

CORROSION RESISTANCE OF SELF-COMPACTING CONCRETE CONTAINING CALCIUM STEARATE

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Abstract

This study aims to determine the corrosion resistance of self-compacting concrete (SCC) combined with calcium stearate (CS), $\text{Ca}(\text{C}_{18}\text{H}_{35}\text{O}_2)_2$. The concrete qualities tested are 20, 30, and 40 MPa. The CS dose used ranges from 0 to 2.85% of the cement weight. Two types of testing were performed in this study, namely compressive strength and accelerated corrosion tests. The compressive test was performed using cylinders 150 mm in diameter and 300 mm in height and accelerated corrosion specimen was a prism 100 x 100 x 200 mm. The results show the improvements of the compressive strength of SCC 20, 30 and 40 MPa without and with CS are 28, 31, 28, and 37%; 16, 8, 10 and 3%; and 20, 14, 6 and -2% respectively, compared with conventional concrete. The corrosion attack decreased by around 29, 46, 86 and 86% for SCC 20 MPa with CS content of 0, 0.28, 2.43, and 2.85% respectively; 23, 27, 34, and 65% for SCC 30 MPa with CS content of 0, 0.24, 1.20 and 2.40% respectively; and around 7, 46, 62 and 63% for SCC 40 MPa with CS content of 0, 0.19, 0.93, and 1.86% respectively compared with conventional concrete.

Keywords: Calcium stearate, Corrosion resistance, Self-compacting concrete, Compressive strength, Accelerated corrosion.

1. Introduction

SCC is a type of concrete that can consolidate itself without any external vibration. This type of concrete is made up of cement, crushed stone, sand, water and admixtures, which usually use a superplasticizer of a high-range water reducer type. It was first developed in Japan in 1988 [1]. The admixture material is a superplasticizer that serves to make fresh concrete more flow able, more viscous [2] and easy to cast [3]. Then the concrete is recognized as SCC. SCC is very suitable for use in concrete structures that have tight reinforcement. This is due to its ability to solidify itself. Finally, more solid hardened concrete is obtained without honeycomb. The porosity present in the hardened concrete is also extremely reduced [4]. Another advantage is that the need to use skilled labour for concrete compaction can be significantly reduced. Recent studies have found that SCC is more resistant to acid attack [5], more difficult for segregation [6], and suitable for casting on site and in precast concrete [7].

Increasing the superplasticizer dose, as one of the added ingredients in SCC, increases the compressive strength of the concrete [8]. Although SCC has many advantages over conventional concrete, the treatment methods affect its mechanical properties [9, 10]. Practically, SCC can not only be made from Ordinary Portland Cement (OPC) but can also be combined with the use of fly ash [11] and rice husk ash [12]. The use of fly ash in the SCC endows the concrete with higher compressive strength and bending capacity. More specific research has found that the compressive strength of SCC is lower than that of conventional concrete at 28 days, but higher at 90 days [13].

In terms of its macrostructure, SCC is a very dense material. However, the microstructure, although the SCC is very solid, still has capillaries. These capillaries are formed during the cement hydration reaction process. Some of the unused water in the hydration reaction of the cement evaporates and leaves the capillary pathways. Corrosive ions, i.e., chloride and sulphate, can then enter through the capillaries [14] to reach the concrete reinforcement surface in the concrete. Some researchers have conducted studies on the corrosion progression and prediction of the corrosion rate [15, 16] in reinforced concrete and prestressed concrete. Corrosion causes a decrease in the compressive strength of the concrete [17, 18], reduces the volume of the original reinforcement [19], and causes the loss of reinforcement capacity and concrete bonds [20, 21], resulting in a decrease in the structural capacity, ductility and service life of the reinforced concrete. These corrosion defect have resulted in a rise in the cost of maintaining reinforced concrete structures [22]. When the concrete cover begins to peel off due to pressure from corrosion products, degradation of reinforced concrete structures occurs faster [23].

The penetration of liquids that carry corrosive ions into the concrete greatly threatens the concrete structure with corrosion attack in the long term. The danger of a corrosion attack on the concrete structure can be reduced by protecting the reinforcement and increasing the properties of the concrete microstructure [24, 25]. Concrete reinforcement can be protected from corrosion using a coating system or by increasing the anodic level of the reinforcement bar. Improved properties of concrete microstructures can be obtained by increasing the hydrophobicity of the hardened concrete [26, 27, 28]. Some researchers have used butyl stearate [29, 30, 31] and other compounds [32] to improve the properties of conventional concrete and to protect concrete from corrosion attack. This study aims to determine the

corrosion resistance of SCC containing calcium stearate. Corrosion attack is simulated with artificial corrosion using chloride ion media. Because compressive strength is an essential mechanical property of concrete, a compressive strength test is also performed to determine the effect of the calcium stearate in the SCC on the concrete quality of 20 MPa, 30 MPa and 40 MPa.

2. Methods

2.1. Material and equipment

The materials used in this study consist of cement (Portland Composite Cement type, PCC), crushed stone, sand, water, superplasticizer (Viscocrete 1003), calcium stearate, 3% sodium chloride solution, ammonium citrate solution and plain steel bar 12 mm in diameter. The chemical content of the cement and calcium stearate used in the study is shown in Table 1. Physical tests including specific gravity, fineness modulus, volume weight, sieve analysis, and clay content were performed on the materials of crushed stone and sand used. The specific gravity, fineness modulus, volume weight and clay content are 2.65, 2.68, 1.49 ton/m³, 1.13% for sand and 2.61, 6.47, 1.51 ton/m³, 0.75% respectively. The maximum aggregate used is 20 mm. Table 2 shows the grading of fine and coarse aggregate. Three concrete strengths were designed and used as shown in Table 3 and, for each of these, three standard cylinder molds of 150 mm diameter and 300 mm height, and three prism molds of 100, 100, and 200 mm were used.

Table 4 shows the variables used in this study. The designation C with two digits indicates the concrete and its strength, SP means superplasticizer, the three-digit number after SP represents the percentage contents of superplasticizer by cement weight, CST is the abbreviation for calcium stearate. The three-digit number after CST is the content of calcium stearate as a percentage of cement weight. The calcium stearate contents for SCC 20 MPa are 0, 0.28, 1.43 and 2.85%, for SCC 30 MPa are 0, 0.24, 1.20, 2.40%, and for SCC 40 MPa are 0, 0.19, 0.93 and 1.865% by weight of cement. A cylindrical specimen with diameter 150 mm and height 300 mm is used for a compressive strength test at 28 days. Another type of specimen used for the corrosion test is a beam with dimensions 100 mm x 100 mm x 200 mm. Three specimens each are used for the compressive strength and corrosion tests.

Table 1. Chemical content of cement and calcium stearate.

Cement (PCC)		Calcium stearate	
Chemical compound	Content (%)	Chemical element	Content (%)
Silicon dioxide (SiO ₂)	18.76	Calcium	6.60
Aluminium oxide (Al ₂ O ₃)	5.54	Carbon	71.29
Ferro oxide (Fe ₂ O ₃)	3.31	Hydrogen	11.55
Calcium oxide (CaO)	63.16	Oxygen	10.56
Magnesium oxide (MgO)	1.73		
Sulphur trioxide (SO ₃)	2.06		
Loss of ignition (LOI)	3.73		
Free lime	1.53		
Insoluble part	0.71		
Alkali	0.44		

Table 2. Sieve analyses of fine and coarse aggregate

Fine aggregate			Coarse aggregate		
Size of sieve (mm)	Passing (%)		Size of sieve (mm)	Passing (%)	
	Result	Requirements		Result	Requirements
9.50	100.00	100-100	38.10	100.00	100-100
4.76	95.00	90-100	19.00	97.50	95-100
2.38	87.50	85-100	9.50	47.30	30-60
1.19	78.30	75-100	4.76	8.50	0-10
0.59	50.79	60-79	2.38	0.00	0-0
0.279	20.09	12-40	1.19	0.00	0-0
0.149	0.29	0-10	0.60	0.00	0-0
Pan	-	Group III	0.30	0.00	0-0
			0.15	0.00	Max. 20 mm
			Pan	0.00	

Table 3. Mixture proportions of self-compacting concrete.

Material	Unit weight (kg/m ³)		
	20 (MPa)	30 (MPa)	40 (MPa)
Cement (PCC)	350	415	535
Sand	910	815	750
Crushed stone	910	920	870
Free water	175	187	180
Superplasticizer (lt)	0.88	1.04	1.34
Water cement ratio (%)	0.5	0.45	0.34
Gmax (mm)	20	20	20
s/a (%)	0.5	0.47	0.46
Calcium stearate (% of cement weight)	0;0.29;1.43;2.85	0;0.24;1.20;2.41	0;0.19;0.93;1.86

Table 4. Specimen designation.

No. of code	Specimen designation	SP content (%)	CST content (kg/m ³ ; %)	Concrete grade (MPa)
1	C20-SP0.00-CST0.00	0	0 ; 0.00	
2	C20-SP0.25-CST0.00	0.25	0 ; 0.00	
3	C20-SP0.25-CST0.28	0.25	1 ; 0.28	20
4	C20-SP0.25-CST1.43	0.25	5 ; 1.43	
5	C20-SP0.25-CST2.85	0.25	10 ; 2.85	
1	C30-SP0.00-CST0.00	0	0 ; 0.00	
2	C30-SP0.25-CST0.00	0.25	0 ; 0.00	
3	C30-SP0.25-CST0.24	0.25	1 ; 0.24	30
4	C30-SP0.25-CST1.20	0.25	5 ; 1.20	
5	C30-SP0.25-CST2.40	0.25	10 ; 2.40	
1	C40-SP0.00-CST0.00	0	0 ; 0.00	
2	C40-SP0.25-CST0.00	0.25	0 ; 0.00	
3	C40-SP0.25-CST0.19	0.25	1 ; 0.19	40
4	C40-SP0.25-CST0.93	0.25	5 ; 0.93	
5	C40-SP0.25-CST1.86	0.25	10 ; 1.86	

The superplasticizer used in this study is Viscocrete 1003, as shown in Fig. 1. Its chemical base is an aqueous solution of modified polycarboxylate copolymers, its density is around 1.065 kg per litre, and the total chloride ion content is under 0.1% per weight of Viscocrete.

This superplasticizer enables the stable generation of free chloride, which does not cause corrosion in concrete reinforcement. The colour of the product is brownish and it has been developed to make the concrete flow, and to reduce segregation and bleeding. This performance is possible, as stated before, because it absorbs the surface of the cement particles and produces a sterical separation effect. The self-compacting particles can be maintained for more than 1 hour at a temperature of 30° C. Figure 2 shows the calcium stearate.



Fig. 1. Viscocrete 1003.



Fig. 2. Calcium stearate.

2.2. Concrete mixing procedures

Fresh concrete is made by mixing cement, sand, crushed stone and water. Mixing is done for 3–5 minutes until the fresh concrete becomes homogeneous. In this process, the fresh concrete is expected to reach a slump of about 3–5 cm. The next step is to add a superplasticizer into the fresh concrete, and the concrete mixer is rotated again for 1 minute to produce a homogeneous mixture. The workability of the fresh concrete can be measured using Abram's cone, where the larger diameter end of the cone is placed on the surface of the baseplate. The slump level is defined by measuring the diameter of the fresh concrete after the Abram's cone is lifted.

The compressive strength test specimens are made by inserting fresh concrete into a cylinder in three layers. Each layer is compacted 25 times with a tamping rod with diameter 16 mm and length 600 mm. The last stage of compaction is in the form of external vibration by tapping the outside of the cylinder molding with a rubber hammer 15 times [33].

2.3. Compressive strength of concrete

When the specimen is 1 day old, the molding is removed and the concrete is then treated for curing the specimen by soaking it in fresh water at temperatures around 25 °C for 27 days. The compressive strength test specimen is lifted out of the curing pond water and aerated to dry it at room temperature for approximately 6 hours. Flattening of the cylinder surface is completed by applying a Sulphur capping. A compressive strength test is carried out by placing the concrete specimens on a UTM machine in a flat position. The concrete compressive strength value can be calculated from the maximum load divided by the area.

2.4. Artificially accelerated corrosion

Before the fresh concrete is cast into a 100 mm x 100 mm x 200 mm prism mold, a plain steel bar with diameter 12 mm and length 100 mm is positioned in the mold. This steel bar is fitted with a cable at one end. This cable is useful for generating artificially accelerated corrosion using an electrolytic medium by connecting it to the power supply. This connecting cable is installed by soldering it to the steel bar. The steel bar is weighed first (A) to obtain the initial weight. The molded specimens are released when the specimen is 1 day old. Then the specimen is treated by covering it with a wet mattress for 27 days.

The artificially accelerated corrosion treatment process begins when the concrete is 28 days old. The existing cable attached to the reinforcement is connected to the power supply. The power supply is used to generate corrosion in four specimens of reinforced concrete beams. The corrosion process with the electrical corrosion system can be seen in Fig. 3. The voltage used for the artificially accelerated corrosion process is about 12 V. This artificially accelerated corrosion process is observed daily to determine which specimens have started to generate corrosion. The occurrence of corrosion can be identified by the presence of cracks on the concrete surface, and the colour of the water with 3% NaCl becomes reddish. The surface of the concrete becomes cracked because of the pressure of the corrosion product, whose volume enlarges to 2–3 times the original steel volume [34]. The artificially accelerated corrosion treatment was stopped after a crack appeared on the concrete surface of the entire specimen.

The reinforced concrete test object is broken down to remove the reinforcing steel embedded inside the concrete as shown in Fig. 4. The corrosion product on the surface of the steel bar as shown in Fig. 5 is cleaned with a wire brush. To completely clean off the rust, the reinforcing steel is immersed in ammonium citrate solution for 24 hours. The steel bar is removed from the ammonium citrate bath and dried with a cloth rag. The corrosion-free steel bar shown in Fig. 6 is weighed and the weight after corrosion attack (B) is obtained. The amount of corrosion can be calculated by the equation below.

$$\text{Corrosion (\%)} = \frac{A-B}{A} \times 100\% \quad (1)$$

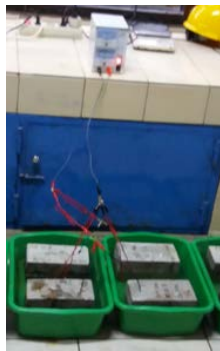


Fig. 3. Artificially accelerated corrosion process.



Fig. 4. Removal of embedded steel bar in concrete.



Fig. 5. Corrosion product on steel bar.



Fig. 6. Corrosion-free steel bar.

3. Results and Discussion

3.1. Fresh concrete

Adding Viscocrete 1003 clearly enhances the concrete's workability, as can be detected in Figs. 7 and 8. Figure 7 shows the measurement of the fresh concrete's workability before Viscocrete 1003 is added. The value of concrete slump indicates 3–5 cm. The concrete looks very thick and not flowable, being difficult to cast. By contrast, Fig. 8 shows the fresh concrete after adding Viscocrete 1003. The concrete becomes very dilute and flowable without using vibrators. Testing of the value of the fresh concrete's slump shows its diameter to be about 70 cm. This shows that concrete with the addition of Viscocrete 1003 meets the criteria for SCC. This results in de-flocculation and dispersion of cement particles. The resulting improvement in workability can be exploited in two ways: by producing concrete with good workability or concrete with a very high compressive strength. SCC can be produced without bleeding or segregation [35].



Fig. 7. Slump of conventional concrete.



Fig. 8. Slump flow of SCC.

3.2. Compressive strength of concrete

Table 5 reveals the results of the compressive strength test. The three categories of concrete strength used are 20, 30, and 40 MPa. The effect of calcium stearate on the compressive strength of SCC 20, 30 and 30 MPa can be seen in Fig. 9.

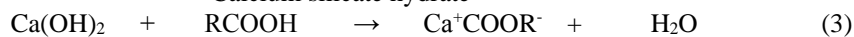
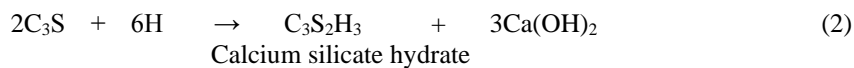
Figure 9 shows the relationship between the code number for concrete grades 20, 30, and 40 MPa and the compressive strength. Specimen number 1 represents

concrete without superplasticizer and calcium stearate, and code number 2 means concrete with superplasticizer and without calcium stearate. Code numbers 3, 4, and 5 are concrete with supplementary superplasticizer and calcium stearate in the doses listed in Table 2.

Figure 9 shows that the compressive strength of SCC is greater than that of conventional concrete. This is because the concrete mix proportions in SCC have a lower water–cement ratio. The low water content causes low pore and capillary values in the hardening concrete. The hardened concrete formed is denser and contains fewer capillaries.

SCC with calcium stearate has a compressive strength that tends to be the same for the 20 MPa quality concrete and tends to fall for the concrete qualities of 30 MPa and 40 MPa when compared with the SCC concrete without calcium stearate. This is caused by the formation of material from the reaction of the stearate and calcium hydroxide. Calcium hydroxide is the residual reaction between C_3S and water. This reaction can be seen in the chemical equations/formulas (2) and (3). The result of this reaction is a material that coats the capillary surface like a wax. This material has a weak bond when compared with the calcium silicate hydrate bond. Finally, this material leads to a decrease of the concrete's compressive strength.

The compressive strength of SCC without and with calcium stearate is higher than that of conventional concrete. The increases in compressive strength of SCC 20, 30, and 40 MPa with calcium stearate, compared with conventional concrete, are 28, 31, 28, and 37%; 16, 8, 10, and 3%; and 20, 14, 6 and -2% respectively.



Calcium hydroxide(lime)+ stearate \rightarrow insoluble calcium stearate + water [27].

Table 5. Results of compressive strength test.

Code no.	Specimen designation	Compressive strength (MPa)	Improved compressive strength (%)	Concrete grade (MPa)
1	C20-SP0.00-CST0.00	19.49		
2	C20-SP0.25-CST0.00	24.98	28	
3	C20-SP0.25-CST0.28	25.54	32	20
4	C20-SP0.25-CST1.43	24.98	28	
5	C20-SP0.25-CST2.85	26.65	37	
1	C30-SP0.00-CST0.00	29.75		
2	C30-SP0.25-CST0.00	34.42	16	
3	C30-SP0.25-CST0.24	32.01	8	30
4	C30-SP0.25-CST1.20	32.75	10	
5	C30-SP0.25-CST2.40	30.72	3	
1	C40-SP0.00-CST0.00	45.27		
2	C40-SP0.25-CST0.00	54.32	20	
3	C40-SP0.25-CST0.19	51.50	14	40
4	C40-SP0.25-CST0.93	48.10	6	
5	C40-SP0.25-CST1.86	44.14	-2	

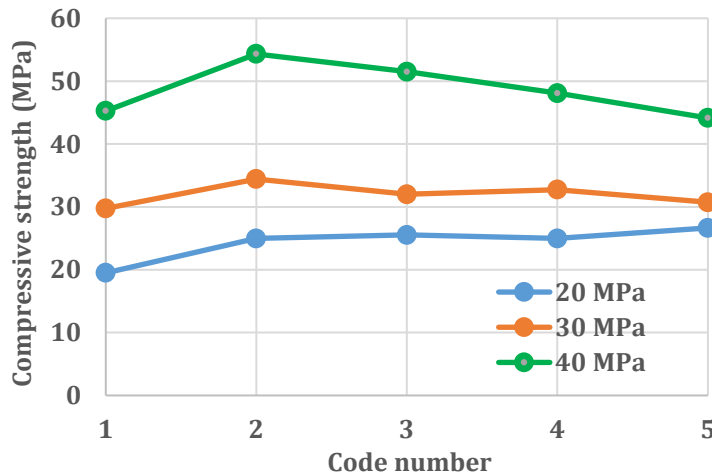


Fig. 9. Compressive strength of concrete 20, 30, 40 MPa.

From Fig. 9, it can be concluded that calcium stearate can be safely used in SCC with a content of 10 kg per cubic metre of concrete. This can be seen from the fact that the average compressive strength of concrete without superplasticizer and calcium stearate was 19.49, 29.75, and 45.27 MPa, while for the SCC with 10 kg/m³ calcium stearate content the values were 26.65, 30.72, and 44.14 MPa for the concrete qualities of 20, 30, and 40 MPa, respectively. The compressive strength of SCC concrete with 10 kg/m³ calcium stearate content is still higher than concrete without superplasticizer and calcium stearate.

3.3. Corrosion of steel bar in reinforced concrete

The corrosion results of the steel bar in the concrete are shown in Table 6. It can be seen that the concrete without superplasticizer and calcium stearate undergoes a greater corrosion attack than SCC without calcium stearate.

SCC with calcium stearate has better resistance to corrosion by chloride ions than SCC without calcium stearate. The SCC's behaviour with addition of calcium stearate can be seen in Fig. 10. This figure connects the code number with the amount of corrosion. Based on Fig. 10, it can be seen that the greater the percentage of calcium stearate added to SCC, the lower the corrosion that occurs in the concrete reinforcement. This trend occurs not only in 20 MPa quality concrete but also in concrete with the quality of 30 MPa and 40 MPa. This behaviour is caused by very fine calcium stearate particles, which are even finer than the cement grains. This physical property causes the calcium stearate to fill smaller pores and smaller spaces when the concrete becomes hard.

The reduction of the corrosion attack on SCC with calcium stearate may also be caused by the formation of a wax-like compound [36-40]. The compound is formed due to the reaction of stearate groups with calcium hydroxide. This wax-like compound is hydrophobic. The positive effect of this hydrophobicity is that when the surface of the concrete is in contact with water, the contact angle is very large. The contact angle is between 90° and 120° [41]. Harald Justnes in 2008 [42] stated that the greater contact angle between the water and concrete surfaces means that

water is not able to penetrate into the concrete capillaries without specific hydrostatic pressure [43].

Table 6. Results of artificially accelerated corrosion test.

Code no.	Specimen designation	Corrosion (%)	Concrete grade (MPa)
1	C20-SP0.00-CST0.00	11.68	20
2	C20-SP0.25-CST0.00	8.26	
3	C20-SP0.25-CST0.28	6.26	
4	C20-SP0.25-CST1.43	1.64	
5	C20-SP0.25-CST2.85	1.61	
1	C30-SP0.00-CST0.00	10.90	30
2	C30-SP0.25-CST0.00	8.36	
3	C30-SP0.25-CST0.24	7.99	
4	C30-SP0.25-CST1.20	7.21	
5	C30-SP0.25-CST2.40	3.85	
1	C40-SP0.00-CST0.00	8.28	40
2	C40-SP0.25-CST0.00	7.73	
3	C40-SP0.25-CST0.19	4.19	
4	C40-SP0.25-CST0.93	3.16	
5	C40-SP0.25-CST1.86	2.68	

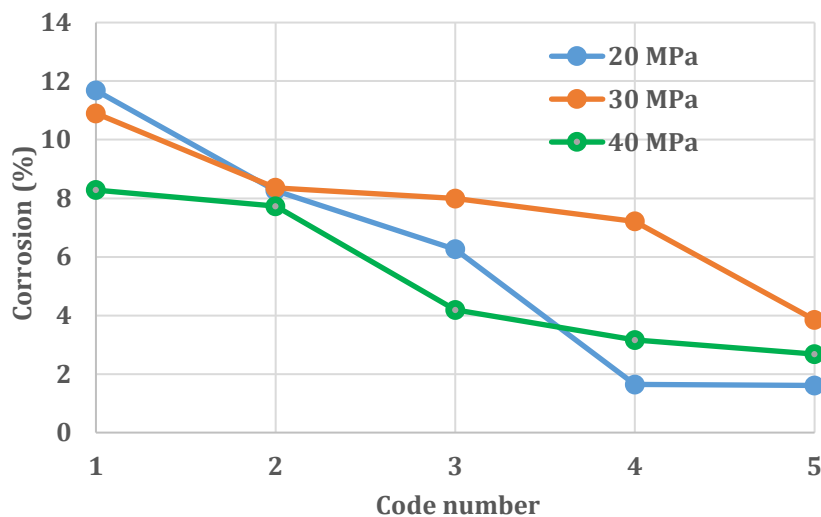


Fig. 10. Corrosion of steel bar in concrete 20, 30 and 40 MPa.

4. Conclusions

The effect of using calcium stearate in SCC together with its compressive strength and corrosion resistance have been discussed in detail. The findings can be summarized as follows:

- Calcium stearate used in SCC has a good effect on the compressive strength and resistance to corrosion attack by chloride ions.
- SCC has better resistance to corrosion attacks by chloride ions compared with conventional concrete.
- The corrosion attack declined by around 29, 46, 86 and 86% for SCC 20 MPa with calcium stearate content of 0, 0.28, 2.43, and 2.85% respectively; by around 23, 27, 34, and 65% for SCC 30 MPa with calcium stearate content of 0, 0.24, 1.20 and 2.40% respectively; and by around 7, 46, 62 and 63% for SCC 40 MPa with calcium stearate content of 0, 0.19, 0.93, 1.86%, respectively, compared with conventional concrete.
- The improvements in the compressive strength of SCC 20, 30 and 40 MPa without and with calcium stearate are 28, 31, 28, and 37%; 16, 8, 10 and 3%; and 20, 14, 6 and -2%, respectively, compared with conventional concrete.
- The use of 10 kg/m³ of calcium stearate in SCC 20 and 30 MPa is still structurally safe because the compressive strength is still greater when compared with conventional concrete with the same cement content. But in the SCC 40 MPa with 10 kg/m³ calcium stearate, the compressive strength is a little lower than that of conventional concrete.

Acknowledgements

This research is funded by Jenderal Soedirman University through a research grant with the International Research Collaboration scheme year 2018. PT. Sika Nusa Pratama Indonesia is grateful acknowledged for giving us the opportunity to use Viscocrete 1003 as a superplasticizer in the concrete.

Nomenclatures

<i>A</i>	Cross-section area of cylinder, mm ²
<i>P</i>	Force, N

Abbreviations

C	Concrete
CST	Calcium stearate
Lt	Litre
SNI	<i>Standar Nasional Indonesia</i>
SP	Superplasticizer
s/a	Sand per aggregate

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