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Using viscosity-modifying admixture to increase the cohesion of low-cement concrete mixture

A Antoni[1*], A Andreas[1], E Christian[1] and D Hardjito[1]

[1]Civil Engineering Department, Petra Christian University, Surabaya, Indonesia

[*]E-mail: antoni@petra.ac.id

Abstract. Low-cement concrete (LCC) is made by considering the particle packing of the constituent material. The minimal content of cement paste is achieved by optimizing the coarse and fine aggregate particle size gradation to reduce the void volume (Vv) between the aggregate particles. Theoretically, the minimum cement paste can be calculated as the cementitious paste volume (Vp) filling the entire void volume (Vp/Vv = 100%). Practically, low fine or powder material content would reduce concrete mixture cohesion and cause bleeding and segregation. Viscosity-modifying admixture (VMA) can be added as an alternative to adding more cement powder or supplementary cementitious materials to improve the cohesion and stability of the LCC matrix. This study investigated the role of VMA addition in increasing stability in low water to cement ratio (w/c) mortar with an excessive dosage of superplasticizer and in high w/c mortar designed with low cement content. The results showed that adding VMA reduced bleeding and increased cohesion in the fresh mixture, and also increased the compressive strength of the hardened mortar. Although the addition of VMA cannot increase the workability of LCC, it had a beneficial effect when added to an LCC mixture as the 28-day compressive strength of the concrete with w/c of 0.5 was increased from 18.68 MPa to 22.93 MPa by adding 0.4% VMA by mass of cement.

1. Introduction

In addition to the high cost, using cement in concrete can increase the risk of cracking caused by shrinkage [1]. Therefore, improvement is needed to make a concrete mix wherein the cement content can be minimized. One method in the mix design is the particle packing method. The particle packing method finds the lowest void volume (Vv) from the combination of coarse and fine aggregate and fills it with cement paste until the volume of paste (Vp) is the same or higher than that of the void volume ($Vp/Vv \geq 100\%$). In other words, the aggregate is used as much as possible to get the highest density and the use of cement paste can be reduced. In our previous study [2], low cement concrete was produced with 309 kg/m^3 cement content using particle packing method. The amount of cement demand has met the standard of low cement concrete, which is less than 310 kg/m^3 [3]. However, the resulting compressive strength frequently was relatively low (~20 MPa). This was due to the unworkable mixture and signs of bleeding and segregation.

According to EFNARC and EFCA [4], one of the uses of viscosity-modifying admixture (VMA) is to change the rheological properties of fresh concrete to be more cohesive and homogeneous, thus avoiding bleeding and segregation. This is an essential aspect because the properties of fresh concrete dramatically affect the quality of hardened concrete. VMA is one type of admixture that is used to maintain rheological stability of the fresh concrete [5]. VMA can consist of a variety of different chemicals. Some VMA is based on fine inorganic materials, such as colloidal silica, while others consist of more complex synthetic polymers [4, 6–9]. The mechanisms of VMA works by increasing viscosity and thickening the mixture to prevent segregation [10]. This increase in viscosity comes from the linking of the VMA polymer chain to free water in the mixture, which in turn inhibits free water flow and increases viscosity [7, 11, 12].

VMA can help produce concrete with better resistance to the variations in aggregate's moisture content, aggregate gradations, and fluctuation of fine sand content. VMA improves the consistency and fluidity retention, and also the cohesion of the matrix. Thus, the use of VMA can be an alternative solution to handle harsh concrete mixtures or improve mixture stability. The viscosity of the fresh concrete mixture reduces typically with the use of superplasticizer [13, 14]. However, overdosage of superplasticizer cause bleeding and segregation; therefore, a combination of VMA and superplasticizer can be used to control the fresh concrete rheology to produce a cohesive and workable concrete [15].

This research aims to investigate the effect of adding VMA on mortar and concrete with low cement content without the addition of supplementary cementitious material. Variation of VMA dosage was applied on the low cement mortar with low w/c with excessive superplasticizer dosage and high w/c. The study was also conducted on concrete with normal w/c.

2. Experimental method

2.1. Materials and testing

The materials used are river sand from Lumajang quarry, East Java, Indonesia, Portland Pozzolan cement (PPC) from Gresik Cement, polycarboxylate-based superplasticizer (SP), SIKA Viscocrete 1003, and viscosity-modifying admixture (VMA), SIKA Stabilizer 4R. Table 1 shows the properties of the admixture used. The mortar mixture used two particle sizes: fine sand (< 1.18 mm) and coarse sand (1.18–5 mm). The coarse aggregate was crushed limestone with a size of 10–20 mm for making concrete.

Several tests were carried out on fresh and hardened mortar and concrete in this study. The flow table test was performed on fresh mortars to measure its flowability and to monitor any bleeding and segregation. A slump test was done on the fresh concrete and the compressive strength test was carried out on mortar cubes at 7 and 28 days with three replications, and on cylinder specimens at 28 days with two replications.

Table 1. Admixtures used in the mixtures.

	SIKA Viscocrete - 1003	SIKA Stabilizer 4R
Function	superplasticizer	Viscosity-modifying admixture
type	Aqueous solution of modified polycarboxylate copolymer	-
Appearance	Brownish	Blue liquid
Specific gravity	1.065 ±0.01 kg/L	Approx. 1.02 kg/L
Dosage	0.6–1.6 % by weight of binder (for flowing and SCC)	65–455 mL/100 kg of cementitious materials

2.2. Mix design and application of admixture

The void volume measurement was done for fine aggregate in the mortar mix design and a combination of coarse and fine aggregate for the concrete mix design. The lowest volume of the void (Vv) was used to calculate the minimum volume of paste (Vp) in the mixture. The mortar mixture was divided into two series, i.e., one with low w/c of 0.35 and excessive dosage of superplasticizer at 1% by mass of cement (A series) and one with a high w/c of 0.70 and excessive water content (B series). Furthermore, the influence of VMA on the concrete mixtures of C series with w/c of 0.5 (representing regular concrete but with low cement content) and the use of superplasticizer to increase its workability were studied. VMA was gradually added while observing the fresh mixture for an increase of cohesion and disappearance of bleeding and segregation.

3. Results and discussion

3.1. Mix design of low-cement mortar

Void volume analysis for the mortar mixture was done using combinations of coarse sand and fine sand. Figure 1 shows that the densest conditions can be achieved at 40% of coarse sand and 60% of fine sand by volume. In this research, the volume of paste is equal to void volume (Vp/Vv = 100%). Changing the water to cement ratio (w/c) affects the amount of cement paste needed. Figure 2 shows the amount of cement content required with different w/c to obtain Vp/Vv = 100%. At w/c 0.35, the lowest cement requirement is 573 kg/m³ while in w/c 0.7 the lowest cement requirement is 376 kg/m³. Thus, the mix design for mortar mixtures for A and B series are reported in table 2. The overdoses of SP used were at 1% mass of cement while the VMA varied from 0 to 0.35 based on the producer's recommendation.

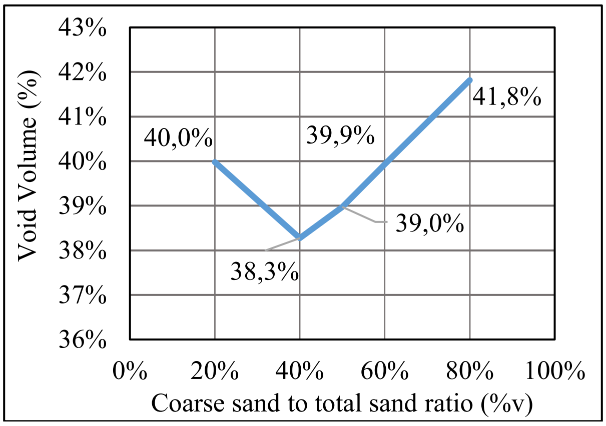


Figure 1. Void volume obtained from combining fine and coarse sand.

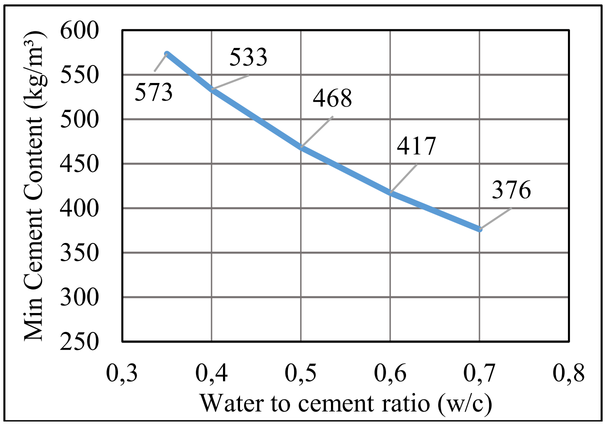


Figure 2. Minimal cement content for mortar mixture with the void volume of 38.3% calculated from the water to cement ratio.

Table 2. Mix design of the mortar series.

Series	Condition	w/c	Cement Mass Ratio	Sand Mass Ratio	SP (%m c)	Code	VMA (%m c)
A	Mortar **Low w/c** with overdosage SP	0.35	1	2.85	1%	A0	0
						A1	0.225
						A2	0.25
						A3	0.275
						A4	0.3
						A5	0.32
						A6	0.335
						A7	0.35
B	Mortar **High w/c** with water bleed	0.7	1	4.35	0	B0	0
						B1	0.2
						B2	0.225
						B3	0.25
						B4	0.275
						B5	0.285
						B6	0.3

3.2. Fresh mortar behavior

A flow table test was done to measure the flowability and plastic viscosity of mortar. Bleeding and segregation could be observed from the appearance of water on the upper surface and the edge of diameter after 25 knocks on the flow table test. Figure 3 shows the result of the A series that have low w/c with excessive SP. The mortar without VMA has a diameter after 25 knocks (D2) of 16.5 cm. Mortars with the increasing addition of VMA doses up to 0.35% has a smaller D2. This result is similar to the one observed by Leemann and Winnefeld [7]. The addition of VMA to the mortar with low w/c and the constant dose of SP reduced the diameter of the flow, showing that the VMA increases the viscosity of the mixture; hence, the resulting mortar has a lower flow diameter.

The B series mortar w/c of 0.70 and 0% SP resulted in a different condition to the A series as shown in Figure 4. There was an increase in the diameter of the D2 with the addition of VMA by up to 0.25%. Flow diameter D2 was increased from 13 cm to 15.8 cm, showing that the mixture had reduced bleeding and segregation, which improved the flowability. A decrease of D2 was showed at the addition of a VMA dosage from 0.275% to 0.30% with D2 of 15 cm at 0.3% VMA dosage.

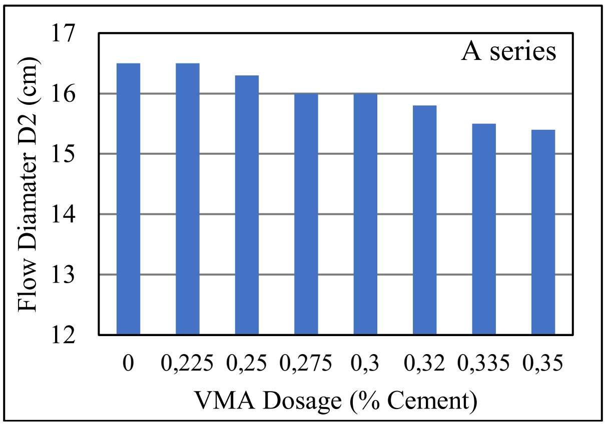


Figure 3. Flow diameter after 25 knocks for A series.

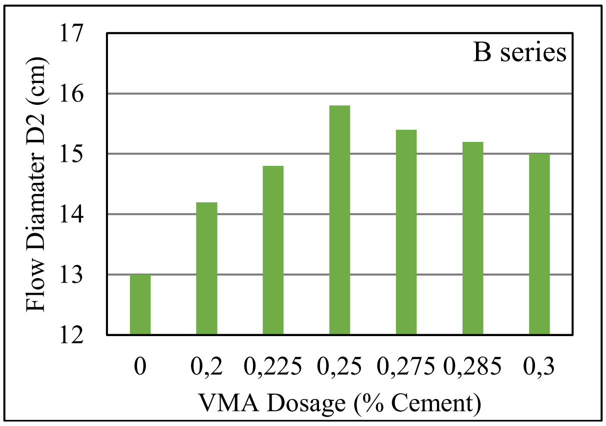


Figure 4. Flow diameter after 25 knocks for B series.

Table 3 records the visual observations of the VMA dosage to the rheological properties of A series mortar with w/c of 0.35 and 1% SP in the increase of VMA. Mortars without VMA experienced bleeding and segregation. Water was separated from the mixture and appeared clearly at the outer edge of the mortar. Furthermore, the spread of the mortar was uneven. Along with increased VMA in the mortar mixture, the bleeding and segregation decreased and the spread of mortar was evenly distributed. The addition of VMA increased the viscosity of the mixture as indicated by the increase of diameter of the mortar after 25 knocks.

Table 4 records the visual observations on the B series mortar with w/c 0.70 and 0% SP with the increase of VMA. In mortar without VMA, the phenomenon of bleeding was more pronounced. Bleed water was seen separating from the mixture and soaking the flow table. Indications of segregation were evident from the uneven distribution of mortar. In mortar with a VMA dosage of 0% to 0.225%, segregation still occurred and the flow diameter continued to increase. In mortars with VMA doses of 0.25%–0.30%, the segregation was decreased as was the flow diameter. The results showed that the addition of VMA could effectively produce a cohesive mixture by removing excessive water from the mixture whether from high w/c or the improper use of superplasticizer dosage.

3.3. Hardened mortar properties

The curing of the sample was done under water for up to one day before testing time. The mortar was tested for compressive strength at 7 and 28 days. The density was measured prior to the compressive strength test and the averages are shown in Figure 5.

Table 3. Visual of flow table test of A series mortar (low w/c with overdosage SP).

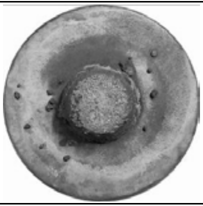
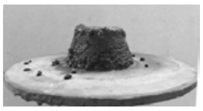
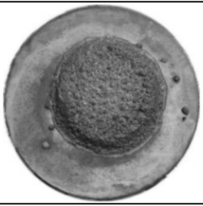
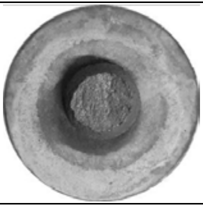
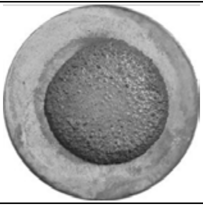
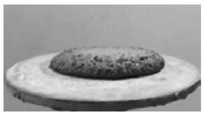
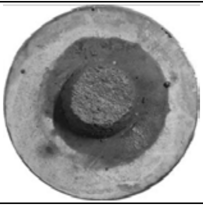
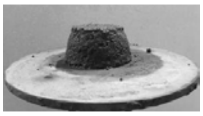
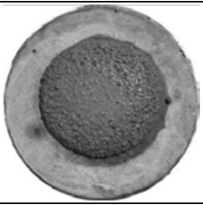
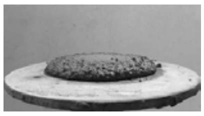
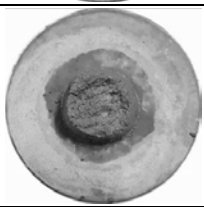
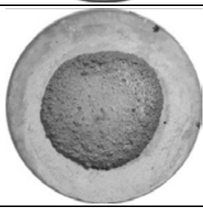
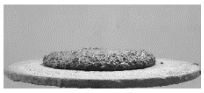
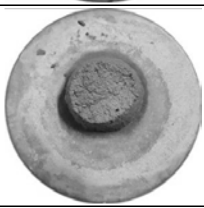
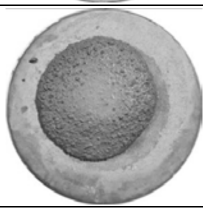
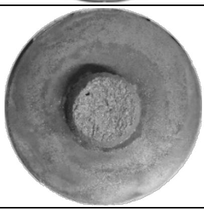
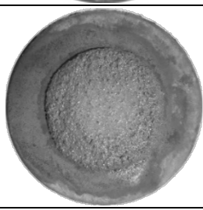
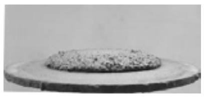
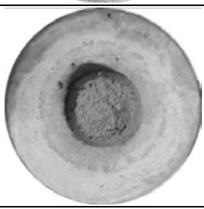
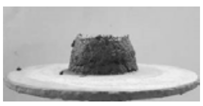
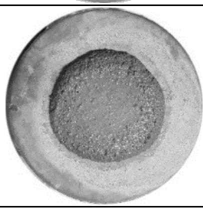
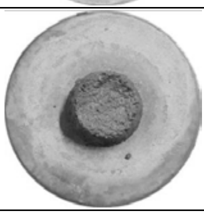
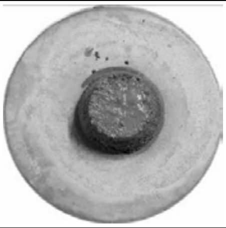
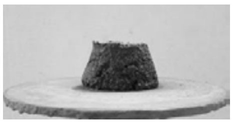
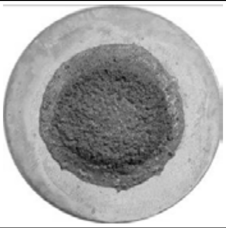
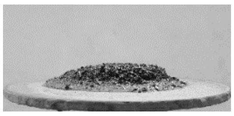
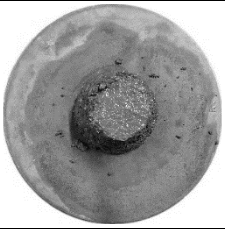
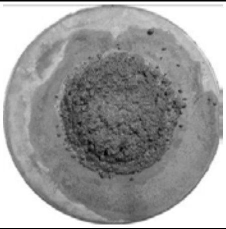
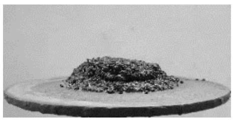
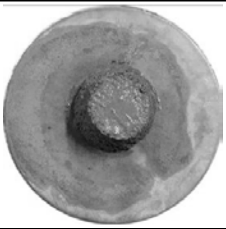
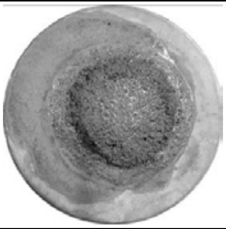
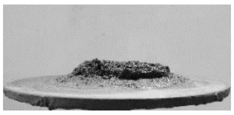
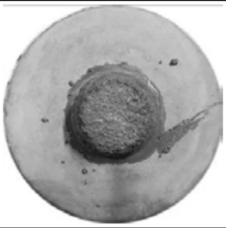
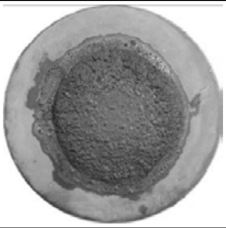
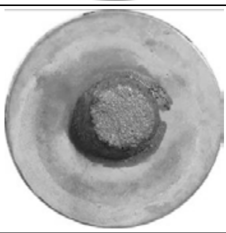
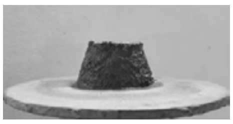
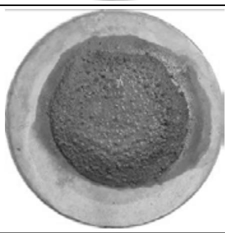
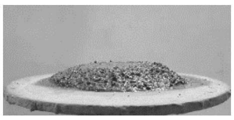
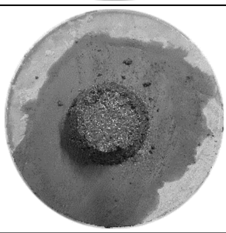
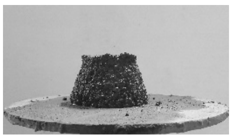
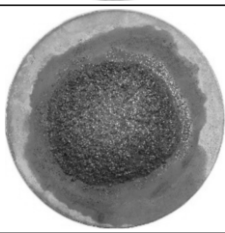
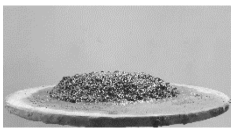
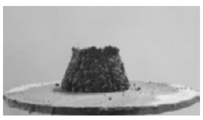
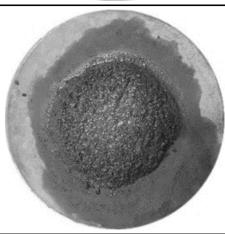
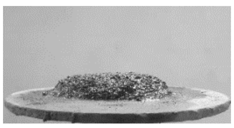
Code (VMA)	D1	D1	D2	D2	Condition
A0 (0)					Bleeding Segregate
A1 (0.225)					Bleeding Segregate
A2 (0.25)					Bleeding Segregate
A3 (0.275)					Bleeding Segregate
A4 (0.3)					Bleeding
A5 (0.32)					Bleeding
A6 (0.335)					Homogeneous
A7 (0.35)					Homogeneous

Table 4. Visual of flow table test of B series mortar (high w/c).

Code (VMA)	D1	D1	D2	D2	Condition
B0 (0)					Bleeding Segregate
B1 (0.2)					Bleeding Segregate
B2 (0.225)					Bleeding Segregate
B3 (0.25)					Bleeding
B4 (0.275)					Bleeding
B4 (0.285					Homogeneous
B6 (0.3)					Homogeneous

The A series mortar with low w/c value showed a higher density than the B series mortar. The addition of VMA was shown to affect the density of the mortar. The higher VMA dosage showed higher mortar density that can be attributed to the improved the rheological properties of the mixture so that the mortar becomes more homogeneous and cohesive.

Figures 6 and 7 show the mortar compressive strength tested at 7 days and 28 days for A and B series, respectively. The addition of VMA had a substantial effect on the mortar's compressive strength. The A series showed some mortar had a slight strength reduction with the addition of the VMA while some specimens also showed a significant increase of the compressive strength. This could be caused by the use of SP that exceeds the reasonable limit and could cause some slowing down of the reaction and prolong the setting time. Thus, it was not recommended to use excessive SP dosage. The results of the B series mortar showed a consistent increase of compressive strength with the addition of VMA doses into the mortar mixture. The compressive strength was increased from 26.73 MPa for mortar without VMA to 33.51 MPa with a VMA dose of 0.30% for 28-day compressive strength. The results show that the interaction of the VMA and superplasticizer need to be carefully assessed, whereas mortar with excessive water content can benefit from the addition of VMA.

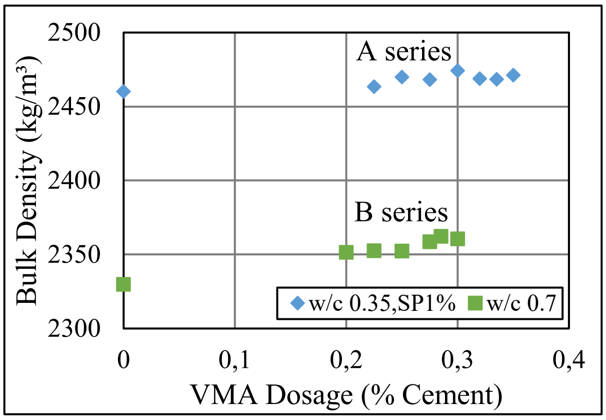


Figure 5. Bulk density of mortar from A and B series.

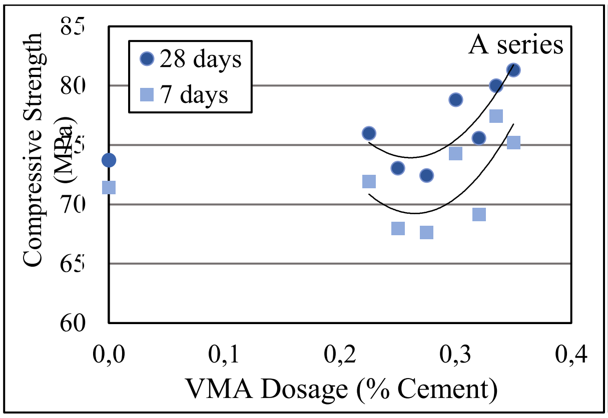


Figure 6. Compressive strength of low water to cement ratio (A series) mortar at 28 days.

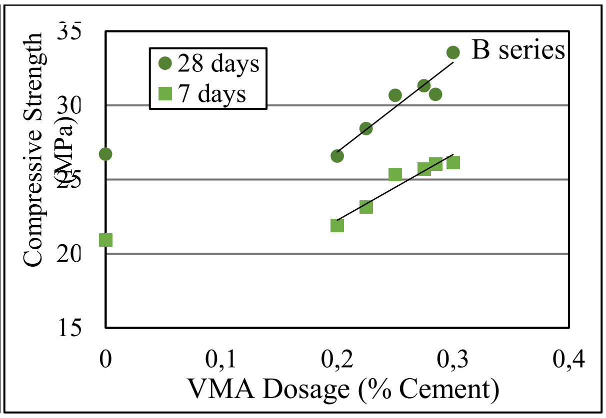


Figure 7. Compressive strength of high water to cement ratio (B series) mortar at 28 days.

3.4. Low-cement concrete with viscosity-modifying agent

The coarse and fine aggregates were combined to obtain the lowest void volume and the result is shown in Figure 8. The lowest void volume (Vv) of 25.1% was found on the combination of 55% coarse aggregate mass size 10–20 mm and 45% fine aggregate. These results are similar to previous studies [2]. The particle packing method was applied to determine the amount of cement that is also influenced by the water to cement ratio. Figure 8 shows the cement content required for concrete with w/c of 0.5 and 0.7 is lower compared with the minimum cement dosage requirements according to ACI 302 [3], which is 310 kg/m³ for a maximum aggregate size of 25 mm.

The control variables for the mix design are the ratio between the volume of paste and the volume of the void between the aggregates (Vp/Vv) with the use of SP and VMA. During the trial casting, it was found that for w/c of 0.5 with Vp/Vv of 100%, the fresh concrete is still dry and cannot be worked. Therefore, the Vp/Vv was increased to 101% with the addition of cement at 309 kg/m³. However, the fresh concrete produced was still not workable; thus, SP of 0.6% was added to the mixture. Bleeding and segregation occurred when the SP was added. Hence, the addition of VMA improved the cohesion of the mixture. The added VMA dosages were from 0.28% to 0.4% by mass of cement. Table 5 shows the concrete mixture of the C series with a variation of VMA dosage.

The cohesion of the mixture can be improved with the use of VMA. However, the slump value did not increase as shown in Figure 10. The results showed that although the cohesion of the mixture can be improved with the use of VMA, the workability of low-cement concrete cannot be improved only by using SP and VMA. The paste content or the Vp/Vv seems to be the controlling variable in improving the workability of the fresh concrete. By gradually increasing the Vp/Vv using cement or other material, such as cementitious or powder material like limestone powder, calcined clay, slag, or fly ash, a more workable concrete can be produced.

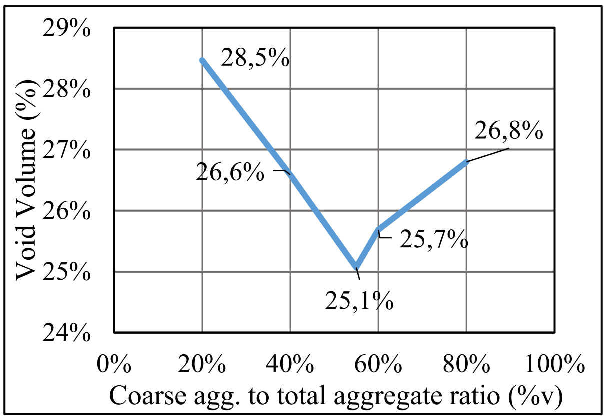


Figure 8. Void volume (Vv) measured for various coarse aggregate fractions to the total aggregate volume.

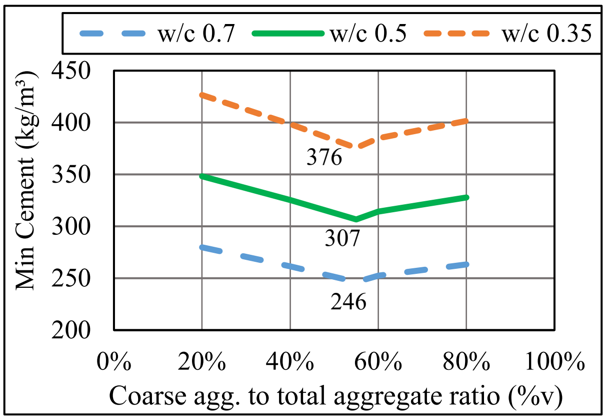


Figure 9. Minimal cement content for concrete mixture with a void volume of 25.1% at various water to cement ratios.

Table 5. Mix design of the concrete series.

Series	w/c	Vp/Vv (%)	Cement (kg/m³)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)	SP (%m c)	Code	VMA (%m c)
C, Concrete with **normal w/c**	0.5	101	309	155	905	1010	0.6	C0	0
								C1	0.28
								C2	0.3
								C3	0.325
								C4	0.35
								C5	0.4

A compressive strength test on concrete was performed at 28 days on two cylinder specimens with diameter of 15 cm and height of 30 cm. The bulk density and compressive strength results are shown in Figures 11 and 12, respectively. The bulk density of the concrete shows some increase with the addition of VMA, but the value was insignificant. Addition of VMA has a positive effect on the compressive strength of the concrete. With reduced bleeding and improved cohesion, the concrete can be cast more homogeneously; hence, the compressive strength can increase. The result of concrete's compressive strength without VMA was 18.68 MPa while the highest compressive strength of 22.93 MPa was achieved when the VMA dose was 0.35% by mass of cement.

The combination of SP and VMA was shown to be complementary to each other as the SP can reduce viscosity and VMA can increase viscosity; hence, controlling the cohesion of the concrete matrix can be more precise. Because adding more admixture would increase the cost of the concrete, the VMA should be used as the backup plan when faced with segregated concrete. Control of the paste volume in the concrete to increase the mixture workability as well as the use of VMA and SP, is needed for the successful application of a low-cement concrete mix design.

Figure 10. Slump test of C4 concrete with w/c 0.5, SP 0.6%; VMA 0.35%; and Vp/Vv 101%.

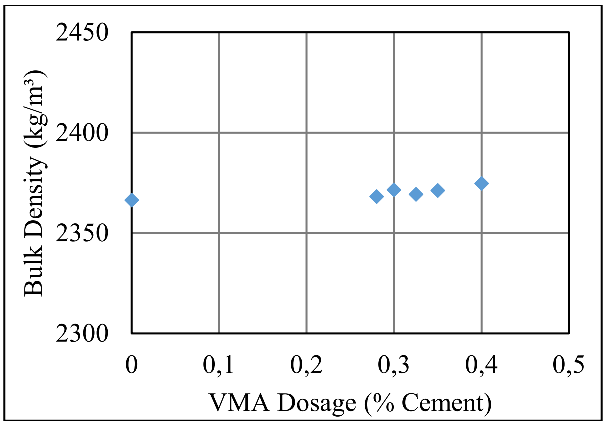


Figure 11. Bulk density of concrete with the increase of VMA dosage.

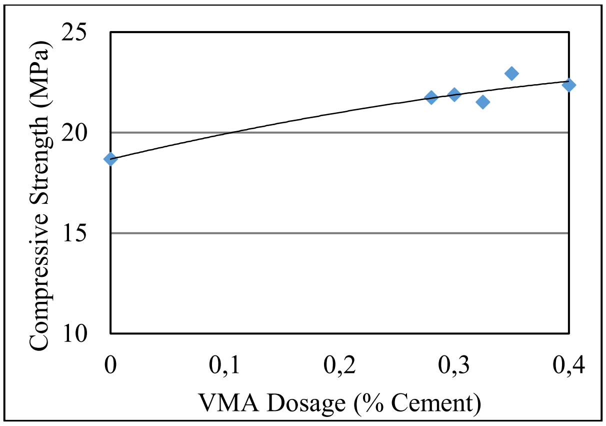


Figure 12. Compressive strength of concrete at day 28 with a various dosages of VMA.

4. Conclusions

Based on the results of this research, the following conclusions can be drawn:

1. Viscosity-modifying admixture (VMA) can have a beneficial effect in increasing the cohesion of the fresh low-cement mortar and concrete mixture. Free water in fresh concrete caused by excessive use of superplasticizer or high water to cement ratio can be absorbed by the addition of VMA.
2. The results show that adding VMA reduces bleeding and increases cohesion in fresh condition and also increases the compressive strength of the hardened mortar. The increase was favorable in high w/c mixture; however, the interaction of the VMA with the superplasticizer in low w/c mixture needs to be investigated further.

3. VMA has a beneficial effect when added to an LCC mixture with a cement content of 309 kg/m³ at w/c of 0.5 with the use of superplasticizer. The 28-day compressive strength of the control concrete (18.68 MPa) increased to 22.93 MPa when 0.4% VMA by mass of cement is added.
4. Adding VMA to low-cement concrete can improve the cohesion of the mixture with a low volume of paste, making it possible to be cast without segregation. However, it was not able to improve the workability of the concrete. The workability is mostly controlled by the Vp/Vv of the mixture.
5. Low-cement mortar can be produced with variations of the cement to sand ratio, depending on the water to cement ratio used and using the particle packing method rather than the constant sand to cement ratio traditionally used in making mortar specimens.

Acknowledgments
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