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*Full Length Research Paper*

# Study of workability of fresh concrete using high range water reducer admixtures

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**The main issue in working with fresh concrete is the workability during filling of formwork. One of the problems found in workability is occurence of segregation depending on w/c ratio. Segregation is strongly related to w/c ratio. 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, a characteristic that is strongly related to w/c ratio, plays a crucial role in the quality of high performance concretes. The aggregates in fresh concrete cause segregation in the final product depending on the flow conditions. In this study, the mechanism of segregation in such a system was theoretically investigated. The mould filling of fresh concrete was numerically investigated and aggregates were considered as Lagrange particles. Segregation was identified from trajectories of such particles. Within this framework, fresh concretes with no admixtures (MC) and those with high range water reducer admixtures (HRWRA) (MCS) were investigated. Minimum agregate segregation in fresh concrete mixtures without HRWRA admixtures was observed to have been higher than in mixtures containing HRWRA admixture.**

**Key words:** Fresh concrete, flow concrete, aggregate segregation, mathematical modelling, particle size distribution.

## INTRODUCTION

One of the major requirements is that during moulding, fresh concrete will easily flow with no segregation to result in a highly consolidated structure. The shape of the formwork, reinforcement steel and concrete mixture parameters may prevent the fresh concrete's consolidation (Arslan et al., 2005). Especially, the lack of consolidation in the structural system may lead to insufficient durability and costly repairs due, to excessive air pocket formations. For this reason, the ACI literature (1992), offers extensive amount of documentation on various factors contributing to congestion and the means to minimize problems resulting from such congestion, including special considerations for detailing reinforcement, formwork selection, mixture proportioning and proper placing and consolidation methods (Arslan and Subasi, 2008). Self compacting concrete (SCC) is commonly used in strengthening reinforced concrete components damaged by earthquakes. According to Takeuchi et al. (1994), self compacting concrete is also used for restricted areas, where access for placing and consolidating fresh concrete is limited as in the case of tunnel lining.

The settlement of larger agregate grains can be detected by the presence of bleeding water. While some quantity of the resulting bleeding water is detained in the concrete, the remaining water under coarse aggregates can rise to the surface of the concrete. And this situation may cause aggregate segregation, sedimentation of cement granules, and early hydration products in the fresh concrete that is already transformed into a dense suspension. Sedimentation and bleeding are similar phenomena. The sagging of the aggregate forces the water to move upwards. The result is an inhomogenous material with larger particles at the bottom and water at the top. This has a direct implication on permeability, durability and strength of the final product. Hoshino (1988),

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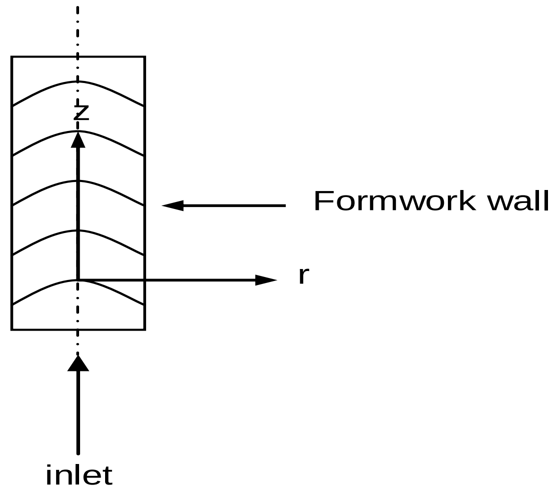


**Figure 1.** Schematic of test configuration (cylindrical formwork).

argues that higher w/c ratios increases the bleeding water leading to different concrete compositions at top and bottom of the structure, resulting in higher porosity.

The stability of concrete decreases with increased w/c ratio. The use of HRWRA allows improving the stability (reduction in seggregation) by reducing the w/c ratio without reduction in fluidity. Khayat et al. (1993), suggested an alternative approach to enhance stability of concrete without reducing it by incorporating a viscosity-modifying admixture in combination with a HRWRA.

Khayat and Guizani (1997), indicated that regardless of w/c ratio, slump, placing height and mode of consolidation; the incorporation of a viscosity modifying admixture significantly enhanced resistance against bleeding, settlement and segregation.

According to ACI (1992), SCC is a concrete that can be cast into a mould with no excessive bleeding water, settlement and segregation having a slump of 190 mm. Wallevik (2006) investigated the relationship between Bingham parameters and slump values for flowing concrete.

The workability of flowing or SCC is defined by its rheological properties and is related to its ingredients. Ferraris (1999) defined workability either qualitatively as the ease of placement or quantitatively by rheological parameters. Tattersall's (1976) interpretation of workability is "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 to perform satisfactorily in some transporting operation or forming process and may be other requirements as well". According to Tattersall (1976), 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. de Larrard et al. (1998) found in some cases that the Herschel-Bulkley equation suited better to describe concrete flow, especially in SCC. Herschel-Bulkley equation encompasses three parameters two of which do not represent a physical entity. However, the Bingham equation is commonly employed by most researchers. The reason for this is that the parameters used in the equation are independently measurable factors. As shown by Tattersall (1976) the flow of real concrete seems to follow this equation fairly well in most cases. Recently, further research for fresh concrete rheology has been conducted both analitically and experimentally (Safawi et al., 2004; Li, 2007; Leeman and Winnefeld, 2007; Bethmont et al., 2009).

In this paper, the effectiveness of viscosity modifying admixtures to reduce agregate segregation of flowing concrete was numerically studied. Aggregate segregation is highly important especially in terms of structural frame. The scenario is that normal concrete with different w/c ratio is filled from bottom of formwork at different inlet velocities. The fresh concrete is assumed to behave as a 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 data on the rheological properties of the fresh concrete used in this investigation to validate the proposed numerical model were extracted from results of a study made by from Ferraris and de Larrard (1998).

## Significance of the research

Concrete is composite material, with aggregates, cement and water as the main components. It should have a homogenous dispersion with a high capacity. Therefore, SCC should have a high stability to minimize the constructional defects. The aim of this study is to present data related to concrete mixtures to produce a stable concrete that will remain homogenous and of high compacity with minimum segregation during pumping and casting. SCC has been moulded starting from the bottom of the formwork, optimizing the stability of concrete to be used in repair of the structural components damaged by earthquakes. The findings of this research should be instrumental by predicting and designing SCC for use in restricted areas.

## Problems 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. The concrete enters from the bottom of the formwork and progressively rises in the formwork forming a free surface. Three different heights for the formworks were chosen as 500, 1000 and 1500 mm, and radius of the formworks was 300

**Table 1.** Values used in calculating viscosity of fresh concrete (Ferraris and de Larrard, 1998)*.

| Mixture | Specific gravity (kg/m³) | Water/cement ratio | Herschel-Bulkley | | |
|---|---|---|---|---|---|
| | | | Viscosity (Pa.s) | a (Pa.s$^b$) | b |
| MC1 | 2.26 | 0.666 | 161 | 55 | 1.72 |
| MC2 | 2.26 | 0.696 | 146 | 87 | 1.35 |
| MC3 | 2.22 | 0.727 | 76 | 43 | 1.39 |
| MC4 | 2.33 | 0.421 | 114 | 42 | 1.66 |
| MC5 | 2.33 | 0.440 | 106 | 93 | 1.09 |
| MC6 | 2.31 | 0.460 | 56 | 50 | 1.09 |
| MC7 | 2.33 | 0.553 | 156 | 111 | 1.23 |
| MC8 | 2.33 | 0.567 | 140 | 86 | 1.33 |
| MC9 | 2.31 | 0.581 | 134 | 74 | 1.40 |
| MC10 | 2.32 | 0.595 | 111 | 62 | 1.40 |
| MC11 | 2.30 | 0.610 | 89 | 102 | 0.90 |
| MC12 | 2.29 | 0.595 | 122 | 70 | 1.38 |
| MC13 | 2.29 | 0.624 | 176 | 57 | 1.75 |
| MCS1 | 2.25 | 0.349 | 561 | 665 | 0.88 |
| MCS2 | 2.32 | 0.361 | 565 | 506 | 1.07 |
| MCS3 | 2.32 | 0.373 | 338 | 191 | 1.39 |
| MCS4 | 2.40 | 0.262 | 2956 | 792 | 1.88 |
| MCS5 | 2.39 | 0.271 | 795 | 269 | 1.73 |
| MCS6 | 2.37 | 0.281 | 376 | 132 | 1.70 |
| MCS7 | 2.38 | 0.362 | 476 | 417 | 1.09 |
| MCS8 | 2.38 | 0.369 | 479 | 385 | 1.15 |
| MCS9 | 2.38 | 0.376 | 501 | 430 | 1.10 |
| MCS10 | 2.38 | 0.383 | 338 | 147 | 1.56 |
| MCS11 | 2.38 | 0.390 | 370 | 205 | 1.40 |
| MCS12 | 2.37 | 0.374 | 425 | 190 | 1.54 |
| MCS13 | 2.40 | 0.388 | 301 | 87 | 1.83 |

* The MC mixtures are those without HRWRA, and MCS mixtures are those with HRWRA.

mm. For specific gravity values, the data in Table 1 were used.

## MATHEMATICAL FORMULATION

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

### 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

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

### Radial momentum

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

where $v$ and $w$ are the radial and axial velocities respectively, $p$ is the static pressure. de Larrard et al. (1998) suggested employing Herchel-Bulkley equation to represent the rheological properties of the fresh concrete due to its non-Newtonian behavior. This relates shear stress to shear strain rate, based on the power function:

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

where, $\tau$ is the shear stress, $\gamma$ 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 the concrete. In this case, plastic viscosity can not be calculated directly. From Ferraris et al. (2001), the yield stress is calculated by the Herchel-Bulkley equation, while the viscosity is calculated using:

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

where, $\mu$ is the slope and $\gamma_{max}$ is the maximum shear strain rate achieved in the test, *a* and *b* are the parameters as calculated by the Herchel-Bulkley equation. For the purpose of determining the viscosity of fresh concrete the values given in Table 1 are used.

## Particles physics

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

$$\frac{dZ_P}{dt} = w_P \qquad (6)$$

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

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

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 $b_g$ is the buoyancy factor, and $\nabla p$ is gradiant operator.

Drag function $D_p$ can be expressed as (Fueyo et al.,1992):

$$D_P = \frac{1}{2}\rho_P A_P C_D \left|\omega - \omega_P\right|^2 \qquad (8)$$

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):

$$C_D = \frac{24}{Re}\left(1 + 0.15\, Re^{0.687}\right) + \frac{0.42}{1.425.10^4\; Re^{-1.16}} \qquad (9)$$

where Re is a particle Reynolds number defined as:

$$\mathbf{Re} = \frac{\left|w_P - w_c\right| d_P}{v_k} \qquad (10)$$

where $v_k$ is the kinematics viscosity of the continuous phase and $d_p$ is the particle diameter.
The buoyancy factor is given by:

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

## Initial 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 boundary conditions can be expressed mathematically as:

$$t = o : \upsilon = \omega = 0 \qquad (12)$$

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

$$\text{at } r = r_o : \upsilon = \omega = 0 \qquad (14)$$

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

## Numerical method

The governing equations were solved numerically with a fully implicit, finite domain scheme embodied in the PHOENICS (Rosten and Spalding, 1986) code. Since the mold filling operation involved 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 resulted in a false numerical diffusion. A van Leer (1977) scheme was employed to resolve such property interface problem.

Due to the coupling between the transport equations governing the continuous phase and particles, a three-step solution procedure was employed. In the fist step, the continuous-phase equations were solved assuming there was 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 were solved again including the particles in the last step. This procedure was repeated until a converged solution was obtained.

A grid system of 300 mm diameter, and of variable heights was employed in all computations. This grid system and a uniform time step of 0.001 s was found to

**Table 2.** Parameters of concrete mixtures (Ferraris and de Larrard,1998).

| Concrete mixture | Dry mixture mass (%) | | | | Composition (kg/m$^3$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Gravel | Sand | Fine sand | Cement | Gravel | Sand | Fine sand | Cement | Super plasticizer | w/c ratio |
| MC1 | 22.5 | 46.2 | 14.3 | 17.0 | 460 | 944 | 293 | 347 | -- | 0.666 |
| MC2 | 22.5 | 46.2 | 14.3 | 17.0 | 455 | 934 | 290 | 344 | -- | 0.696 |
| MC3 | 22.5 | 46.2 | 14.3 | 17.0 | 450 | 925 | 287 | 340 | -- | 0.727 |
| MC4 | 40.6 | 26.2 | 8.1 | 25.1 | 851 | 549 | 170 | 527 | -- | 0.421 |
| MC5 | 40.6 | 26.2 | 8.1 | 25.1 | 843 | 543 | 169 | 522 | -- | 0.440 |
| MC6 | 40.6 | 26.2 | 8.1 | 25.1 | 834 | 537 | 167 | 517 | -- | 0.460 |
| MC7 | 45.0 | 29.0 | 9.0 | 17.0 | 957 | 617 | 191 | 362 | -- | 0.553 |
| MC8 | 45.0 | 29.0 | 9.0 | 17.0 | 952 | 614 | 190 | 360 | -- | 0.567 |
| MC9 | 45.0 | 29.0 | 9.0 | 17.0 | 947 | 611 | 189 | 358 | -- | 0.581 |
| MC10 | 45.0 | 29.0 | 9.0 | 17.0 | 943 | 607 | 189 | 356 | -- | 0.595 |
| MC11 | 45.0 | 29.0 | 9.0 | 17.0 | 938 | 604 | 188 | 354 | -- | 0.610 |
| MC12 | 57.6 | 19.3 | 6.0 | 17.0 | 1207 | 405 | 126 | 356 | -- | 0.595 |
| MC13 | 57.6 | 19.3 | 6.0 | 17.0 | 1194 | 401 | 124 | 352 | -- | 0.624 |
| MSC1 | 21.2 | 43.0 | 12.3 | 23.5 | 468 | 947 | 271 | 519 | 12.97 | 0.349 |
| MSC2 | 21.2 | 43.0 | 12.3 | 23.5 | 465 | 941 | 269 | 516 | 12.89 | 0.361 |
| MSC3 | 21.2 | 43.0 | 12.3 | 23.5 | 462 | 935 | 267 | 513 | 12.81 | 0.373 |
| MSC4 | 40.0 | 24.9 | 7.1 | 28.0 | 904 | 563 | 161 | 634 | 15.86 | 0.262 |
| MSC5 | 40.0 | 24.9 | 7.1 | 28.0 | 899 | 559 | 160 | 630 | 15.76 | 0.271 |
| MSC6 | 40.0 | 24.9 | 7.1 | 28.0 | 893 | 556 | 159 | 627 | 15.66 | 0.281 |
| MSC7 | 45.0 | 28.0 | 8.0 | 19.0 | 1015 | 632 | 180 | 429 | 10.71 | 0.362 |
| MSC8 | 45.0 | 28.0 | 8.0 | 19.0 | 1012 | 630 | 180 | 427 | 10.68 | 0.369 |
| MSC9 | 45.0 | 28.0 | 8.0 | 19.0 | 1009 | 628 | 179 | 426 | 10.65 | 0.376 |
| MSC10 | 45.0 | 28.0 | 8.0 | 19.0 | 1006 | 626 | 179 | 425 | 10.62 | 0.383 |
| MSC11 | 45.0 | 28.0 | 8.0 | 19.0 | 1003 | 624 | 178 | 423 | 10.59 | 0.390 |
| MSC12 | 57.0 | 18.7 | 5.3 | 19.0 | 1278 | 419 | 120 | 426 | 10.66 | 0.374 |
| MSC13 | 57.0 | 18.7 | 5.3 | 19.0 | 1270 | 416 | 119 | 424 | 10.59 | 0.388 |

be sufficiently refined for a numerically accurate result. A typical calculation required approximately 5 h of CPU time on a personal computer with a Pentium III processor.

## RESULTS AND DISCUSSION

Many factors are affecting the workability and stablity of the concrete like the geometry of the formwork, speed of filling, the mixture composition and the rheological properties of the fresh concrete. The aggregate segregation while concrete is being placed in the formworks of 300 mm diameters and 500, 1000, and 1500 mm height was numerically investigated. The results were compared to with the rheological properties of the concrete. During the filling of the concrete into the formwork, fifty percent of the inlet area was simulated and the second half of the formwork was considered to be symmetrical. The parameters of concrete mixtures used in this study are summarized in Table 2.

The aggregate segregation varies depending on the the concrete filling speed. In this study, the optimum filling velocity of the fresh concrete to the mould was taken as $V_{in}$ = 0.9 m/s. As seen in Figure 2, Bilgil and Yeşilyurt (2002) have shown that the lower segregation is linked to the higher filling velocity. They showed that segregation declines dramatically for an inlet velocity exceding 0.9 m/s. In industrial applications, concrete pumps discharge concrete at an average speed of 1 m/s, and this fact shows that 0.9 m/s velocity corresponds with industrial applications.

Trajectories of the representative velocity of aggregate particles in flowing concrete are shown in Figures 3 and 4. Behaviors of the aggregate during filling of concretes with different w/c ratios are given as examples in Figures 3 and 4. Since filling heights of fresh concrete of different w/c ratioes are variable according to Table 2, in Figures 3 and 4, the numbers of the samples of the concretes without admixtures (MC), and with admixtures (MCS) were minimized allowing the samples not to occupy more place.

In this study, the behaviour of the particles of coarse aggregate during filling of the mould was described

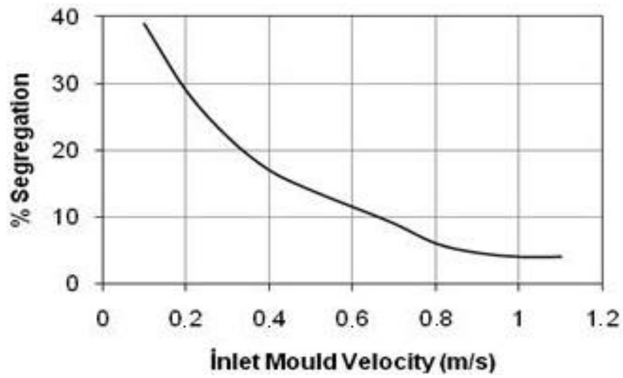


**Figure 2.** The percentage of aggregate segregation inlet mould velocity.

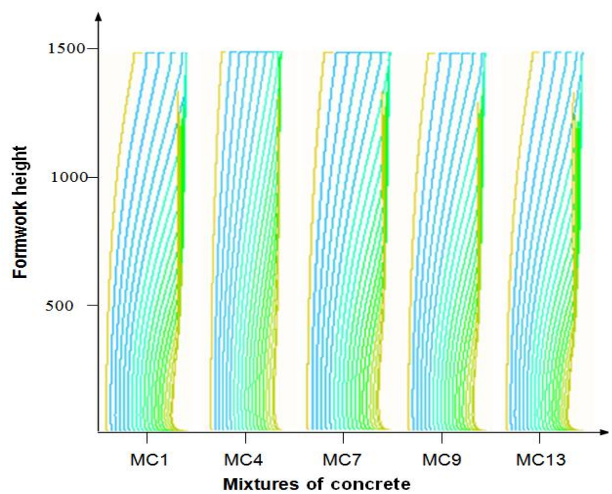


**Figure 3.** Trajectories of aggregate particles in formwork for different MC mixtures.

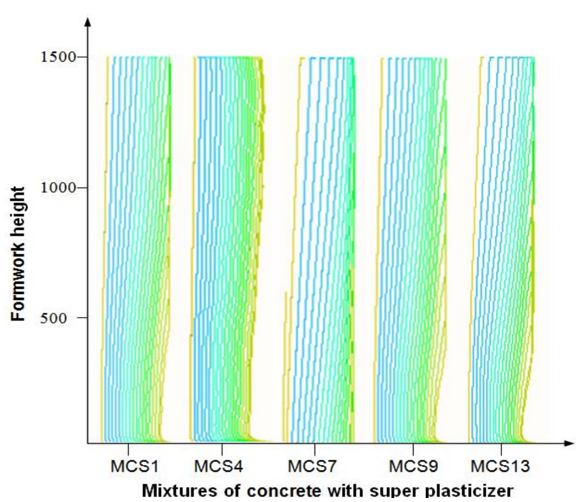


**Figure 4.** Trajectories of aggregate particles in formwork for different MCS mixtures.

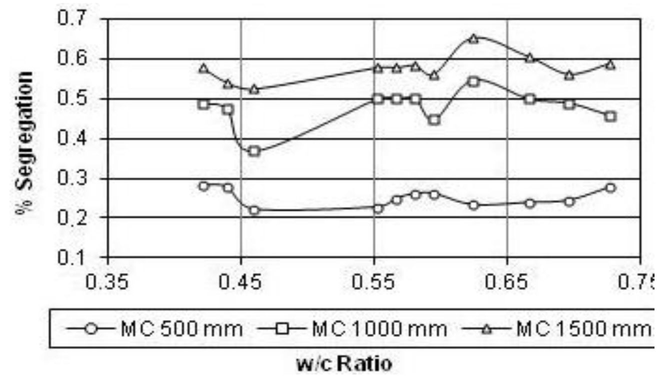


**Figure 5.** Effect of w/c ratios on aggregate segregation in MC mixtures.

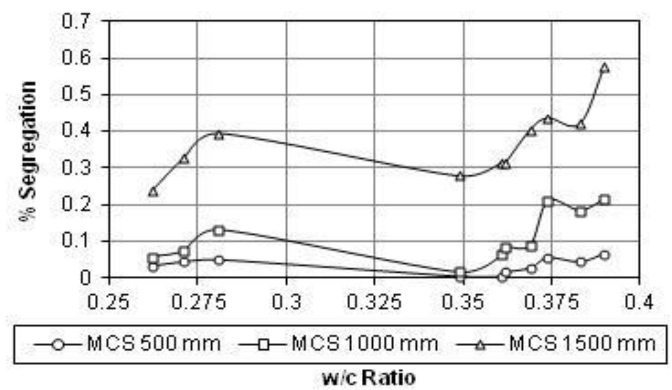


**Figure 6.** Effect of w/c ratios on aggregate segregation in MCS mixtures.

(Figures 3 and 4). Data on aggregate segregation of MC and MCS mixtures are prescribed in Figures 3 and 4, respectively.

Space limitations prevent describing particle behaviours of all mixtures. Moreover, similar particle behaviour in moulds of 500, 1000 and 1500 mm height allows concentrating on only the last case. Since the particle behaviours of the concrete in the moulds of heights 500, 1000 and 1500 mm were congruent, the values for 500 and 1000 mm high moulds were not given. Behaviour of particles is colour-coded as to their speed in Figures 3 and 4. Due to the effect of "boundary shear", the movement of those particals involved are colour-coded green. At higher speed, the particles are colour-coded light blue.

Variation in aggregate segregation for MC and MCS mixtures is presented as a function of w/c ratio in Figures 5 and 6, respectively. In Figure 5, the variation of aggregate segregation for various w/c ratios was studied. *h* represents the height of the mould in this and subsequent figures. The fraction of seggregation is defined by the following equation:

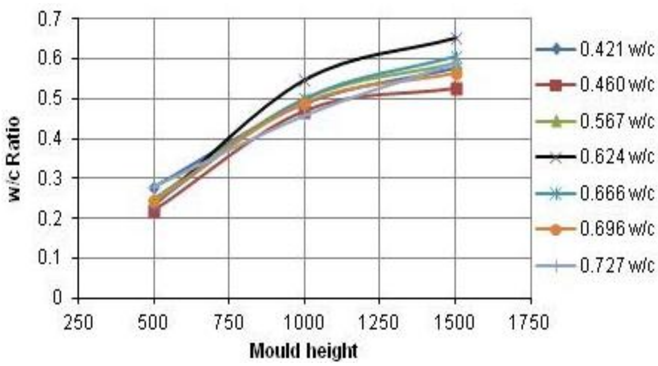


**Figure 7.** Aggregate segregation through mould height for different w/c ratios in MC mixtures.

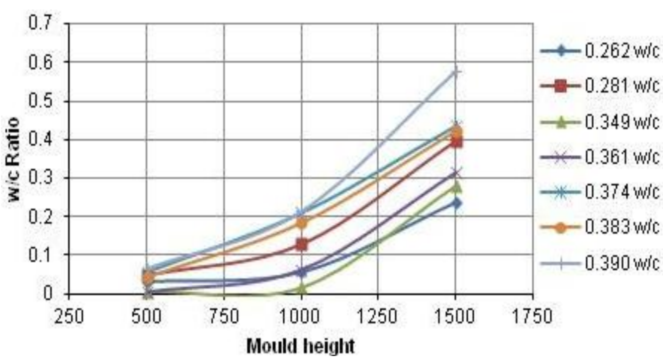


**Figure 8.** Aggregate segregation through mould height for different w/c ratios in MCS mixtures.

$$\eta = 1 - \frac{\sum N}{N_O} \quad (16)$$

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

As seen in Figure 5, it can be seen that there is no specific w/c influence in the percentage of seggregation for a given height. On the contrary, we can deduce, from Figure 6, that above a certain w/c ratio (in this case about 0.35) the seggregation strongly increases.

The aggregate segregation values in the formworks of 500, 1000 and 1500 mm heights of MC mixtures were not affected dramatically by w/c ratios, and revealed a parallel segregation to each other but it was observed that segregation was affected by formwork heights. Maximum segregation was determined as 65% at w/c ratio of 0.624 and minimum segregation was determined as 53% at w/c ratio of 0.460. As indicated in Figure 6, in MCS mixtures; maximum segregation was determined to have been 58% at the mould height of 1500 mm, w/c ratio of 0.390; and minimum segregation was determined to have been 23% at the w/c ratio of 0.262 for the same height of formwork. At the mould heights of 500 and 1000 mm, similar results were obtained. However, aggregate distribution did not present linearity in MC and MCS mixtures at different w/c ratios and the mixtures accompanied by admixtures revealed lower ratios than those accompanied by no admixtures. In MC mixtures, it has been observed that denser aggregate segregations were formed compared to MCS mixtures.

Murata and Kikukawa (1992) stated that the temperature of the mixture and viscosity of the concrete varies in considerably small values but are linear when compared to the w/c ratio. But in this study, the temperatures of the mixture and medium were neglected since the data were obtained at constant room temperature.

In Figure 7, the change in aggregate segregation with regard to mould filling height was studied for different w/c ratios of MC mixtures. As seen in the figure, aggregate segregation presents a tendency towards decreasing as the mould filling height increases. Though that decrease is not so much distinct, it might be concluded that the agregate segregation is a function of mould height. The figure also implies that the change in w/c ratio does not have a significant effect on aggregate segregation. Thus, the conclusion that the most distinct effect on segregation is wall shear stress is achieved.

In Figure 8, the change in aggregate segregation in MCS mixtures, for different w/c ratios with regard to mould filling height was studied. As seen in the figure, aggregate segregation, to the contrary of that in MC mixtures, presents a tendency of increase as the mould filling height increases. Though this increase is not precisely linear, the conclusion that aggregate segregation in MCS mixtures is a function of mould height is achieved. However, segregation slightly increases with the increase of w/c ratio though it is not distinctly clear. Resultingly, aggregate segregation is not a function of w/c ratio, and the main factors that cause segregation are mould height and wall shear stress.

## Conclusions

The degree of seggregation during the formwork-filling operations of fresh concrete slurry was numerically investigated. This study, particularly assessed influence of adding a HRWRA on segregation. The degree of segregation was derived from the trajectories aggregate particles contained in the fresh concrete introduced under pressure at the bottom of the formwork. The concrete was introduced into the formwork from bottom under pressure.

The risk that the flowing concrete decomposes was observed as a funtion of w/c ratio and formwork height.

However, aggregate dispersions did not reveal linearity along the formwork height for different w/c ratios in MC and MCS mixtures. This situation is thought to have taken its root from rheological properties of the concrete. Minimum degree of segregation in MC mixtures were observed to have been higher than that in MCS mixtures. Maximum degree of segregation in MC mixture was 65% for 1500 mm high formwork, while minimum segregation was 53% for the same height of formwork. For the MCS mixtures, maximum degree of segregation was 58% for 1500 mm high formwork, w/c ratio of 0.390; and minimum degree of segregation was 23% for the same height of formwork but w/c ratio of 0.262.

As the height of the formwork increases, aggregates in the MC and MCS mixtures get affected by the wall shear stress that develops on the formwork wall and this phenomenon causes segregation. Segregation shows decreasing and increasing tendency for different w/c ratios. It was observed that w/c ratios did not affect segregation especially in MC mixtures. However It was seen that agregate segregation increased slightly as w/c ratio increased in MCS mixtures. Resultingly, it was concluded that w/c ratio did not have significant effect on segregation, and segregation is a function of formwork height.

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**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; $v_k$ , kinematics viscosity; $V_{in}$, inlet velocity; ***W,*** axial velocity; ***Z,*** axial coordinate; $\gamma$, shear rate; $\Delta$, deformation tensor; $\eta$, fractionation; $\mu$, dinamic viscosity; $\rho$, 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.

Arslan M, Subaşı S (2008). The effects of controlled-permeable formworks on the surface hardness of the concrete, J. Fac. Eng. Arch.Gazi Univ., 23(4): 885-894.

ACI Committee 309 (1992). Guide for Consolidation of Concrete in Congested Areas, ACI 309. 3R-92, American Concrete Institute, Detroid, p.10

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

Bethmont SD, Aloia SL, Stefani C, Tailhan JL, Rossi P (2009). Contribution of granular interactions to self compacting concrete stability: Development of a new device, Cement and Concrete Research, 39, 30-35.

Clift R, Grace JR, Weber ME (1978). Bubbles Drops and Particles, Academic Press New York, pp. 1-380.

de Larrard F, Ferraris CF, Sedran T (1998). Fresh Concrete: A Herschel-Bulkley Material, Materials and Structures, 31: 494-498.

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

Ferraris FC, de Larrard F (1998). Testing and Modelling of Fresh Concrete Rheology, NISTIR 6094, February, pp. 54-56.

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, CHAM Limited (UK) Technical Report, TR/211, pp. 1-117.

Hoshino M (1988). Difference of the w/c Ratio, Porosity and Microscopical Aspect between the Upper Boundary Paste and the Lower Boundary Paste of the Aggregate in Concrete, Materials and Structures, 21: 336-340.

Khayat KH, Gerwick BC, Hester WT (1993). Self-Levelling and Stiff Consolidated Concretes for Casting High-Performance Flat Slabs in Water, ACI Concrete Int., 15: 36-43.

Khayat KH, Guizani Z (1997). Use of Viscosity-Modifying Admixture to Enhance Stabiliy of Fluid Concrete, ACI Mater. J., 97: 332-340.

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

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

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

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

Rosten H, Spalding DB (1986). PHOENICS beginner's guide and user's manual, CHAM Limited (UK) Technical Report, TR/100, pp. 1-27.

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

Takeuchi M, Higuchi M, Nanni A (1994). Application of Flowable Concrete in a Tunnel Lining, Concrete International, Apr., 16: 26-29.

Tattersall GH (1976). The workability of Concrete: A Viewpoint Publication. PCA, U.S.A, pp. 85-92.

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

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