, γ is the shear strain rate imposed on the sample, $\tau_0^{'}$ is the yield stress, a and b are new characteristic parameters describing the rheological behaviour of concrete. In this case, plastic viscosity can not be calculated directly. Ferraris et al. (2001) calculated the yield stress using the Herschel-Bulkley equation, while viscosity is calculated using the following equation;

$$\mu=\frac{3a}{b+2}\gamma_{max}^{b-1} \quad (5)$$

where, μ stands for the viscosity, γ_{max} is the maximum shear strain rate achieved in the test, and a and b are the parameters calculated using the Herschel-Bulkley equation (Ferraris et al., 2001). In calculating the viscosity of fresh concrete, values in Table 1 are used. It has to be noted that Equation 4 stands for the generalized formulation of Bingham fluids and Herschel-Bulkley equation is employed to calculate rheological properties for fresh concrete flow (Equation 5).

Particle physics

The evolution of particle position Z_p is determined from the solution of the following equation proposed by Mat et al. (1999);

$$\frac{dZ_p}{dt}=w_p \quad (6)$$

Table 1. Values used in calculating the viscosity of fresh concrete (Ferraris and de Larrard, 1998) (used by authorization of the authors).

Mixtures of concrete group	Mixtures code	Specific gravity	Water/cement (W/C) ratio	Slump (mm)	Herschel-Bulkley		
					Yield stress (Pa)	a (Pa.s^b)	b
A	MC1	2.26	0.666	95	1234	55	1.72
	MC2	2.26	0.696	95	1071	87	1.35
	MC3	2.22	0.727	160	906	43	1.39
B	MC4	2.33	0.421	105	1841	42	1.66
	MC5	2.33	0.440	170	1115	93	1.09
	MC6	2.31	0.460	205	901	50	1.09
C	MC7	2.33	0.553	80	1804	111	1.23
	MC8	2.33	0.567	100	1599	86	1.33
	MC9	2.31	0.581	130	1341	74	1.40
	MC10	2.32	0.595	165	983	62	1.40
	MC11	2.30	0.610	225	778	102	0.90
	MC12	2.29	0.595	80	2019	70	1.38
	MC13	2.29	0.624	185	2151	57	1.75
A*	MCS1	2.25	0.349	150	865	665	0.88
	MCS2	2.32	0.361	225	476	506	1.07
	MCS3	2.32	0.373	260	413	191	1.39
B*	MCS4	2.40	0.262	265	675	792	1.88
	MCS5	2.39	0.271	285	457	269	1.73
	MCS6	2.37	0.281	290	385	132	1.70
C*	MCS7	2.38	0.362	215	759	417	1.09
	MCS8	2.38	0.369	180	774	385	1.15
	MCS9	2.38	0.376	205	608	430	1.10
	MCS10	2.38	0.383	210	537	147	1.56
	MCS11	2.38	0.390	235	471	205	1.40
	MCS12	2.37	0.374	150	1741	190	1.54
	MCS13	2.40	0.388	120	1457	87	1.83

in which w_p is the particle velocity vector, obtained from the following particle momentum equation:

$$m_p \frac{dw_p}{dt} = D_p\left(w - w_p\right) + m_p b_g - V_p \nabla p \tag{7}$$

where, m_p is the mass of particle, D_p is the drag function, V_p is the volume of particle, p is the pressure, w is the continuous phase velocity and b_f is the buoyancy factor. Drag function D_p can be expressed as (Fueyo et al., 1992);

$$D_p = \frac{1}{2}\rho_p A_p C_D \left|\omega - \omega_p\right|^2 \tag{8}$$

where, A_p is the particle projected area and C_D is the drag coefficient. C_D is calculated from a correlation developed by Clift et al. (1978):

$$C_D = \frac{24}{Re}\left(1 + 0.15 Re^{0.687}\right) + \frac{0.42}{1.42510^4\ Re^{-1.16}} \tag{9}$$

where, Re is a particle Reynolds number defined as;

$$Re = \frac{\left|w_p - w_c\right| d_p}{\nu} \tag{10}$$

where; ν is the kinematics viscosity of the continuous phase and d_p is the particle diameter. The buoyancy factor is given as:

$$b_f = \left(1 - \frac{\rho_c}{\rho_p}\right) \tag{11}$$

Table 2. Cases considered (Ferraris and de Larrard, 1998) (used by permission of authors).

	Mixtures code	Dry mixture mass (%)				Composition (kg/m^3)					
		Gravel	Sand	Fine sand	Cement	Gravel	Sand	Fine sand	Cement	Super plasticizer	Free water
	MC1	22.5	46.2	14.3	17.0	460	944	293	347	--	231
A	MC2	22.5	46.2	14.3	17.0	455	934	290	344	--	239
	MC3	22.5	46.2	14.3	17.0	450	925	287	340	--	247
					25.1	851	549	170	527	--	222
	MC4	40.6	26.2	8.1							
B	MC5	40.6	26.2	8.1	25.1	843	543	169	522	--	230
	MC6	40.6	26.2	8.1	25.1	834	537	167	517	--	238
			29.0	9.0	17.0	957	617	191	362	--	200
	MC7	45.0									
	MC8	45.0	29.0	9.0	17.0	952	614	190	360	--	204
C	MC9	45.0	29.0	9.0	17.0	947	611	189	358	--	208
	MC10	45.0	29.0	9.0	17.0	943	607	189	356	--	212
	MC11	45.0	29.0	9.0	17.0	938	604	188	354	--	216
	MC12	57.6	19.3	6.0	17.0	1207	405	126	356	--	212
	MC13	57.6	19.3	6.0	17.0	1194	401	124	352	--	220
	MCS1	21.2	43.0	12.3	23.5	468	947	271	519	12.97	181
A*	MCS2	21.2	43.0	12.3	23.5	465	941	269	516	12.89	186
	MCS3	21.2	43.0	12.3	23.5	462	935	267	513	12.81	191
	MCS4	40.0	24.9	7.1	28.0	904	563	161	634	15.86	166
B*	MCS5	40.0	24.9	7.1	28.0	899	559	160	630	15.76	171
	MCS6	40.0	24.9	7.1	28.0	893	556	159	627	15.66	176
	MCS7	45.0	28.0	8.0	19.0	1015	632	180	429	10.71	155
	MCS8	45.0	28.0	8.0	19.0	1012	630	180	427	10.68	158
C*	MCS9	45.0	28.0	8.0	19.0	1009	628	179	426	10.65	160
	MCS10	45.0	28.0	8.0	19.0	1006	626	179	425	10.62	163
	MCS11	45.0	28.0	8.0	19.0	1003	624	178	423	10.59	165
	MCS12	57.0	18.7	5.3	19.0	1278	419	120	426	10.66	160
	MCS13	57.0	18.7	5.3	19.0	1270	416	119	424	10.59	165

Initial and boundary conditions

The formwork is initially assumed to be filled with a quiescent gas (air). The semi-solid slurry is allowed to fill the formwork at t > 0. Only half of the formwork is considered due to symmetry at the formwork axis. The formwork wall is assumed to be impermeable and a non-slip condition to be valid on the wall. The initial and boundary conditions can be expressed mathematically as:

$$t = o : \upsilon = \omega = 0 \tag{12}$$

t>0 at $r > 0 : \frac{\partial \omega}{\partial r} = \frac{\partial \upsilon}{\partial r} = 0$ (13)

at $r = r_o : \upsilon = \omega = 0$ (14)

at $z = 0 : \omega = V_{in}$ (15)

Numerical method

The governing equations are solved numerically with a fully implicit, finite domain scheme embodied in PHOENICS Code (Rosten and Spalding, 1986). Since the mold filling operation involves a free surface or the interaction of two distinct media (slurry and air) separated by sharply deformed interfaces, the discretization of the governing equation with a conventional upwind scheme usually results in a false numerical diffusion. Accordingly; a Van Leer scheme (Van Leer, 1977) is employed to resolve such property interface. Due to the coupling between the transport equations governing the continuous phase and particles, a three-step solution

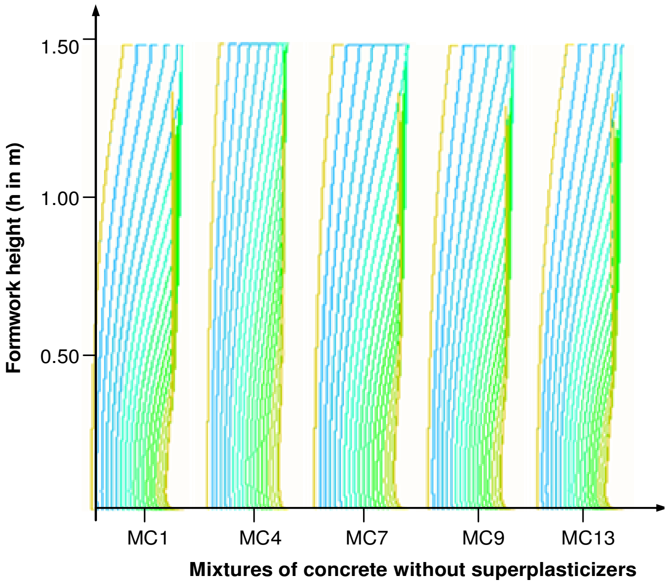

Figure 2. Aggregate particle trajectories in the formwork for different mixtures of concrete without superplasticizers (MC mixtures).

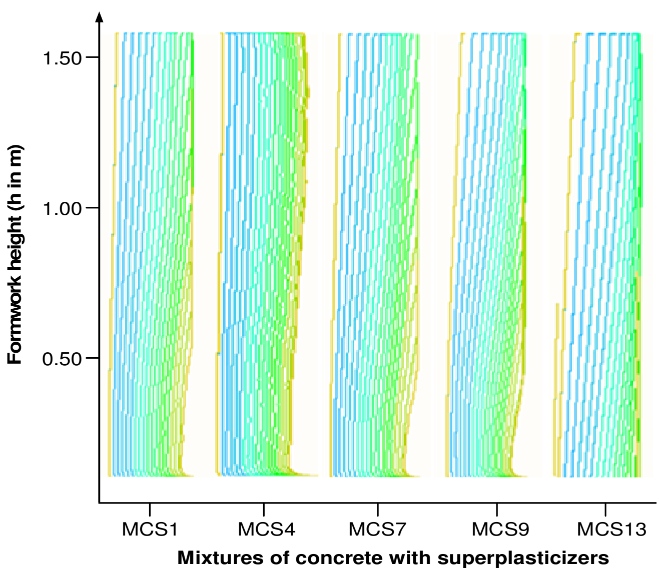

Figure 3. Aggregate particle trajectories in the formwork for different mixtures of concrete with superplasticizers (MCS mixtures).

procedure is employed. In the first step, the continuous-phase equations are solved assuming there is no particle. The next step followed the integration of particle equations using the current value of continuous phase velocity and calculation of the inter-phase sources. The continuous phase equations are solved again including the particles in the last step. This procedure is repeated until a converged solution is obtained. An hx30 grid system is employed in all computations. This grid system and a uniform time step of 0.001 s are found to be sufficiently refined for a numerically accurate result.

RESULTS AND DISCUSSION

There are many factors affecting the workability and stability of concrete that is, geometry of formwork, speed of filling, composition and the rheological properties of the fresh concrete. The aggregate segregation during the placement of concrete in the formworks of 30 cm diameters and 50, 100, and 150 cm height is numerically investigated. The results are compared to the rheological properties of the concrete. Fifty percent of the inlet area is taken by the nozzle which is used to introduce the concrete in the formwork. The cases considered in this study are summarized in Table 2.

The aggregate segregation varies depending on the concrete filling speed. In this study, the optimum filling velocity of the fresh concrete to the mould is taken as V_{in} = 0.9 m/s. Bilgil and Yeşilyurt (2002) have shown that segregation decreases as the filling velocity increases. They showed that, for a speed higher than V_{in} = 0.9 m/s inlet formwork velocity, the percentage ratio of segregation stays constant. On the other hand, the inlet velocity of V_{in} = 0.9 m/s is appropriate in application for concrete discharge pump. Meanwhile, Bilgil et al. (2005) numerically investigated the mechanism of segregation during the filling of fresh concrete into formwork.

Trajectories of the representative velocity of aggregate particles in flow concrete are shown in Figure 2 and 3 where half of the formwork is presented with a total width of 15 cm (radius of the origina l full-width formwork). In Figures 2 and 3, behaviours of aggregate during filling of concretes with different slump values are given as examples. The filling heights of fresh concrete of different slump values vary. These values are shown in Table 2. Accordingly, in Figures 2 and 3 only five samples for each of concrete mixtures with admixtures (MCS) and without admixtures (MC) are kept, in order not to allow the samples to occupy extensive amount of space. Figures 2 and 3 show the trajectories of large particles.

In Figure 2, large aggregate particles segregate while the elevation of concrete fill increases. In Figure 3, the trajectories of aggregate particles are shown for the same mixture as in Figure 2 with super-plasticizers added. It is observed that aggregate segregation is more common in concrete mixtures with no admixtures (Figure 2) compared to Figure 3. However, since filling from bottom of the formworks are involved, the consolidations in both cases are assumed to behave similarly. In Figures 2 and 3 different colours show the velocity distribution of aggregate particles. According to the presence of shear stress, velocity distribution of aggregate particles change during the filling of fresh concrete. The particle velocity at the central axis of formwork is shown with dark green,

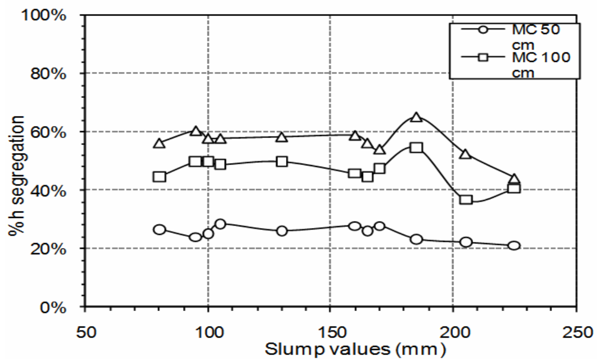

Figure 4. Effects of Slump values on aggregate segregation in MC mixtures of concrete.

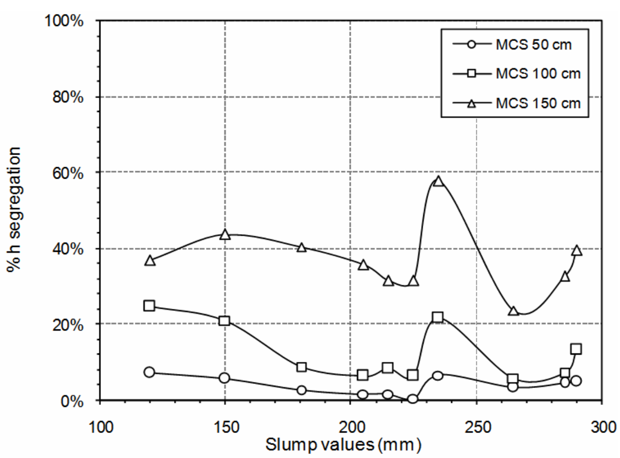

Figure 5. Effects of Slump values on aggregate segregation in MCS mixtures of concrete.

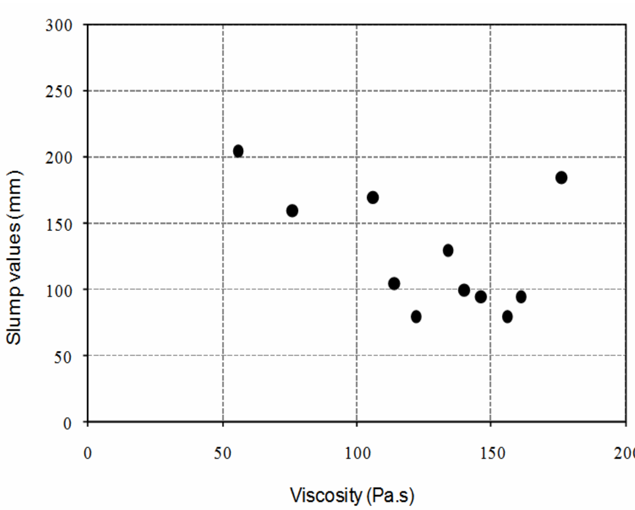

Figure 6. Comparison of slump with viscosity calculated by Herschel- Bulkley equation in MC mixtures.

while at the boundary where particle velocity reduces, trajectories are shown with a dark blue colour. In Figure 4, variation of aggregate segregation compared to mould height is given for various slump values. *H* represents height of the mould in Figure 4 and the subsequent figures. The fraction of segregation is defined by the following equation:

$$\eta = 1 - \frac{\sum N}{N_0} \tag{16}$$

where, N_0 is the total number of particles introduced at the inlet and $\sum N$ is the predicted sum of all particles that reach to the top of the mould. At the top of the formwork, the aggregate segregation is at its maximum value.

In Figures 4 and 5, the aggregate segregation at different slump values are given for fresh concrete mixtures with no admixtures, labeled as MC; and those with HRWRA admixture, labeled as MCS, which are placed in the moulds of 50,100, and 150 cm height, respectively. In Figures 4 and 5, it is observed that the data is scattered. Therefore, for both MC and MCS mixtures the influence of slump on the fractionation of segregation is not clear. The aggregate segregations in the formworks of 50, 100, and 150 cm high of MC mixture of fresh concretes reveal a parallel distribution. Maximum segregation is determined as 65% at a slump value of 185 mm while minimum segregation is determined as 53% at a slump value of 105 mm. As indicated in Figure 5, for cases where HRWRA mixtures (MCS) are used; maximum segregation is determined as 58% at a mould height of 150 cm for a slump value of 235 mm while minimum segregation is determined as 23% for a slump value of 265 mm. At mould heights of 50 and 100 cm, similar behaviour is obtained. However, aggregate distribution did not present linearity in MC and MCS mixtures at different slump values. Concrete mixtures with admixtures (MCS) revealed lower ratios than those

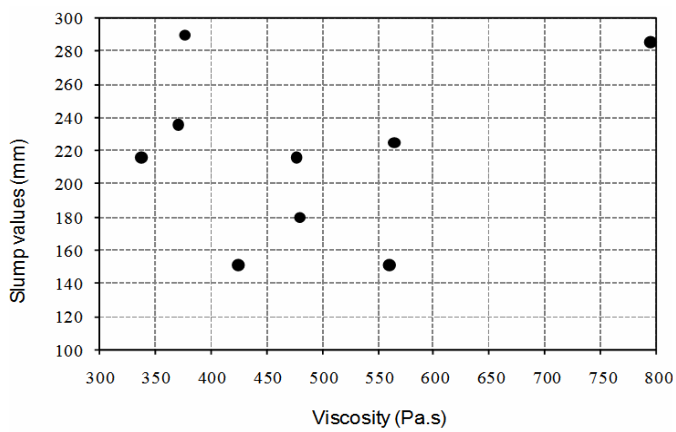

Figure 7. Comparison of slump with viscosity calculated by Herschel- Bulkley equation in MCS mixtures.

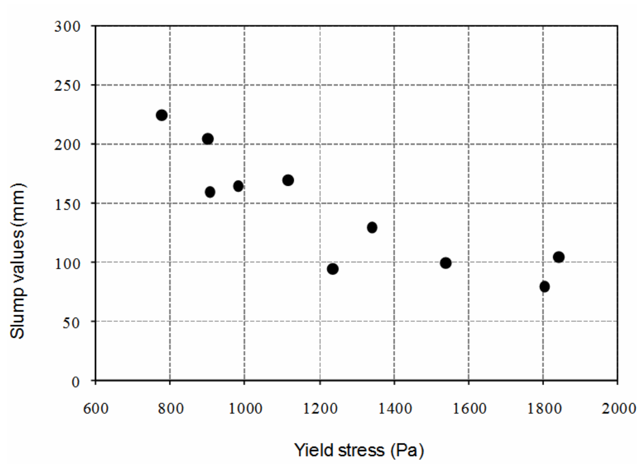

Figure 8. Relationship between yield stress and slump values of fresh concrete specimen (MC mixtures).

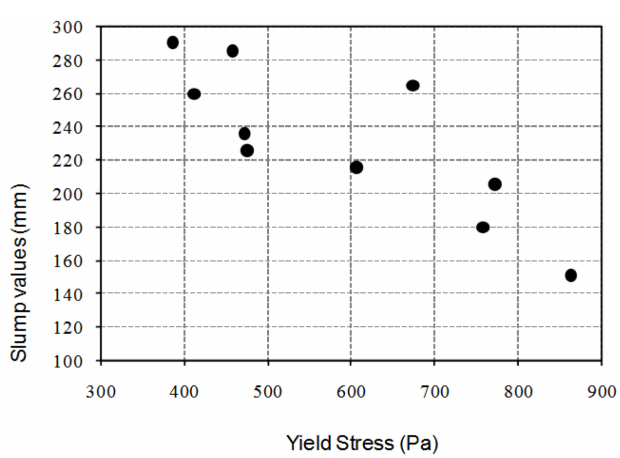

Figure 9. Relationship between yield stress and slump values of fresh concrete specimen (MCS mixtures).

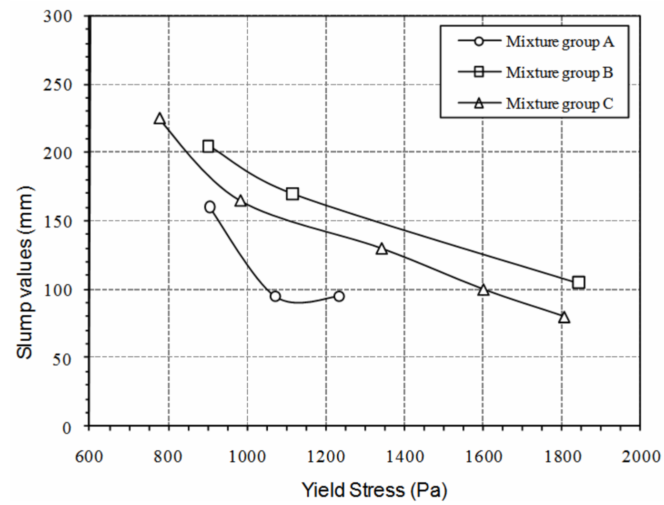

Figure 10. Relationship between yield stress and slump values for fresh concrete (MC mixtures: Group A, Group B, Group C).

without any admixtures (MC).

In Figures 6 and 7, the alterations of the fresh concretes for both in MC mixtures and in MCS mixtures are given for different slump values. The viscosity values (Ferraris and de Larrard, 1998) are calculated with the help of Herschel-Bulkley equation. The figures reveal that, there is not a linear distribution for different slump values. This situation may be due to the fact that concrete cannot be described only by its slump values. According to Murata and Kikukawa (1992), the temperature of concrete mixture and its viscosity vary in considerably small amounts, but are linear compared to slump values. Thus, in this study the temperatures of the mixture and medium are neglected. In this study, the relationship between yield stress and slump values of fresh concrete, which acts as a Bingham fluid, is investigated. In Figures 8 and 9 the relationships between yield stress and slump values of fresh concrete (both for MC and MCS mixture) are shown. It is observed that, as yield stress increases slump values decrease. This is the expected behaviour for Bingham fluids and it supports the assumption made for fresh concrete. In Figures 10 and 11, the relationship between slump values of fresh concrete and, their corresponding yield stresses which constitute one of the mechanical properties of concrete, is investigated for different concrete mixtures (Mixtures A, B and C). It is observed that, slump values decrease as yield stress of fresh concrete increases.

In Figures 12 and 13, the relationship between slump values and aggregate segregation (%) of fresh concrete is investigated. This relationship is given for fresh concrete both for MC and MCS mixtures. There is not a certain trend that is observed in Figures 12 and 13 for slump value–aggregate segregation (%) relationship.

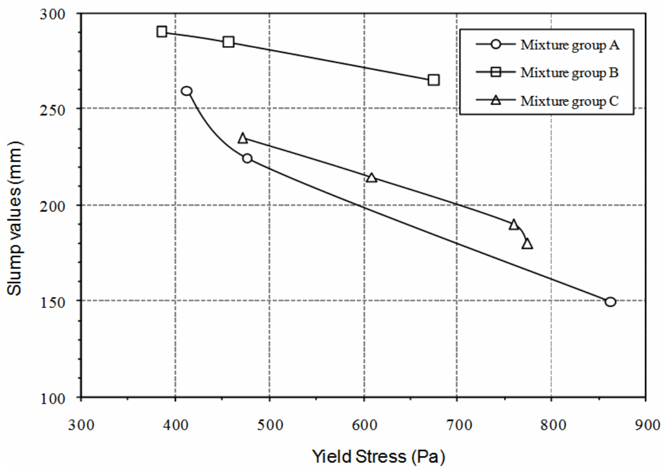

Figure 11. Relationship between yield stress and slump values for fresh concrete (MCS mixtures: Group A*, Group B*, Group C*).

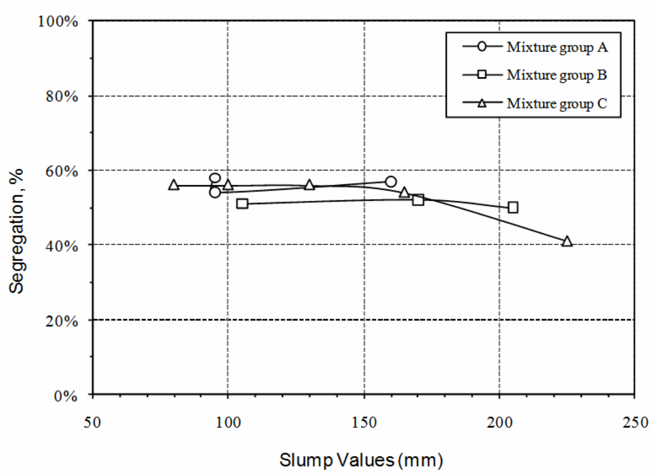

Figure 12. Relationship between slump values and segregation (%) for fresh concrete (MC mixtures: Group A, Group B, Group C).

(i) The relationship between slump values and aggregate segregation (%) can not be defined exactly. However, in Figures 4 and 5, it is observed that MCS (super-plasticizer added) mixtures have higher slump values and less aggregate segregation (%) compared to MC mixtures for the same compositions of fresh concrete.
(ii) In Figures 6 and 7, it is observed that viscosity acts independent of different slump values. As it is noticed in these figures, it is hard to correlate them with each other. In Figures 8 and 9, it is observed that slump values decrease as yield stress increases for both MC and MCS fresh concrete mixtures.
(iii) In Figures 10 and 11, it is observed that, for fresh concrete mixtures with the same composition, when yield

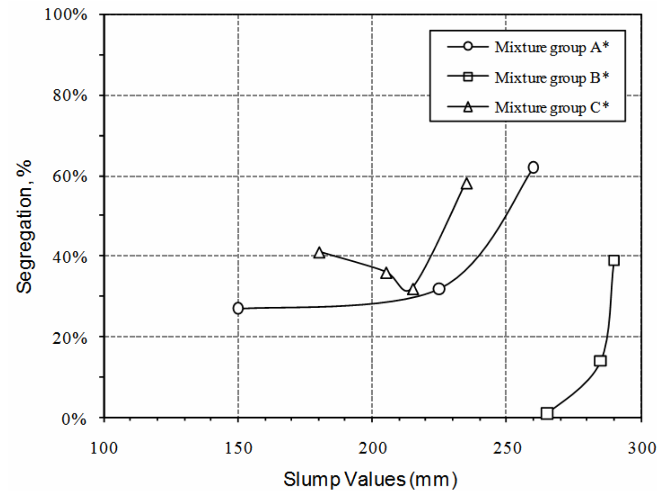

Figure 13. Relationship between slump values and segregation (%) for fresh concrete (MCS mixtures: Group A*, Group B*, Group C*).

stress increases, slump values decrease (both for MC and MCS mixtures). There is a significant reduction in:

(i) The relationship between slump values and aggregate segregation (%) can not be defined exactly. However, in Figures 4 and 5, it is observed that MCS (super-plasticizer added) mixtures have higher slump values and less aggregate segregation (%) compared to MC mixtures for the same compositions of fresh concrete.
(ii) In Figures 6 and 7, it is observed that viscosity acts independent of different slump values. As it is noticed in these figures, it is hard to correlate them with each other. In Figures 8 and 9, it is observed that slump values decrease as yield stress increases for both MC and MCS fresh concrete mixtures.
(iii) In Figures 10 and 11, it is observed that, for fresh concrete mixtures with the same composition, when yield stress increases, slump values decrease (both for MC and MCS mixtures). There is a significant reduction in yield stress, when super-plasticizers are used (MCS mixtures) compared to MC mixtures. This is the expected behaviour for Bingham fluid.
(iv) In Figures 12 and 13, it is observed that, there is not a definite relation between slump values and aggregate segregation for fresh concrete mixtures (both for MC and MCS). They act independent of each other.
(v) In this study; the experimental data provided by Ferraris and de Larrard (1998) constitute the basis of the numerical analysis. The computational results obtained by the use of PHOENICS (Rosten and Spalding, 1986) are plotted in Figures 4 - 13. It has to be noted that among the computational results plotted in Figures 4 - 13, not all of them follow a certain trend. Rather, it is observed that in some of the figures the data are

scattered which is not desirable in Numerical Analysis.

Conclusions

In this study, slump-yield stress, slump-segregation and slump-viscosity relations are investigated using Computational Methods and Numerical Analysis techniques provided by PHOENICS (Rosten and Spalding, 1986). The effect of slump values of fresh concrete on yield stress, segregation and viscosity in accordance with the rheological properties of fresh concrete is investigated during filling of formwork. Fractionation, which is determined from the trajectories of aggregate particles introduced at the formwork interface during the formwork-filling operations of fresh concrete slurry, is numerically investigated.

The rheological properties of concrete are used to investigate the segregation of fresh concrete during the fill of formwork. Experimental data obtained from concrete experiments (Ferraris and de Larrard, 1998) are used in Lagrangian equations for this numerical study. The segregation values obtained from the simulation of mathematical model of concrete used in PHOENICS program constitute the basis of this research. Slump values decrease as yield stress increases for both MC and MCS fresh concrete mixtures . When superplasticizers are used (MCS mixtures), there is a significant reduction in yield stress compared to MC mixtures which is the expected behaviour for Bingham fluid. It is very likely to define the relationship in between slump values and yield stress when more experimental data is available in the future.

The relationship between slump values and aggregate segregation (%) for fresh concrete mixtures (both for MC and MCS) can not be defined exactly. However, it is observed that MCS (superplasticizer added) mixtures have higher slump values and less aggregate segregation (%) compared to MC mixtures for the same compositions of fresh concrete. In addition, it is noticed that, it is hard to correlate viscosity and slump values with each other.

ACKNOWLEDGEMENTS

Authors would like to thank Dr. Mahmut D. Mat of Nigde University for setting up the modeling parameters in PHOENICS and for his valuable advices. They would like to thank also Dr. Ferraris for her valuable comments and her authorization to let us use her data.

Nomenclature

A	particle projected area,
a, b	parameters in the Herschel-Bulkley equation
C_D	drag coefficient
d	particle diameter
D	drag function
H	formwork height
m	mass
N	number of particles
p	static pressure
Re	Reynolds number
r	radial coordinate
r_o	radius of formwork
t	time
v	radial velocity
V_{in}	inlet velocity
w	axial velocity
z	axial coordinate
γ	shear rate
Δ	deformation tensor
η	fractionation
μ	viscosity
ρ	density
τ	shear stress

REFERENCES

Arslan M, Şimşek O, Subaşı S (2005). Effects of Formwork surface Materials on Concrete Lateral Pressure, Construction and Building Materials, 19: 319-325.

Bilgil A, Yeşilyurt E (2002). Mathematical modelling of aggregate segregation during concrete flow, 2nd International Symposium, European University of Lefke, North Cyprus. pp. 187-196.

Bilgil A, Ozturk B, Bilgil H (2005). A numerical approach to determine viscosity-dependent segregation in fresh concrete, Appl. Math. Comput., 162(1): 225-241.

Clift R, Grace JR, Weber ME (1978). Bubbles, Drops and Particles. Academic Press, New York, U. S. A.

De Larrard F, Ferraris CF, Sedran T (1998). Fresh Concrete: A Herschel-Bulkley Material, Mater.Struct. 31: 494-498.

Dzuy NQ, Boger DV (1985). Direct Yield Stress Measurement with the Vane Method, J. Rheol., 29(3): 335-347.

Ferraris FC (1999). Measurement of Rheological Properties of High Performance Concrete: State of the Art Report, J. Res. Natl. Inst. Stand. Techl., pp.104: 461-478.

Ferraris FC, de Larrard F (1998). Testing and Modelling of Fresh Concrete Rheology, NISTIR 6094, NIST, U. S. A.

Ferraris FC, de Larrard F, Martys N (2001). Fresh concrete rheology: recent developments, Reprinted from Materials Science of Concrete VI, The American Ceramic Society, 735 Ceramic Place, Westerville. pp. 215-241.

Fueyo NA, Hamill I, Zhang Q (1992). The GENTRA User Guide, Technical Report, TR/211, CHAM Limited, U. K.

Iwasaki N (1983). Estimation of workability-why has the slump remained being used so long?, Concrete J., 21(10): 4-12.

Leeman A, Winnefeld F (2007). The effect of viscosity modifying agents on mortar and concrete, Cement and Concrete Composites, pp. 29: 341-349.

Li Z (2007). State of workability design technology for fresh concrete in Japan, Cement and Concrete Res., pp. 37: 1308-1320.

Mat MD, Altınışık K, Karakoç F, Kaplan Y (1999). Mathematical modelling of fractionation during the mold filling of semi-solid metal slurries, Turk. J. Eng. Environ. Sci., pp. 281-288.

Morinaga S (1973). Pumpability of concrete and pumping pressure in pipelines, Fresh Concrete: Important Properties and their Measurement. In: Proceedings of a RILEM Conference, Leeds, England. 7(3): 1–7.3-39.

Murata J (1984). Flow and deformation of fresh concrete, Materials of Construction, 17(98): 117-129.

Murata J, Kikukawa H (1992). Viscosity equation for fresh concrete, ACI Materials, J., 89: 230-237.

Pashias N, Boger DV (1996). A Fifty Cent Rheometer for Yield Stress Measurement, J. Rheol., 40(6): 1179-1189.

Rosten H, Spalding DB (1986). PHOENICS beginner's guide and user's manual, CHAM Limited (UK) Technical Report, TR/100, U.K.

Saak AW, Jennings HM, Shah SP (2004). A generalized approach for the determination of yield stress by slump and slump flow, Cement and Concrete Res., pp. 34: 363-371.

Safawi MI, Iwaki I, Miura T (2004). The segregation tendency in the vibration of high fluidity concrete, Cement Concrete Res., pp. 34: 219-226.

Schowalter WR, Christensen G (1998). Towards a Rationalization of the Slump Test for Fresh Concrete: Comparisons of Calculations and Experiments, J. Rheol., 42(4): 865-870.

Soshiroda T (1981). Segregation characteristics of concrete containing a high-range water-reducing admixture. In: Proceeding ACI SP-68, pp. 121-137.

Tattersall GH (1976a). The Workability of Concrete: A Viewpoint Publication. PCA, U. S. A.

Tattersall GH (1976b). Relationship between the British standard tests for workability and the two-point test, Mag. Concrete Res., 28(96): 143-147.

Tattersall GH, Banfill PFG (1983). The Rheology of Fresh Concrete. Pitman, Boston, MA, U. S. A.

Tattersall GH (1991). Workability and Quality Control of Concrete. E&FN Spon, London, U. K.

Van Leer B (1977). Towards the ultimate conservative difference scheme, iv. a new approach to numerical convection, J. Comput. Phy., pp. 23: 276-299.

Wallevik JE (2006). Relationship between the Bingham parameters and slump, Cement and Concrete Res., 36: 1214-1221.