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# A study on the applicability of vibration in fresh high fluidity concrete

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**Abstract**

The introduction of superplasticizers (Sp) in the production of concrete has produced highly flowable mixtures with enhanced viscosity. In cases of optimum flowability and viscosity, for example self-compacting concrete (SCC), no vibration is necessary for placement. However, such ideal conditions are not practically easy to achieve and deviations are possible. This paper reviews the results of a study to investigate the vibration of such high fluidity concrete. Two criteria were used to characterize the fresh mix, that is, slump flow and V-funnel time (V-time). Firstly, the feasibility of vibration on such mixes was studied. Then, the significance of flowability and viscosity was determined. Next, the relationship between workability and its segregation tendency was investigated. Finally, concrete mixes that missed SCC criteria were vibrated. Three different scenarios of vibration were concluded: namely, mix that accept vibration freely, mix that required controlled vibration and mix that needed prior treatment of viscosity enhancing agent (VEA) before vibration.

*Keywords:* Fresh concrete; Rheology; Vibration; Workability; Stability

## 1. Introduction

High performance concrete that relies on the use of superplasticizer (Sp) can be made to flow easily by virtue of its own weight. In a standard slump cone test, the fresh concrete spread into a circular shape, instead of retaining the shape of the cone as is the case for conventional concrete. The perpendicular distance of the circular spread is known as slump flow. Thus, the mix is considered as flowable or high fluidity. A high fluidity concrete is thus a concrete that can flow by virtue of its own weight, while keeping the coarse aggregate homogenous in the mix.

Due to the possibility of producing a flowable yet viscous mix, a high performance self-compacting concrete (SCC) was founded in Japan in the late 1980s [1]. By careful adjustment of both the concrete ability to flow and achieving an optimum viscosity, SCC can be placed without the need of vibration. In testing SCC, two tests are common practice in Japan. One is the slump flow test and the other is the V-funnel test [2]. Fresh concrete is filled in a V-shaped funnel and the time taken for it to flow out is taken as the V-funnel time or simply V-time. A high V-time indicates a high viscous condition of mix. These two tests (slump flow and V-time) are for adjusting the mix proportion and used to test its deformability and viscosity. Generally, the target value for SCC in both the slump flowability and V-time are 650±50 mm and 10 s, respectively [3].

The manufacture of such high performance concrete is, however, not an easy task. On a construction site, the possibility of missing the SCC criteria is always high [4]. These concrete that miss SCC criteria could still be placed by alternative ways. One option will be the use of vibrator, which is a common practice for conventional concrete. The vibration of such concrete and its effects on segregation of coarse aggregates has been the motivation of this study.

In this study, the condition of high fluidity concrete is characterized by two simple criteria: slump flow and V-time. The slump cone test is to determine the flowability of

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concrete while the V-funnel test is to quantify the viscous condition of mix. Having understood the degree of vibration acceptable by the concrete, the placing of such flowable concrete that misses SCC criteria by means of vibration can be performed with utmost confidence.

## 2. Experimental program

The entire study covered four main stages of the work. Different sets of experiment were done to achieve the aims of the respective stage.

A. Preliminary feasibility study
Mortars of different flowability and viscosity were vibrated and its degree of segregation was compared. The aim was to determine the feasibility of vibrating such high flowability mix.

B. Significance of flowability and viscosity
Concrete mixes of different flowability and viscosity were vibrated to determine the significance of either parameter in determining segregation conditions. By understanding their significance, the factors that contribute towards the segregation behavior of concrete can be explained easily.

C. Relation between workability and segregation tendency
The segregation tendency of mix was studied against its workability. Mixes of high and low workability were vibrated and the segregation pattern was determined.

D. Vibration of mixes that missed SCC criteria
Mixes that missed SCC criteria were made in the laboratory and vibration was applied. The type of vibration applicable on such concrete mixes was concluded.

## 3. Materials and equipments

The mixtures investigated in this study were prepared with ordinary Portland cement. Continuously graded crushed granite, with Saturated Surface Dry (SSD) density of 2.86 g/cm$^3$, was used as coarse aggregate. A maximum aggregate size of 20 mm was employed for coarse aggregates, as is commonly the case in SCC mixes. Coarse aggregates were washed to remove fine sandy particles that can hinder rheological properties. Well-graded pit sand, with SSD density of 2.60 g/cm$^3$, having maximum size 5 mm and a fineness modulus 2.63, was employed as the fine aggregate. The sand was used both in the mixing of mortar and concrete. A new generation of copolymer-based Sp, containing air-entraining agent, was used. The admixture was measured as percentage by mass of powder. Since it was in an aqueous condition, the amount of Sp used was added into the amount of mixing water. In the final experiment, cellulose based viscosity enhancing agent (VEA) was used to treat very high fluidity mix before application of vibration. The VEA agent was cellulose based, in powdered form. The product was a new one as compared to the conventional aqueous type. Table 1 gives the chemical properties of the admixture.

Table 1
Basic properties of chemical admixtures used

| Type of admixture | Basis | Recommended dosage |
|---|---|---|
| Air-entrained superplasticizer | Polycarboxylic | 0.5–5.0% (%×$C$) |
| Viscosity enhancing agent | Cellulose ethyl | 300–600 g/m$^3$ |

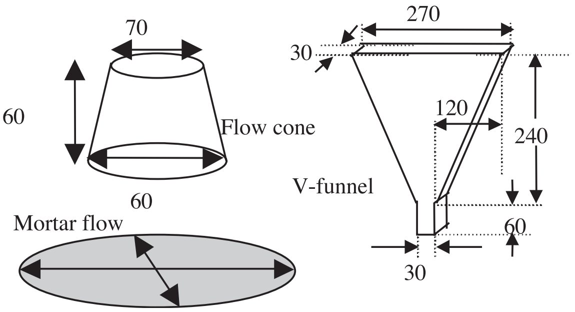


Fig. 1. Dimension of cone and V-funnel used in mortar experiments.

Concrete mixes were prepared in 0.05 m$^3$ batches and mixed in an open pan mixer in the laboratory. The mixing sequence consisted of homogenizing the sand and cement for half a minute before adding water and Sp. The mortar was mixed for 2 min before adding the coarse aggregates. Once the coarse aggregates were added, the concrete was mixed for another 2 min. The slump flow and V-time were taken at the end of mixing.

The mix proportion of concrete adopted the Japanese guide defined for making SCC [5]. This means that the volume of coarse aggregate in concrete is limited to 30%, the maximum size of coarse aggregate is 20 mm and the sand over mortar ratio by volume lies between 0.40 and 0.46. To ensure substantial self-compacting ability, the $W/C$ ratio was kept in the range of 0.27–0.33. High flowability was achieved through different dosages of Sp.

For the measurement of flowability and V-time, two different sets of equipment were used for mortar and concrete. Figs. 1 and 2 show the dimensions of the measuring equipments for mortar and concrete, respectively. In the case of vibrator, both a poker and form vibrator were used in the different stages. The poker vibrator has diameter of 27 mm and frequency of 12,000 VPM. The use of form vibrator allowed the changing of frequency and amplitude of vibration as per requirements. The range of frequency and

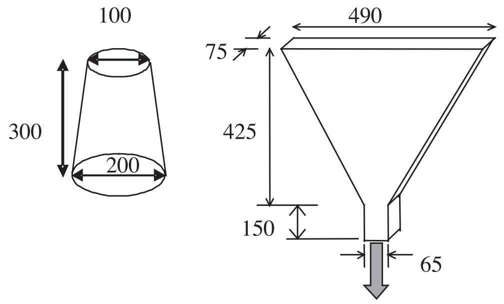


Fig. 2. Dimension of cone and V-funnel used in concrete experiments.

amplitude tested in this study were 160–180 Hz and 0.03–0.10 mm, respectively.

## 4. Experimental results

The following section will discuss the experimental works and results according to the different stages.

### *4.1. Stage A—preliminary feasibility study with mortars*

This stage involved the vibration of high fluidity mortar. As a control, one set of normal mortar was also vibrated. The mix proportions for the mortars are given in Table 2 and its fresh properties in Table 3. Mortar with prefix N represents a normal mix while that with prefix F represents flowable mix. The following number shows the ratio of sand over mortar ($s/m$) calculated from the mix proportion. Slump flow and V-time were taken at the end of mixing. The slump spread for the flowable mortar was due to its self-weight whereas the slump flow for the normal mortar was taken according to JIS R 5201 [6]. In taking the slump flow for normal mortar, a standard flow table was dropped 15 times at a rate of 1 drop/s. This caused the mortar paste to slowly spread out into a circle.

Fig. 3 summarized the experimental procedure. In this experiment, the mixed mortar was poured into six cylindrical moulds 300×150 mm in diameter. Three cylinders were vibrated using a poker vibrator. The mortars were left to settle for 1 h. Then the mortar in each cylinder was scooped out into three division; top, middle and bottom portion. After taking the weight of the top and bottom mortar, it was sieved using 0.09 and 1.2 mm sieves. Particle size less than 0.09 mm is assumed as powdered material [7]. Using running water, the entire powder constituent was washed off. The sand retained in the sieves was kept in 110 °C chamber for 24 h before the weight was taken again. The moisture content of sand in each experiment was measured and multiplied to the oven-dry weight.

The $s/m$ ratio for the top and bottom were compared with the $s/m$ ratio calculated. The equation for $s/m$ calculated is given as Eq. (1).

$$s/m_{\mathrm{calculated}} = \frac{S}{W+C+S} \tag{1}$$

An average value of $s/m$ was taken from all three samples in each group. Fig. 4a and b shows the graph of segregation $s/m$ for mortar in all three cases. The mortar without vibration did not show any change in the ratio of $s/m$ for top and bottom portion. This should be expected because no changes would occur in the mix without any vibration. The ratio of $s/m$ obtained from the experiment was equal to that calculated from the mix proportion. The mixing was homogeneous and sand particles were evenly distributed in the mix.

Table 2
Mortar mix for Stage 2

| Label | $W/C$ | $W$ | $C$ | $S$ | Sp (%×$C$) | AE agent (%×$C$) |
|---|---|---|---|---|---|---|
| N-63 | 0.55 | 0.55 | 1.0 | 2.65 | – | 0.025 |
| F-60 | 0.32 | 0.32 | | 2.00 | 3.0 | |
| F-51 | 0.32 | 0.32 | | 1.36 | 1.3 | |

Table 3
Fresh properties of mortar

| Label | Slump flow (mm) | V-time (s) |
|---|---|---|
| N-63 | 216[a] | 7.32 |
| F-60 | 220[b] | 10.82 |
| F-51 | 222[b] | 5.84 |

[a] Mortar flow induced by tapping.
[b] Mortar flow due to self-weight.

In the case of mortars experiencing vibration, a segregation pattern was obvious. Under the experimental condition, the vibration was categorically rigorous. As such, significant segregation would be expected. However, flowable mortars showed less amount of segregation than normal mortar. The normal mortar N-63 exhibited the highest difference in $s/m$ ratio for top and bottom portions. This can be inferred that it segregated most. On the other hand, F-60 showed the least difference between the two ratios. Comparing the fresh properties in Table 3, F-51 is less viscous than F-60. Its V-time is 5.84 s while the latter has V-time of 10.82 s. Since both mixes were flowable, F-51 showed more segregation than F-60. This could be attributed to the difference in viscosity.

Through this experiment, it was established that vibration of high fluidity mortar has a lower tendency to segregation than normal mortar. The fact that high fluidity mortar is flowable and viscous could be the contributing factor. The object of vibration is to cause particle rearrangement. High fluidity mortar has the advantage to absorb this rearrangement of particles much better than normal mortar by virtue of its flowability and plasticity conditions. As such, the idea of applying vibration on such concrete proved to be a feasible one.

### *4.2. Stage B—significance of flowability and viscosity of concrete mixtures*

High fluidity mix has both flowability and viscosity. Both parameters are not directly related. Depending on the mix constituent, particularly $W/C$ and powder content, the viscosity of mix could differ from one another. At the same time, its flowability is a direct result of adding different dosages of Sp. Normally, if the dosage of Sp is high, the flowability increases. In this respect, it became necessary to understand the significance of both parameters in determining segregation of coarse aggregates upon vibration. This is the main objective of this stage.

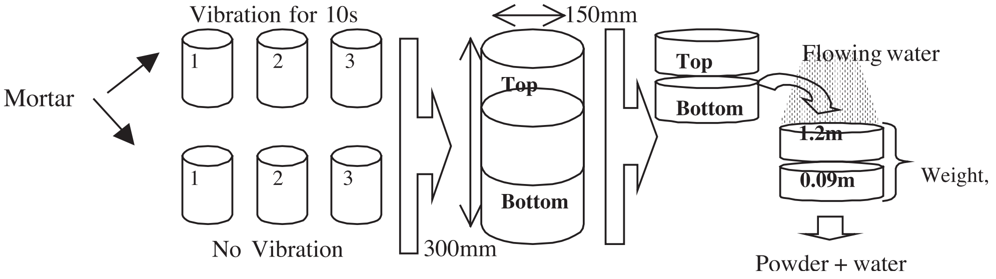
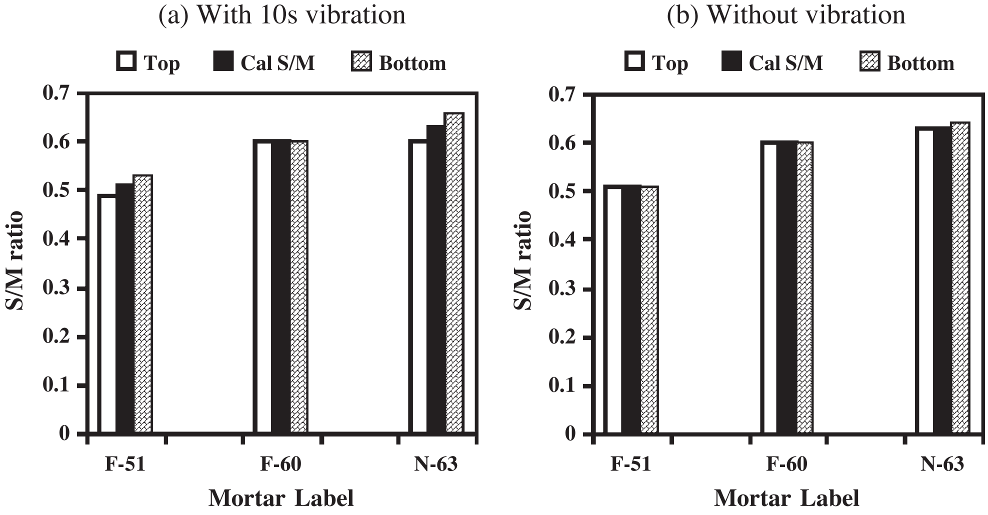


Fig. 3. Schematic diagram of experimental procedures for Stage A.

In this stage, the vibration of high fluidity concrete of different V-time was compared. All the concrete mixes were vibrated for 20 s using the poker vibrator. SCC targeted V-time of 10 s was taken as a reference value. The concrete mixes can be divided into two categories.

In the first category, the significance of flowability was investigated. Vibration was applied to mixes having V-time within the range of 10±2 s but their slump flow lied in the range 480–750 mm. By maintaining the same viscosity, the relationship between flowability and segregation tendency can be investigated. In the second category, the significance of viscosity was investigated. High fluidity mixes having slump flow in a range of 580±50 mm but having broad range of V-time of 10–60 s were vibrated. The relationship between the different V-time and segregation tendency can then be investigated. The mix proportions are shown in Table 4.

The experimental steps are schematically shown in Fig. 5. The mix was prepared, filled in a wooden form 250×250×400 mm and then vibrated for 20 s. The form was made of plywood of smooth interiors. All sides were pasted with silicon bond and bolted together to prevent leakage. One side of the form was loosely tightened so that it could be taken off easily. After vibration, the concrete was left to set for 1 h or so depending on the mix. A low viscosity mix was left for longer time. The form was then covered and tightened by means of rods and bolts. The form was slowly made to lay 90° from original position. The loosely bonded sidewall was carefully pried open. The fresh concrete mixture in the form was divided into five equal parts by using metal slides. Metal slides were inserted through aluminum grooves fixed on both sides to ensure vertical insertion. Four pieces of slides were used to divide the concrete into five portions. The concrete from the different portions was put into individual trays and the respective concrete weights, $C_i$, were taken. Finally, the concrete in the tray was washed out using water. Two sieves, 5 and 13 mm size, one on top of the other were used to collect the coarse aggregates. Using a hose, flowing water washed away the powdered materials leaving coarse aggregates on the sieves. The aggregates retained in the sieves were wiped using a cloth until a saturated surface dry condition was obtained. The weight of the coarse aggregate, $G_i$, was taken. The percentage of coarse aggregates at level $i$ was calculated as a weight ratio of coarse aggregate retained in the sieve to that of the concrete, $(G/C)_i$. The $(G/C)_{\text{ave.}}$ is the total weight of coarse aggregates retained divided by the total weight of concrete in the form. To quantify the degree of


(a) With 10s vibration

(b) Without vibration

Fig. 4. $s/m$ ratio for cases with and without vibration for mortars.

Table 4
Mix proportioning for Stage B

| Label | Water (kg/m$^3$) | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Gravel (kg/m$^3$) | Sp (%×$C$) | $W/C$ | $s/m$ | $V_w/V_c$ |
|---|---|---|---|---|---|---|---|---|
| *Part 1* | | | | | | | | |
| HF1 | 175 | 600 | 750 | 850 | 1.5 | 0.29 | 0.44 | 0.92 |
| HF2 | 175 | 600 | 750 | 850 | 2.5 | 0.29 | 0.44 | 0.92 |
| HF3 | 165 | 570 | 750 | 850 | 2.0 | 0.29 | 0.45 | 0.92 |
| HF4 | 175 | 600 | 750 | 850 | 2.8 | 0.29 | 0.44 | 0.92 |
| *Part 2* | | | | | | | | |
| HF5 | 165 | 611 | 750 | 850 | 2.2 | 0.27 | 0.45 | 0.85 |
| HF6 | 175 | 630 | 750 | 850 | 2.0 | 0.28 | 0.44 | 0.88 |
| HF7 | 175 | 641 | 650 | 750 | 2.0 | 0.27 | 0.40 | 0.86 |
| HF8 | 175 | 600 | 650 | 750 | 2.0 | 0.29 | 0.41 | 0.92 |
| HF9 | 165 | 570 | 750 | 850 | 2.0 | 0.29 | 0.45 | 0.91 |

segregation, a segregation coefficient was defined as Eq. (2).

$$SC = \sqrt{\frac{s\sum_{i=1}^{i=5}(1-x_i)^2}{H}} \tag{2}$$

$$x_i = \frac{(G_i/C_i)}{(G/C)_{\text{ave.}}} \tag{3}$$

$$(G_i/C_i) = \frac{\text{weight of coarse agg. in each tray}}{\text{weight of concrete in each tray}}$$

$$(G/C)_{\text{ave.}} = \frac{\text{total weight of coarse agg.}}{\text{total weight of concrete}}$$

Height of form, $H = 400$ mm

Distance between slides, $s = 80$ mm

In this experimental study, the value of SC ranged between 0.05 and 0.35. A low value of SC indicates minimal segregation while a higher value indicates significant segregation.

Fig. 6 shows the graph of SC values against slump flow. A horizontal line describes the data well with an equation of SC=0.26. The plot of data shows that changes in flowability of concrete does not affect the segregation of high fluidity concrete when vibration is applied. In cases of high flowability mix with same viscosity, the tendency of segregation seemed to be independent of the magnitude of flowability. The magnitude of flowability is directly related to the dosages of Sp added in the mix.

From previous experiments on the development of slump flow with respect to Sp dosage, a saturation limit exists for the increase of slump flow and Sp. Initially, an increase in Sp dosage caused an increase in slump flow. At the same time, the viscosity of mix is reduced as manifested by a shorter V-time. However, when an optimum dosage of Sp is reached, the slump flow continued to show further increase but the V-time recorded a steady value. Hence, it was defined that an optimum flowability is reached when the V-time showed a constant value despite an increase in Sp dosage [8]. In the present case, all mixes had reached the optimum flowability limit. The range of slump flow was high yet the V-time was the same in all cases. As such, the viscous conditions of all mixes were similar to one another. It was concluded that any vibration of high fluidity concrete needs to consider whether the optimum flowability has been reached or not.

Fig. 7 shows the vibration results of high fluidity concrete of varying V-time. A logarithmic relationship describes the data accurately with a coefficient correla-

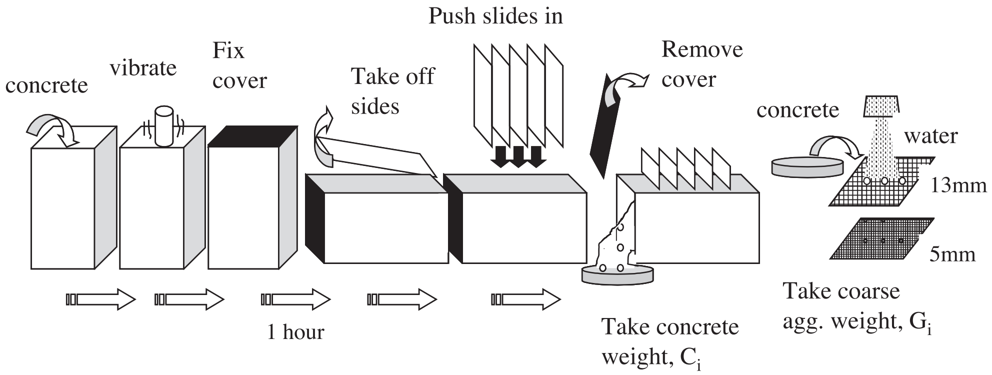


Fig. 5. Schematic diagram of experimental procedure for Stage B.

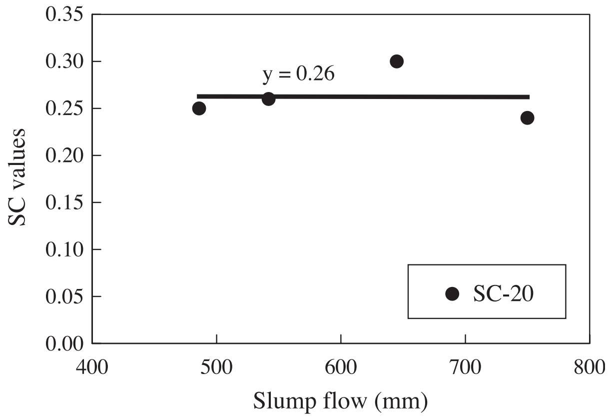


Fig. 6. Checking the significance of slump flow.

tions square ($R^2$) value of 0.95. The equation is given below:

$$SC = -0.10\ln(V - time) + 0.48 \quad (4)$$

From Fig. 7, at V-time=10 s the segregation of coarse aggregates was obvious because the SC value was 0.26. If SC<0.10, there is little segregation of coarse aggregates observed. This was defined from earlier studies on the relationship between SC and the segregation profiles [8]. As the V-time was increased, say V-time=43 s, the SC values decreased to less than 0.10. This means there is no segregation of coarse aggregates. There seemed to be a direct relationship between V-time and segregation effects. In all cases, the effect of slump flow was negligible because slump flow was kept relatively high. Any influence on SC would be directly due to the difference in viscosity as manifested by the V-time.

Basically viscosity is the resistance a material has to change in form. This property can be thought of as an internal friction. When fresh concrete flows, the particles slide over one another. However, there is some friction between the molecules being past each other. The more the particles cling to one another, resisting flow, and the higher the friction between flow. This amount of clinginess is called viscosity.

Concrete can be assumed to consist of coarse aggregates in a mortar suspension. The interactions between finer particles, like cement and sand, constitute to the viscous condition of mortar. The relative distance between the cement and fine aggregate particles are closer to one another in high viscosity as compared to low viscosity mix. This can be assumed from the high volumetric ratio of sand over mortar (*s*/*m*) in the case of high viscosity mix. With respect to interparticles lubrication in the presence of water, a low *W*/*C* as in high viscous mix means that there is less lubrication. Since a low viscous mix have high *W*/*C*, interparticle lubrication is better. Both the above-mentioned variables, *s*/*m* and *W*/*C*, are important parameters in determining the viscosity of concrete.

As a summary, the flowability of mix does not affect the segregation tendency provided an optimum flowability is reached. For mixes with slump flow above the optimum limit, segregation tendency depends on the viscosity of mix. A concrete with V-time 10 s or less will segregate easily when vibrated. At high V-time above 40 s, segregation of coarse was negligible when the mix was vibrated. This result, however, is limited to the use of high amplitude vibration in the case of a poker vibrator.

### 4.3. Stage C—relationship between workability and segregation tendency

In high fluidity concrete, it is necessary to ensure that segregation does not occur during flow. Resistance to segregation depends on the optimum viscosity of concrete to hold aggregates in homogeneity. Hence, the ability to flow must be complimented by the ability to hold aggregates in homogeneity. However, general conditions are that low flowability mix has high V-time. In the case of SCC mix, the balance between high flowability and optimum viscosity is considered as a special case. Prudent mix proportioning is necessary to achieve such conditions. In the following stage, the correlation of mix workability, particularly the slump flow and V-time, was tested against segregation of coarse aggregates.

For this stage, seven mixes of high fluidity concrete were made for the vibration test. Table 5 gives the mix proportions for all mixes. These mixes were contrived so as the change in V-time correspond to that of slump flow. This means that either the concrete has small slump flow and high V-time or large slump flow and low V-time.

The experimental steps are shown in Fig. 8. The procedure was similar to previous experiment except in the use of form vibrator. Instead of using a poker vibrator, a form vibrator was used. Generally, the vibratory force induced in the mix by a form vibrator is smaller. The time of vibration was also reduced to 10 s due to the low amplitude of vibration. Therefore, it was decided that the

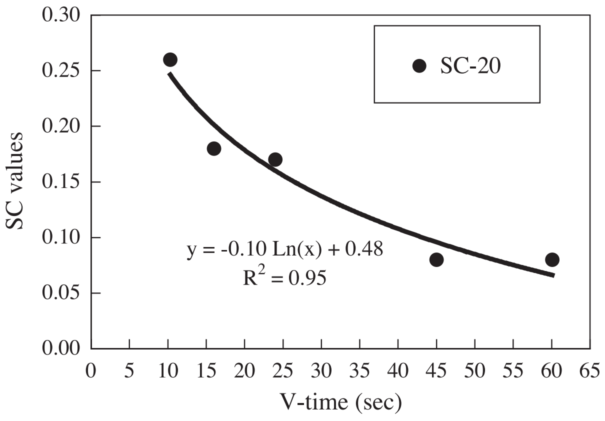


Fig. 7. Checking the significance of V-time.

Table 5
Mix proportion used in Stage C

| Label | $W$ (kg/m$^3$) | $C$ (kg/m$^3$) | $S$ (kg/m$^3$) | $G$ (kg/m$^3$) | Sp (%×$C$) | $W/C$ ratio | $w/p$ ratio | $s/m$ |
|---|---|---|---|---|---|---|---|---|
| HF10 | 165 | 600 | 800 | 850 | 1.7 | 0.27 | 0.9 | 0.46 |
| HF11 | 165 | 600 | 800 | 850 | 2.3 | 0.27 | 0.9 | 0.46 |
| HF12 | 175 | 594 | 785 | 841 | 1.5 | 0.29 | 0.9 | 0.45 |
| HF13 | 175 | 594 | 785 | 841 | 1.6 | 0.29 | 0.9 | 0.45 |
| HF14 | 175 | 600 | 800 | 850 | 1.8 | 0.29 | 0.9 | 0.45 |
| HF15 | 175 | 600 | 800 | 850 | 1.9 | 0.29 | 0.9 | 0.45 |
| HF16 | 185 | 588 | 772 | 833 | 3.0 | 0.31 | 1.0 | 0.44 |

range of V-time for mixes tested in Stage C was limited to 30 s or less.

The gravitational acceleration and frequency of vibration was kept at 160 Hz and 6 G (average displacement=0.05 mm), respectively. This magnitude of vibration should be vigorous enough to induce segregation. In this stage, the main objective was to investigate the ability of the mortar to hold the coarse aggregate in respective position. Thus, the segregation tendency of high fluidity mixtures was established with respect to its workability (defined in terms of slump flow and V-time).

Figs. 9 and 10 show the results of segregation coefficient (SC) with respect to V-time and slump flow, respectively. The best-fit line between the SC and V-time was given by a power rule. The equation of the line is given as:

$$SC = 1.51(V - time)^{-0.97} \tag{5}$$

In the range of high V-time (above 15 s), the segregation was minimal as shown by small SC values but SC started to show drastic change at low V-time especially less than the 10-s mark.

For 15-s V-time, the SC value lied in the range of 0.09. Concrete with V-time greater than 15 s hardly showed any segregation. The viscosity of the mixtures could hold the aggregate in position despite the vigorous vibration. On the other hand, concrete with V-time less than 10 s exhibited high degree of segregation and the SC values showed steep increase.

The experimental results showed that the cohesiveness of coarse aggregate in the mortar lied between two extreme conditions. On one extreme, either the coarse aggregates are kept effectively cohesive to resist any segregation or on the other extreme, they are loosely kept in position such that the aggregates would settle downward easily when vibrated. In this experiment, the former case was found in the region where SC value is less than 0.10. The latter case was quite subjective but it should correspond to the condition where the SC value increases steeply, inferring lack of resistance against segregation. By reference to Fig. 9, this condition corresponded to SC=0.20. In between SC=0.10 and SC=0.20 the coarse aggregates in the mortar medium were suspended by a certain degree of cohesive forces. In other words, the coarse aggregates were neither strongly restrained by frictional forces nor readily settled downwards. In the production of SCC, the condition of mortar and coarse aggregates should lie in this range. As the concrete flows, the mortar should be able to hold the coarse aggregates together with it. This understanding of the way coarse aggregate are homogenized in mortar would be significant when dealing with vibration of concrete mixtures that missed SCC criteria. Provided the amplitude and frequency of vibration were controlled, the vibration force applied should match the resistance ability of the mixture against segregation.

By considering slump flow (Fig. 10), the relationship between slump flow and SC was linear. By using the same arguments in previous section, an SC of 0.10 was found in slump flow less than 470 mm. This would be the region where vibration is easily acceptable. Similarly, at SC=0.20 corresponds to a slump flow of 600 mm, which coincidentally the target slump flow for SCC mixtures. Thus, any slump flow above 600 mm would not be advisable to apply vibration. Beyond this range of slump

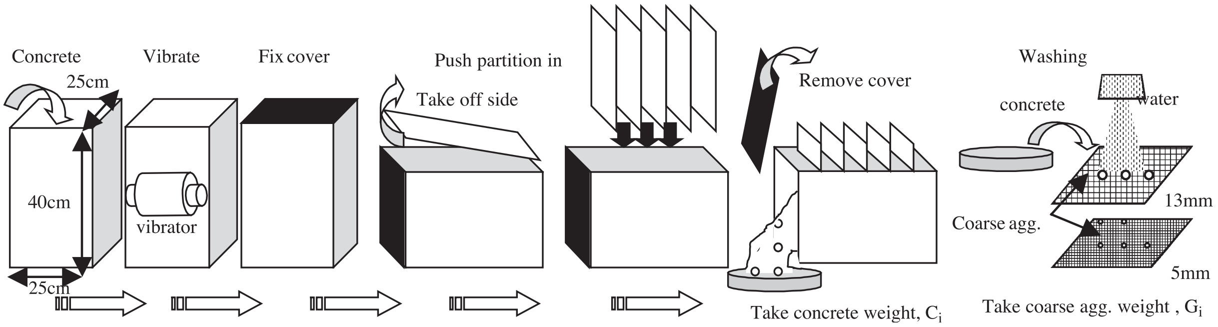


Fig. 8. Experimental procedure for vibration experiment for Stages C and D.

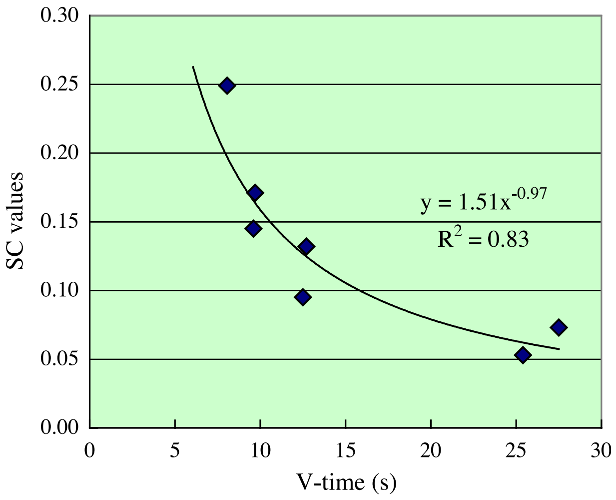


Fig. 9. Variation of SC with V-time.

flow, the V-time should be considered as the more important criteria when considering applying vibration. Between slump flow 500 and 600 mm, a more controlled amount of vibration would be necessary if segregation effect were to be minimized.

### *4.4. Stage D—vibration of mixes that missed SCC criteria*

At this point, an attempt was made to study high fluidity mixes that missed SCC criteria. The main objective was to study the effect of frequency and amplitude of vibration on the segregation pattern. There are two parameters involved in the experiment. One is the vibrator parameter (frequency and amplitude) and the other is the concrete parameter (slump flow and V-time). Since this study attempted to determine the effect of vibration parameter on high fluidity concrete, it was deemed necessary to keep the concrete parameter constant. In all cases, the workability of concrete mix, in terms of slump flow and V-time, followed the pattern shown in Fig. 11. Vibration of varying amplitude and frequency was applied on such mixes.

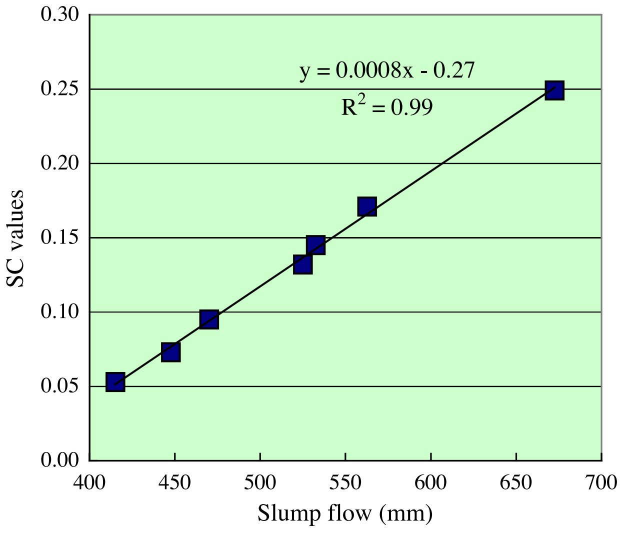


Fig. 10. Variation of SC with slump flow.

Table 6 shows the mix proportion used. The mix consisted of three portions:

(1) Low flowability, less than 500 mm, having a high V-time above 12 s. With respect to SCC target flowability and viscosity, this mix has lower flowability and higher viscosity.
(2) Moderate slump flow between 500 and 600 mm, having V-time between 8 and 13 s. The mix achieved SCC V-time target but insufficient flowability.
(3) High slump flow above 600 mm, having V-time less than 8 s. Lastly, this mixes have sufficient slump flow but very low V-time.

The whole experimental program was subdivided into three parts. In Part 1, high fluidity mixes with slump flow in the range of 400 and 650 mm were vibrated by using a vibrator with frequency 160, 170 and 180 Hz. The amplitude of vibration was kept at 0.05 mm, while Part 2 involved vibration experiments using different amplitude of vibration. Keeping the frequency at 160 Hz throughout, the amplitude was changed to 0.03 and 0.10 mm. Lastly, Part 3 aims to study the possibility of adding VEA as a form of treatment to high fluidity concrete mixtures above 700 mm slump flow and less than 10 s V-time. The VEA will enhance the viscosity of the mix and make it possible to apply vibration. The dosage of VEA was varied in order to observe the resulting change in segregation tendency.

Part 1 involves the vibration of high fluidity concrete using a vibrator with amplitude of 0.05 mm and frequency of 160, 170 and 180 Hz. All three frequencies are essentially the same. The difference of 30 Hz centered at 170 Hz would usually be considered as a narrow band since the entire group of frequencies fall within 1/6 of an octave. At these frequencies, there will be little difference

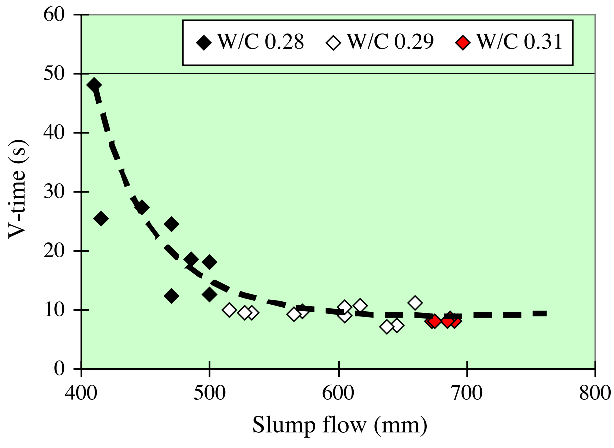


Fig. 11. Relationship between slump flow and V-time for vibrated mix.

Table 6
Mix proportion used in Stage D

| Label | $W$ (kg/m$^3$) | $C$ (kg/m$^3$) | $S$ (kg/m$^3$) | $G$ (kg/m$^3$) | Sp (%×$C$) | $W/C$ | $s/m$ |
|---|---|---|---|---|---|---|---|
| Mix 1 | 172 | 613 | 807 | 868 | 1.7–2.5 | 0.28 | 0.46 |
| Mix 2 | 176 | 606 | 809 | 859 | 1.5–2.5 | 0.29 | 0.46 |
| Mix 3 | 185 | 600 | 800 | 850 | 2.4–3.0 | 0.31 | 0.46 |

in the vibration due to varying values of tightening torque used. The use of three frequencies was to substantiate the pattern of SC data obtained from all three cases of frequencies.

Fig. 12 shows the results of segregation coefficient, SC with respect to slump flow. The SC values for all data with frequency 160, 170 and 180 Hz follows the same pattern to one another. For concrete with slump flow less than 500 mm, there is little segregation in coarse aggregate. The SC value lied below 0.10, which is the threshold limit for segregation to be significant. The physical nature of these mixes was very sticky and not so flowable. At a slump flow of 410 mm, the V-time was 48.1 s, but when the mix increased in slump flow to 500 mm, the V-time became 12.7 s. There is an increase in SC values as the slump flow increases.

As the flowability increases to the range 500–600 mm and the V-time achieved SCC target of 10 s, the segregation pattern as shown by SC value tends to be the same throughout. At a slump flow of 500 mm, the SC value was about 0.12, while at slump flow of 600 mm SC value was 0.16. The rate of change, however, is not obvious and the data points are almost level. The V-time was the same, that is, close to 10 s but only the slump flow was different. This indicated that the viscosity of the mixes remained the same and the difference lies in the flowability. Physically, the mix exhibited some degree of cohesiveness and compactness, despite its high flowability. With respect to the segregation pattern, this was a similar condition to that experienced in Stage B. It is possible that if vibration could be controlled, the degree of segregation would also be reduced. If the force of vibration were kept to a certain limit, there should not be any segregation of coarse aggregates expected. Since a vibrator has two independent variables, that are frequency and amplitude, either variable could be manipulated. To what extent the controlled vibration would be viable will be the topic of another research.

At slump flow above 600 mm, there was an abrupt increase in SC value. The concrete mix had V-time gradually ranging from 9 to 6 s. Physically, at such low V-time the condition of mix is not very cohesive and also very much like fluid. The SC value increased proportionately with slump flow but at a much faster rate than the previous cases. The coarse aggregates segregate heavily to the bottom of the form after vibration. Such a fluid-like mix should never be vibrated because the mortar viscosity is too weak to hold the aggregates in position.

In Part 2, the amplitude of vibration was changed to 0.03 and 0.10 mm. The frequency of vibration was maintained at 160 Hz. The segregation results are shown in Fig. 13. At amplitude of 0.03 mm, the SC value is smallest compared to the other amplitudes. From slump flow of 500 to 600 mm, there is no apparent segregation present. Only when slump flows reached 600 mm and above, there was a drastic increase in segregation pattern. Due to the small magnitude of vibration, there was no segregation occurring despite a V-time of 10 s. This implied that low level of amplitude is acceptable for such mixes. The viscosity of the mix has enough resistance not to allow segregation of coarse aggregates. Only at V-time less than 10 s was there an increase in SC value.

In the case of 0.10 mm amplitude, the overall SC value is the highest comparatively. Noticeably at a slump flow of 550 mm, the line starts to increase rapidly. There was an

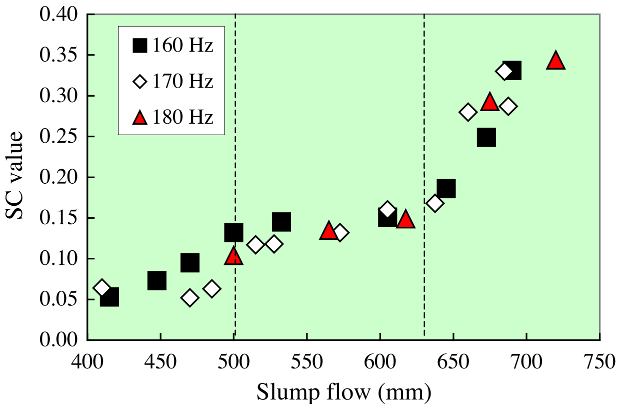


Fig. 12. Segregation coefficient, SC, with respect to slump flow.

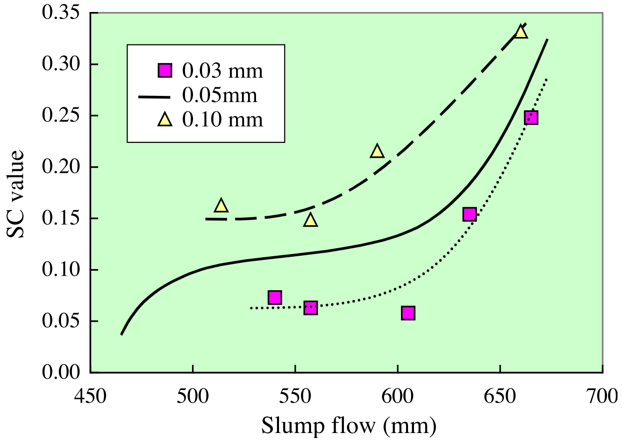


Fig. 13. Segregation results by different amplitude of vibration.

obvious correlation between bigger amplitude and segregation tendency. Vibrators impart a vibratory force into the concrete through a combination of frequency and amplitude. Amplitude moves the coarse aggregates and determines the radius of action. The higher the amplitude the bigger the vibratory force exerted on the concrete mass. That explains the reason for the larger segregation in bigger amplitude.

The slump flow at which there was an abrupt increase in SC was also different in all three cases. A threshold value for the slump flow existed in all cases. This threshold slump flow represents the condition where the viscosity of mix cannot keep the aggregate in suspension when vibration is applied. At these points, the mix could never accept any form of vibration. The following experiment in Part 3 attempts to investigate the possibility of enhancing such low viscosity to allow the use of vibrator.

Part 3 of the study investigated the treatment of very high fluidity mix with VEA and then vibrate the mix. At such slump flow above 700 mm and V-time 6 s, the mix is fluid-like and would segregate easily if vibration were applied. After mixing all the constituents, some portion was taken out for measuring slump flow and V-time. Then, VEA was then added and the mix was stirred for another 2 min. By adding the VEA, the mix became more viscous than before. In this experiment, three different dosages of VEA were investigated, that is, 50, 100 and 200 g/m$^3$. As a control, one mix without any dosage of VEA was also vibrated.

Fig. 14 shows the result of slump flow and V-time for such mixes. As the dosage of VEA increased from 50 to 200 g/m$^3$, there was a steady increase in V-time. The more VEA was added, the more viscous the mix became. The mix without any VEA had a V-time of 6 s. When 50, 100 and 200 g/m$^3$ VEA was added, the V-time increased to 7, 10 and 14 s, respectively. However, a different pattern was observed with respect to slump flow. The reduction in slump flow was not proportionate. Without any VEA, the slump flow was initially 730 mm. Addition of 50 and 100 g/m$^3$ caused a reduction in slump flow from 730 to 640 mm. However, as the dosage of VEA increases to 200 g/m$^3$, the slump flow reduced significantly to 540 mm. The condition of mix was very sticky and viscous, even though the slump flow was still high. Compared to previous mixes, the washing of coarse aggregates also took much longer time due to cement paste sticking to the aggregates.

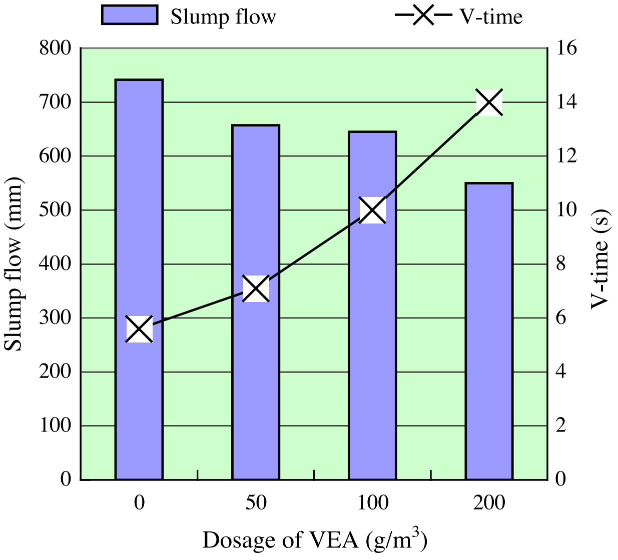


Fig. 14. Effect of adding VEA on slump flow and V-time.

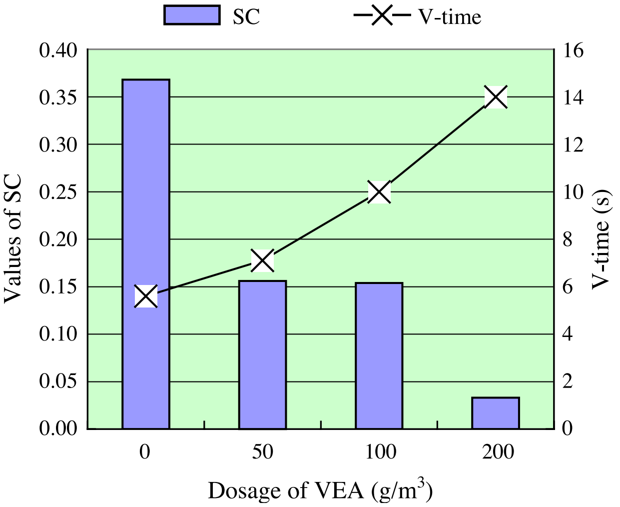


Fig. 15. SC values for vibrated mix after addition of VEA.

The use of VEA in low viscosity mix is a common practice. The purpose is to reduce the variations in flowability. In the production of concrete, the use of Sp at high dosages sometimes resulted in large variations of the flowability. This is due to the cement–Sp incompatibility [9]. Yurugi et al. reported that the use of the VEA tended to make the mortar flowability less sensitive to the addition of Sp. As such, if appropriate dosage is introduced in the mix, it could stabilize the range of slump flow obtained. That also explains why, SCC mixtures, having high slump flows, depended on the use of VEA to stabilize the flowability. There is a distinct difference between the effect of VEA and Sp. The former adheres to water molecules in the mix. Due to their complex forms consisting of long chain polymers, these molecules can intertwine and develop attractive forces through weak bonding and entanglement. The latter is incorporated to decrease the yield value of the mix. It is achieved through the dispersion of the Sp molecules on cement particles.

All the concrete mixes were vibrated with frequency of 160 Hz and amplitude of 0.10 mm. Fig. 15 shows the result of vibration of the above mixes. The mix without any VEA showed significant segregation with an SC value of 0.35. For the case of 50 and 100 g/m$^3$ VEA addition, the SC values reduce to 0.15. The mix with 200 g/m$^3$ VEA, however, showed very little segregation when vibration is applied. Due to the high dosage of VEA, the mix was sticky and hard to handle. The resistance against segregation increased tremendously.

As a summary, depending on the amplitude and frequency of vibration, the ability of the mix to hold aggregate in suspension was dependent on its workability. Also, the addition of VEA to enhance the viscosity of high fluidity concrete with high slump flow above 700 mm allowed the use of vibration on such concrete. Depending on the mix, the optimum dosage of VEA would need to be established beforehand.

## 5. Discussion

Based on the experimental results above, a vibration susceptibility graph is proposed. Fig. 16 shows the region of high fluidity concrete mix in terms of slump flow and V-time that would readily accept vibration or not. The slump flow can be divided into four parts; between 400 and 500, 500 and 600, 600 and 700 and 700 and 800 mm. Generally, any mix less than 500 mm should be highly viscous because it does not flow easily.

Slump flows of 500–600 mm indicate a change in viscosity of mix and transition to develop more flowability. By the time the slump flow reached 600 mm, the viscosity of the mix would be expected to be optimum and it flows easily by virtue of its own weight. At this range of flow, it would be more practical to consider the viscosity of mix before applying any vibration. Finally, a mix with slump flow between 700 and 800 mm would be prone to segregation easily.

From this study, V-time can be generalized to three distinct parts; less than 8 s, 8–12 s and above 13 s. For mixtures less than 8 s, the viscosity was deemed very low. SCC target value aimed for V-time 10 s. For simplicity, it was assumed that V-time 10±2 s be an appropriate range for SCC mix. Physically, a mix with V-time of 10 s showed some degree of cohesiveness. Therefore, the third category assumed that V-time above 13 s would be very cohesive and hard to handle.

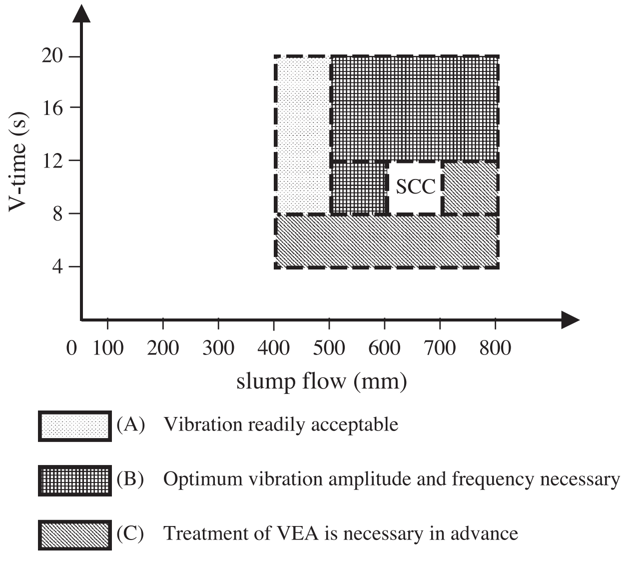


Fig. 16. Vibration susceptibility for high fluidity concrete.

With respect to vibration, three different scenarios, labeled as Regions A, B and C, are possible. Region A consists of concrete with low flowability and high viscosity. Such concrete have high resistance against segregation and can readily accept vibration. Region B consisted of those concretes that have high flowability yet high viscosity. In order to vibrate the concrete, an optimum amplitude and frequency of vibration is necessary. The optimum vibration depends on the range of value for slump flow and V-time. More research is necessary to develop the range of amplitude and frequency for concrete mix in these ranges. Region C basically consists of low viscosity mix. Either the V-time could be as low as 7 s or the flowability is above 700 mm. For such concrete, prior to vibration the viscosity needs to be enhanced. The use of VEA is a viable option but the best dosage of VEA need to be established.

With respect to the practical use of Fig. 16, site engineers can check the workability of mix that arrived on site by means of slump and V-funnel test. These two parameters are necessary to define the condition of mix. If the mix was found to fulfill the SCC targeted slump flow and V-time, then it could be placed without vibration. However, if the slump flow or V-time or possible both parameters were insufficient, vibration could be applied on the mix depending whether it fall into region A, B or C on the above graph. As such, it would be easy for engineers to decide on site what level of vibration could be applied on the mix or whether there is a need to treat the viscosity by VEA or not before placing the mix.

## 6. Conclusion

1. The relative viscosity of concrete was manifested in terms of V-time. At low V-time, the tendency to segregate was higher than at high V-time. This simply implies that low viscosity mix segregate easily than higher viscosity ones. It was further concluded that the V-time proved to be an important tool to describe segregation tendency.
2. In experimenting cases of the same viscosity but different flowability, the study concluded that flowability alone did not contribute to the segregation pattern. As far as vibration of mix with the same viscosity is concern, flowability on its own did not have much influence on the segregation tendency. An optimum flowability was defined whereby beyond this optimum value the V-time remained the same.

3. To assess adequate level of vibration, consideration should be given to match the amplitude of vibration and concrete viscosity. High amplitude means greater vibratory forces. The viscosity of the mix should be strong enough to bear these forces while keeping the suspensions of coarse aggregates. Thus, the amplitude of vibration should match the viscosity of mix when applying vibration.
4. Treatment of VEA on high fluidity with low viscosity was treated as a possible solution to allow vibration on such mixtures. Depending on the dosage of VEA, it was possible to increase the viscosity of the mix without significant reduction on the slump flow. Vibration of such mixes after treatment of VEA revealed reduced segregation tendency.
5. Finally, a vibration susceptibility graph is proposed for different workability of concrete. The different workability of mix could be divided into three different regions when vibration is concerned; mix that accept vibration freely, mix that required controlled vibration and mix that needed prior treatment of viscosity enhancing agent before vibration.

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