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Characteristics of self-compacting green concrete

Hung Ling Lim[1] · Mohammad Abdul Mannan[1] · Rana Shamseldeen Fakhri[2] · Eethar Thanon Dawood[2] · Delsye Ching Lee Teo[3] · Sadia Tasnim[4]

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Abstract
Locally, conventional concrete is still created utilizing river sand and crushed stone as filer materials. The massive quarry dust by-product remain untapped in the production of concrete. The coal-fired power station produce significant quantities of Type F fly ash. Self-compacting concrete (SCC) provides many advantages for creating high-quality concrete. Consequently, the main objective of this research is to create a mix design for high-strength SCC utilizing a binary blends, hybrid fibers and fine aggregates that meet both hardened and fresh concrete characteristics. The study is conducted in amendment of w/b ratio, superplasticizer, proportion of fine aggregate to coarse aggregate, optimumal cement replacing by fly ash, dosage of low macro fibre and micro fibre. Mix-50c-X is the best mix design that was produced. The mix quantity for 1m3 concrete was 315 kg Class F fly ash, 315 kg OPC, 630 kg quarry dust, 508 kg river sand, 400 kg coarse aggregate, 0.7% superplasticizer,0.32% w/b, 0.10% macro fiber, and 0.01% micro fiber. This SCC mixture showed fresh characteristics as well as compressive strengths of more than 22 MPa and 62 MPa after 1 day and 28 days, respectively. The results of high-strength SCC demonstrated the enormous potential for the local construction, especially precast product.

Keywords High-strength self-compacting concrete · Fly ash · Quarry dust · Fibers · Precast industry

1 Introduction

There has been a significant demand on concrete due to rapid urbanization in Sarawak, Malaysia. Due to the continuation of quarry activities, the extraction of large amount of aggregate from quarry has caused major environmental impact. The quarry dust which is a by-product produced in significant amount from the extraction process remains unexplored in concrete making. Similarly, the continuous mining of river sand has caused river bank erosion, destruction of aquatic lives and ecosystem.

As there are many benefits, the government has encouraged on the use of Industrial building system (IBS). The self-compacting concrete (SCC) is commonly used in the precast concrete industry as it offers several advantages in producing high quality precast products. However, high brittleness is often a problem encountered in high strength concretes particularly SCC. Numerous studies have been previously carried out by a number of researchers regarding the use of

✉ Rana Shamseldeen Fakhri, rana.shams@ntu.edu.iq; Hung Ling Lim, hunlin1288@yahoo.com; Mohammad Abdul Mannan, mannan@unimas.my; Eethar Thanon Dawood, eethar2005@yahoo.com; Delsye Ching Lee Teo, DelsyeTeo@melbournepolytechnic.edu.au; Sadia Tasnim, sadia.tasnim@smtafe.wa.edu.au | [1]Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia. [2]Department of Building and Construction Engineering, Technical College of Mosul, Northern Technical University, Mosul, Iraq. [3]Bachelor of Engineering Technology (Civil) Program, Department of Business and Construction (Higher Education), Melbourne Polytechnic, Epping Campus, Cooper St & Dalton Rd, Epping, VIC 3076, Australia. [4]Applied Engineering, South Metropolitan TAFE, 9 Gardiner Ave, Munster, WA 6166, Australia.

fibre in reinforcing high strength concretes Sam et al. [22] on glass fibre reinforced SCC, Niş [17] on steel fibre reinforced SCC, and, Chakra and Kavitha [6] and Ling [11] on hybrid fibre reinforced SCC. The utilization of fibre reinforcement is capable of improving the performance of concrete from fresh to hardened state including durability against fatigue. Hence, precast concrete pavement can be more sustainable and economical if the high-performance SCC is reinforced by fibres [19].

Even-though self-compacting concrete (SCC) has excellent mechanical performance and quality, SCC is susceptible to spalling, cracking and various other stress-related defects. High strength concrete material usually has high brittleness and poor resistance against cracking. Based on a number of studies, it was found out that the incorporation of fibres in SCC is capable of improving its mechanical and durability properties. As the amount of fibre used can affect the fresh SCC's workability, it is therefore important to determine the exact amount of fibre usage to improve the mechanical properties without compromising SCC's workability.

Precast concrete products should not be moved until the concrete has gained sufficient compressive strength. The Occupational Safety and Health Service (2002) specified that the recommended minimum concrete compressive strength for lifting and handling is 10 MPa. The required compressive strength at the period of lifting or transporting must be achieved within one day so that precast slab panels will be competitive as compared to the cast in-situ reinforced concrete slab.

Thus, it is to formulate acceptable mix design of SCC incorporating 55% quarry dust in hybrid fine aggregate, 50% fly ash in binary binder and hybrid fibres in achieving good flowability, self-compactability and, 1-day and 28-day compressive strength of more than 20.0 MPa and 50.0 MPa respectively.

2 Materials

The ordinary Portland cement, OPC used in this study is ASTM Type I cement and it also meets Malaysian Standard EN 197–1:2014. Consequently, the fly ash used for this study is locally generated at Mukah coal-fired power plant, Sarawak. The fly ash used has 47.50% SiO_2, 25.18% Al_2O_3, 12.34% Fe_2O_3, 3.10% K_2O, 0.15% Na_2O, 5.60% CaO, 2.69% MgO, 1.03% SO_3, 0.98% TiO_2 and 0.22% BaO. It is classified as Class F Fly ash according to ASTM C618 Standard. The specific gravity of the fly ash is 2.74 according to ASTM C311M-18 test procedure.

Apart from that, the specific gravity of river sand is 2.68 and it has fineness modulus of 1.66. Prior to mixing, the sand is kept air dried in the laboratory. Quarry dust which is available in excess in the quarry site is a by-product from the crushing process during quarrying. The use of quarry dust in concrete is very much encouraged as it will eliminate disposal problem, saving river sand and reducing cost. Both quarry dust and coarse aggregate is sourced from the same quarry of Limestone. According to test result, the quarry dust has a specific gravity of 2.69 and fineness modulus of 3.45. Similarly, prior to mixing it is kept air dried in the laboratory.

Consequently, the chemical admixture used in this study is MasterGlenium ACE 8589 is manufactured by BASF Construction Chemicals and is a Type F superplasticizer (SP) complying with ASTM C494-19. Two different kinds of fiber are used in this study which is SikaFiber® Force PP-48 (to be known as Macro fiber) and SikaFibre® M (Micro fiber). The SikaFiber® Force PP-48 (Micro fiber) has a specific gravity of 0.92, length = 48 mm and mean width = 1.37 mm). Meanwhile, SikaFibre® M (to be known as Micro fiber) has a specific gravity = 0.91, length = 12 mm and diameter = 18 μm.

3 Mix design for high-strength SCC mixes

There is no formally standard for designing SCC; instead, the initial blend proportions for SCC is designed using a method of trial and error with locally obtainable ingredients. Due to the inclusion of angular materials in the mix design, such as macro fiber and quarry dust, it was decided to base the mix design on EFNARC's (European Federation of Specialist Construction Chemicals and Concrete Systems) SCC type concept, by trial-and-error on quarry dust quantity and others while maintaining a high powder percentages. Using the principle guarantees that there is enough fresh mortar to move the increased angular particles. According to Naik et al. [16], 430 to 700 kg/m^3 will be required to create high-strength SCC. The quantity of cement binder used in this research is 630 kg/m^3. The objective is to increase the paste volume in order to provide adequate plastic viscosity and best segregation resistance.

Table 1 Mix proportions of SCC based on binder (binder kept at 630 kg/m^3)

Mix	Binder		Filler			w/b ratio	SP (%)
	OPC (ASTM Type I)	Fly ash (Class F)	Fine aggregate		Coarse aggregate		
			Quarry dust	River sand			
Control	1	–	1	0.55	0.89	0.34	1.67
Mix-40	0.60	0.40	1	0.55	0.89	0.34	1.67
Mix-45	0.55	0.45	1	0.55	0.89	0.34	1.67
Mix-50	0.50	0.50	1	0.55	0.89	0.34	1.67
Mix-55	0.45	0.55	1	0.55	0.89	0.34	1.67
Mix-60	0.40	0.60	1	0.55	0.89	0.34	1.67

Table 2 Compressive strength development of concrete with partial replacement of OPC with Class F Fly ash

Comp. St. (MPa)	Control	Mix-40	Mix-45	Mix-50	Mix-55	Mix-60
3-day	37.63	25.98	24.96	17.13	7.52	5.92
7-day	56.31	43.21	38.45	36.54	28.48	25.81
28-day	58.86	57.91	52.60	51.58	39.95	38.51

3.1 Using the trial-and-error method in mix designs

It is also to replace OPC by fly ash for attaining 28 days compressive strength of increase than 50 MPa. High powder percentage is retained in the mix at the same time. For powder-type SCC to obtain adequate viscosity without applying a viscosity modifying additive, high powder content is necessary. As indicated by Ma and Dietz [12], the high performance SCC used water/cement ratio between 0.28 and 0.38. Due to incompatibility of the exact ratio of water to cement with SP dosage, 1.67% superplasticizer with recommended water/cement ratio of 0.34 is attempted in the initial mix design.In accordance with JSCE [9], an absolute volume for coarse can range from 0.28 to 0.35 m^3/m^3. Utilizing 0.35 m^3/m^3 multiplied with the bulk density of the coarse aggregate (1603 kg/m^3), 561 kg/m^3 for the coarse aggregate contents is achieved. Subsequently, the unit fine aggregate content is then determined as 977 kg/m^3 by binder content, coarse aggregate content, and water content for the total unit weight of concrete. Large amounts of quarry dust are produced as a byproduct during quarry operations in Sarawak, Malaysia. Consequently, hybridization of sand with quarry stone dust attempted at a random mix ratio of 35.5:64:5 to investigate whether a high proportion of quarry stone dust as a fine aggregate can enhance to SCC performance**.**

Therefore, the initial mix design as 'control mix' of SCC is shown in Table 1. The target of the mix design is to achieve the compressive strengths of at least 20.0 MPa on 1-day and 50.0 MPa on 28-day. Another intention is to replace OPC with high amount of fly ash starting from 40 to 60% as shown in Table 1. therefore, as indicated in Table 2, it has been proven that excessively substituting cement with fly ash will gradually decrease the compression strength of SCC because pozzolanic material cause concrete to gain strength at a rate that is slower than cementitious materials. The similar influence of high substitution of cement by fly ash on SCC compressive strength is also additionally found in Mohamad et al. [14]'s study. According to the study's control mix compressive strength, after 60% cement substitution by fly ash, the strength steadily decreased from more than 50.0 MPa to less than 30.0 MPa [14]. A similar pattern of declining SCC compressive strength with a rising proportion of cement replacement by fly ash has also been demonstrated by Dasarathy et al. [7]. Therefore, to prevent an excessive fall in the SCC's 28-day compressive strength, it is necessary to properly balance the proportions of cement and fly ash in the binder. The best amount of fly ash to replace cement in the SCC mix design, it can be concluded, is 50%. On the other hand, at 24 h after casting, it is discovered that the 100 mm cube specimens in all mixtures indicated in Table 1 cannot be demoulded because the samples have not yet completely hardened. As a result, these blends are unable to be tested for 1-day compressive strength. The delay in concrete hardening is possibly due to high dosage of superplasticizer used which has the potential in retarding the setting time of concrete. A minimum 10.0 MPa compression strength is important for the mass manufacturing of precast concrete structures to enable secure demolding.

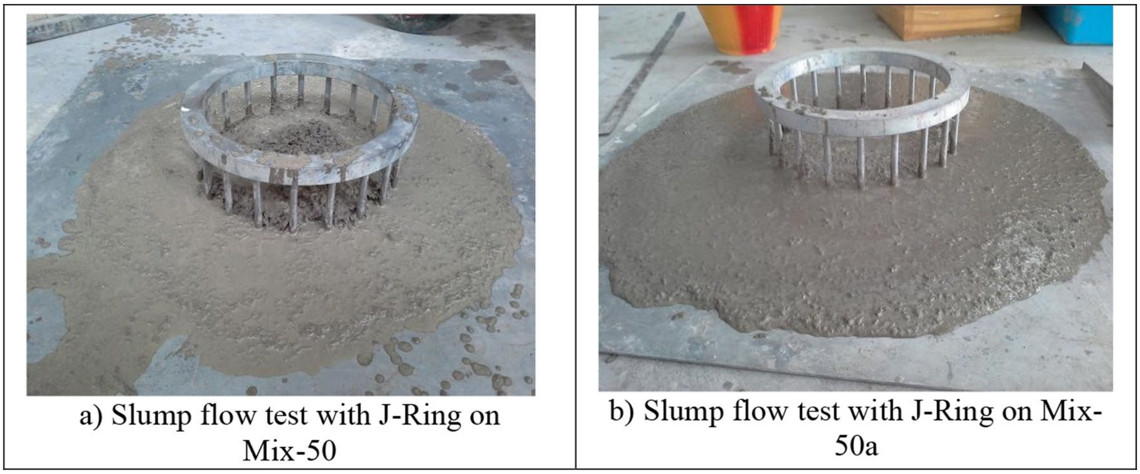

Fig. 1 Slump flow test **a** J-Ring test on Mix-50 and **b** J-Ring test on Mix-50a

Table 3 Mix proportions of SCC based on binder content with modification of fine aggregate (F.A) to coarse aggregate (C.A) ratio

Mix No	Binder (content = 630 kg/m^3)		Filler			F.A/C.A ratio	w/b ratio	SP (%)
	OPC (ASTM Type I)	Fly ash Class F	Fine aggregate		Coarse aggregate			
			Quarry dust	River sand				
Mix-50	0.50	0.50	1.00	0.55	0.89	1.74	0.34	1.67
Mix-50a	0.50	0.50	1.00	0.80	0.63	2.85	0.34	1.67

3.2 Adjustment of the fine aggregate to the Coarse aggregate ratios

While the fresh properties in Mix-50, an SCC mix design with established optimal 50% cement substitution by fly ash, are evaluated, it is discovered that Mix-50 has weak passing and filling capabilities. As demonstrated in Fig. 1, a pile of the coarse aggregates could be seen clumped together inside or before J-ring bars. The SCC's fresh mortar mix instead has flowed by J-ring's bars containing a small quantity of coarse aggregates. Low fine aggregate to coarse aggregate ratios may result in SCC having less flowability and passing ability, claim Yardimci et al. [24]. As a result, the existing SCC mix design has to increased fine aggregate to coarse aggregate ratio. Quarry dust's high the fineness and angular particles shape, when compared to sand, limit its capacity to improve SCC's flowability [10]. Instead, an increase in the sand content is tried. In order to preserve the overall amount of aggregate in the mix design, the amount of sand is increased 347.0–508.0 kg/m^3, but the amount of coarse aggregate is dropped from 561.0 to 400.0 kg/m^3. As consequently, the initial fine to coarse aggregate ratio in the mix design is adjusted from 1.74 to 2.85, as indicated in Table 3. The weak passing capacity of Mix-50 (Fig. 1a) has been enhanced after the ratio is altered, as illustrated in Fig. 1b for Mix-50a.

The value for the passing ability test was reduced from 27.0 to 8.75 mm, so it's below 20.0 mm according to requirements by the EFNARC's guidelines. According to Yardimci et al. [24], increasing the ratio of fine aggregate to coarse aggregate has the impact of improving passing capacity. Yardimci et al. [24] was increased ratio from 0.94 to 2.50 and found that also blocking ratio, which was formerly 0.87, was increased to 0.95; a blocking ratio of 1.0 indicates the highest passing ability. After when the ratio of fine to coarse aggregate is increased, the slump flow's T500 would drop, according to test data from Yardimci et al.'s (2014) research. However, this study showed that T500 increased from 2.34 to 4.6 s. The SCC slump's concrete liquid or fresh mortar is shown before the ratio alteration, having flowed out within the J-ring without properly conveying the coarse particles and giving "false" slump flow test values of T_{500} and $D_{average}$. The SCC's viscosity has increased due to an increase in fine aggregate content. As a result, the slump has now been flowed away together with all of the coarse particles, indicated the real filling capacity of SCC. The ratio-modified mix design, on the other hand, improved its filling ability from 59.66 to 16.1 s, as shown in Table 4, but it still fails against the filling ability criterion by the V-Funnel test technique.

Table 4 Properties of Mix-50 and Mix-50a with different fine aggregate (F.A) to coarse aggregate (C.A) ratio

Mix No	Mix-50	Mix-50a
Different fine aggregate to coarse aggregate ratio		
F.A/C.A ratio	1.74	2.85
Quantity of river sand (kg/m^3)	347.0	508.0
Quantity of 10 mm Coarse Aggregate (kg/m^3)	561.0	400.0
Fresh properties		
Slump flow test with J-Ring		
Filling ability		
T500 (3.5–6.0 s)	2.34	4.60
Daverage (600–750 mm)	660.0	785.0
Passing ability (≤ 20 mm)	27.0	8.75
V-Funnel test		
Filling Ability, T0min (6–12 s)	59.66	16.1
Segregation Resistance (0–3 s)	1.90	4.30
Mechanical property		
28-day Comp. St. (MPa)	51.58	58.81

Increased volume of fresh mortar mixes also rises the distance between the coarse aggregate. As a result, the ability of the coarse aggregate was increased, allowing for easy flow through a V-Funnel apparatus. The ratio modifications is shown to have slightly reduced segregation resistance from 1.9 to 4.3 s. Finally, it can be concluded that Mix-50's fresh properties cannot be properly compared to Mix-50a because Mix-50 failed to behave in a manner that was consistent with the characteristics established by SCC, as evidenced by the results of Slump Flow with V-Funnel test and J-Ring test. Because of the excessive superplasticizer dosage utilized, Mix-50a failed to achieve segregation resistance lower than the minimum 3.0 s. Overdosing on the superplasticizer, while increasing the fluidity of the concrete, can produce segregation and bleeding. Antoni et al. [4], discovered similar issues when optimising polycarboxylate-based superplasticizer dosage in mixing. Furthermore, the formation of foams on the Mix-50a blend surface is produced by the addition of the superplasticizer during mixing, as demonstrated in Mönnig and Lura [15]'s study. Thus, while the modified fine to coarse aggregate ratio of 2.85 is adequate for increasing passing ability at the present, the superplasticizer dosage for Mix-50a could be decreased next to decrease segregation and foam formation.

3.3 Determination of Superplasticizer dosage and w/b ratio

The main function of superplasticizer for SCC is to eliminate the need for a high water/cement ratio because of the large proportion of particles in the SCC mix and to maintain SCC workable. However, when using an inappropriate superplasticizer dosage, the quantity of water utilised in mixing SCC may become excess. This may cause several issues, including aggregate segregation, a decrease of compression strength due to more shrinkage, and a delay in the SCC's setting time. Initially, the SCC experimental mix designs utlized a 1.67% dose of Master Glenium ACE 8589 (superplasticizer) to the weight of binders material, which is the maximum dosage recommended by the BASF manufacturer. Because of the large quantity of binder and fine aggregates in the blend design, a high superplasticizer dosage dosage is attempted in order to produce a highly workable SCC with a water-to-cement ratio that is low of 0.34. However, it is discovered that the SCC cube samples did not acquire the needed early strength of more above 10.0 MPa to allow acceptable demoulding at the 24 h. In the precast industry, this SCC's weak initial strength cannot be acceptable. The mass manufacture of the precast components will take longer because SCC needs to be thoroughly hardened over more than 24 h. Thus, it may be concluded that the superplasticizer dosage utilised in this research may have overdosed, which has resulted in a very significant delay in SCC's setting time. As a result, the trial mixes listed in Table 1 cannot be used to determine the compressive strength after 1 day. Two factors that can be slowing the SCC's early strength development include an excessive amount of superplasticizer and a high substitute for cement by fly ash. However, because high substitute for cement by fly ash is necessary in the SCC mix design to decrease excessive cement content, the issue of inadequate early strength is overcome by lowering superplasticizer dosage instead. Other issues, such as a surface of foam and aggregate segregation, have been reported in previous fresh blends. During SCC mixing, when the amount of water is

Table 5 Mix proportions of SCC based on binder of 630 kg/m^3 through various w/b ratios and SP dosages

Mix No	Binder (binder kept at 630 kg/m^3)		Filler			w/b ratio	SP (%)
	OPC (ASTM Type I)	Fly ash Class F	Fine aggregate		Coarse aggregate (kg/m^3)		
			Quarry dust (kg/m^3)	River sand (kg/m^3)			
Mix-50a	0.50	0.50	1.00	0.80	0.63	0.34	1.67
Mix-50b	0.50	0.50	1.00	0.80	0.63	0.31	0.80
Mix-50c	0.50	0.50	1.00	0.80	0.63	0.31	0.60
Mix-50d	0.50	0.50	1.00	0.80	0.63	0.31	0.50

Table 6 Properties of SCC with various combinations of w/b ratio and superplasticizer dosage

	Mix-50a	Mix-50b	Mix-50c	Mix-50d
Different w/b ratios and SP dosages				
w/b ratio	0.34	0.31	0.31	0.31
Superplasticizer dosage (%)	1.67	0.8	0.6	0.5
Fresh properties				
Slump flow test with J-Ring				
Filling ability				
T500 (3.5–6.0 s)	4.6	2.15	3.90	3.97
Daverage (600–750 mm)	785.0	745.0	770.0	495.0
Passing ability (≤ 20 mm)	8.75	8.75	10.25	23.5
V-Funnel test				
Filling ability, T0min (6–12 s)	16.1	7.41	9.46	9.31
Segregation resistance (0–3 s)	4.30	3.02	2.74	2.62
Mechanical property				
1-day Comp. St. (MPa)	–	3.11	13.53	13.59
28-day Comp. St. (MPa)	58.81	64.43	60.48	58.98

too significantly the foam and segregation may rapidly develop. Poor surface finish is thus brought on by the foams. So, using dosage of the superplasticizer, the water to cement ratio was decreased.

According to Table 5, the modification on the w/b ratio and superplasticizer dosage was tried with the w/b ratio decreasing from 0.34 to 0.31 and the superplasticizer dosage decreasing from 1.67 to 0.8% for mix Mix-50b. The Mix-50b mix has improved from having a low filling ability of 16.1 to 7.41 s inside the required range, according to the V-Funnel test method. The segregation resistance is also enhanced from 4.30 to 3.02 s, while is still 0.02 s higher than the adqute limit of 3.0 s. thus, Mix-50b's 28-days, the compressive strength is observe increased by 9.56% in Mix-50a's 58.81 MPa, although superplasticizer dosage is decraesed. A similar impact was also found by Antoni et al. [4]. Antoni et al. [4] demonstrated that increasing the superplasticizer dosage over the optimum dosage or overdosing decreases instead of increases the compressive strength of concrete. Reduced w/b ratio also contributes to increased compressive strength. Blend Mix-50b's 1-day compressive strength, on the other hand, was determined to be 3.11 MPa (Table 6), which is still less than the intended 1-day compression strength of 10.0 MPa for safe demoulding. This demonstrates that the quantity of superplasticizer still utilised is excessive. As a result, as shown in Table 6, the superplasticizer dosage for the Mix-50c is reduced to 0.6%. Its filling ability, passing ability, and segregation resistance have all been evaluated and found to meet EFNARC's recommendations.'The test results showed that Mix-50c's fresh characteristics are excellent. It has a compressive strength of 13.53 MPa at the 24th hour, which allows for safe demoulding for precast elements during mass manufacturing. However, on the 28th day, its compressive strength reduces from 64.43 to 60.48 MPa because of a decrease of superplasticizer dosage. This has shown that the 0.6% superplasticizer dosage is low of the required superplasticizer dosage for increasing the compressive strength of the SCC. Therefore, the effect of superplasticizer dosage in the compressive strength of the SCC in this research is comparable to that of Antoni et al. [4]. However, because the compressive strength remains higher than the desired 50.0 MPa, it is more significant to determine the optimal superplasticizer dosage using SCC in order to obtain the acceptable fresh characteristics.

While the w/b ratio remains at 0.31 in the following mix Mix-50d, the dosage of superplasticizer is slightly decreased to 0.5% to determine if the general of SCC could still be enhanced with a less dosage of a superplasticizer In contrast, SCC's fresh characteristics should to meeting the recommended standards. Thus, although its segregation resistance and filling ability are good which have exceeded the established requirements, however its passing ability and slump flow diameter have been unable to meets the requirements due to excessive viscosity. Reduced superplasticizer dosage without raising w/b ratio decreased SCC fluidity and increased viscosity. Although higher viscosity is advantageous in enhancing segregation resistance, that has been increased from 2.74 to 2.62 s when compared to Mix-50c's, it contributed to the fresh SCC mixes slump to the flow and spread in a smaller diameter. Eldarwish et al. [8] discovered an identical situation in which the incorporation of limestone powder to the study's SCC mix increased the viscosity of the fresh SCC and, as a result, decreased the slump flow diameter. The superplasticizer dosage was raised in the study in order to lower SCC viscosity and improve slump flow diameter. This demonstrated the relationship between superplasticizer dosage and SCC viscosity. As a result of the reduced superplasticizer dosage, the slump flow diameter of Mix-50d is reduced from 770.0 to 495.0 mm, which is less than the necessary 600.0 mm. A large amount of fresh slump has yet to flow out of the J-ring and produced a failure of passing ability testing, which is 3.5 mm greater than required ultimate height difference of 20.0 mm. Mix-50d's 1-day compressive strength is similar to Mix-50c's, but its 28-day compressive strength is 1.5 MPa lower due to a 0.1% decrease in superplasticizer dosage. Mix-50c with 0.31 w/b ratio and 0.6% superplasticizer dosage, MasterGlenium ACE 8589 have been the best combination for obtaining the recommended fresh and hardened characteristics of SCC. As a result, Mix-50c is selected as the optimum blend.

3.4 Determination of dosage of Macro fibre using two Aspect ratios

The Mix-50c trial mix is utilized as the basic mix design to be included with fibers in producing fiber reinforced SCC since it is the ideal plain SCC mix and has attained the necessary workability and strength. Used macrofiber with an aspect ratio of 35 and a length of 48.0 mm. The dosages of the 48.0 mm macro fiber have been tried at 0.05%, 0.10%, 0.30%, 0.50%, and 1.0% by volume of concrete as indicated in Table 7, because the compatible dosage of the 48.0 mm macro fiber to the simple SCC mix design is unavailable. As shown in Table 8, the SCC still achieved good filling abilities but acceptable bypassing ability, 18.25 mm, which is near to the requirement of maximum 20.0 mm, up to 0.1% dosage of 48.0 mm macro fiber. The filling ability and passing ability of mixes Mix-50c-48MF30, Mix-50c-48MF50, and Mix-50c-48MF100 failed to meet the requirements EFNARC when more than 0.1% dosage of 48.0 mm macro synthetic fiber was utilized. All SCC bleds (utilizing 48 mm macro fiber having 0.05–1.0%) found little resistance to segregation which is less than 3.0 s.

The aspect ratio and amount of the macro fibre are influenced in the fresh characteristics of SCC. Rao and Ravindra [20] reported a similar issue in this study when they investigated the performance of SCC reinforced using macro steel fibre at different dosage and aspect ratios.

When tested using the Slump Flow test, the V-Funnel test method, the L-Box test, and the J-Ring test, the filling ability and passage capacity of SCC in this research gradually decreased with increasing dosage of macro steel fibre. The study's trial mixes with adequate dosages of macro steel fibre at various aspect ratios were compared, and it was discovered that

Table 7 Mix proportions of SCC based on binder of 630 kg/m^3 through Macro fibre with two Aspect ratios

Mix no	Binder (kept at 630 kg/m^3)		Filler			w/b ratio	SP (%)	Macro fiber (%)	
	OPC (ASTM Type I)	Fly ash (class F)	Fine aggregate		Coarse aggregate			48 mm Macro fibre	24 mm Macro fibre
			Quarry dust	River sand					
Mix-50c	0.50	0.50	1.00	0.80	0.63	0.31	0.60	-	–
Mix-50c-48MF05	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.05	–
Mix-50c-48MF10	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.10	–
Mix-50c-48MF30	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.30	–
Mix-50c-48MF50	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.50	–
Mix-50c-48MF100	0.50	0.50	1.00	0.80	0.63	0.31	0.60	1.00	–
Mix-50c-24MF10	0.50	0.50	1.00	0.80	0.63	0.31	0.60	–	0.10
Mix-50c-24MF20	0.50	0.50	1.00	0.80	0.63	0.31	0.60	–	0.20
Mix-50c-24MF30	0.50	0.50	1.00	0.80	0.63	0.31	0.60	–	0.30

Table 8 Properties of SCC incorporating various dosages of 48 mm Macro fibre

Mix no	Mix-50c	Mix-50c-48MF05	Mix-50c-48MF10	Mix-50c-48MF30	Mix-50c-48MF50	Mix-50c-48MF100
Dosage of macro fiber						
48 mm macro fibre (% by volume)	0.0	0.05	0.1	0.3	0.5	1.0
Fresh properties						
J-Ring test						
Filling ability						
T500 (3.5–6.0 s)	3.90	2.86	2.94	3.37	3.59	5.19
Daverage (600–750 mm)	770.0	730.0	750.0	615.0	565.0	545.0
Passing ability (≤ 20 mm)	10.25	17.0	18.25	33.25	37.0	81.75
V-Funnel test						
Filling ability, T0min (6–12 s)	9.46	10.66	11.56	17.82	21.34	Stuck
Segregation resistance (0–3 s)	2.74	4.9	6.97	43.61	80.05	Nil
Mechanical property						
1-day Comp. St. (MPa)	13.53	14.09	14.27	13.85	14.02	13.49
28-day Comp. St. (MPa)	60.48	61.57	62.83	59.23	59.59	57.41

as the aspect ratio of the fibre increased, it also decreased SCC's filing and passing abilities. Sable and Rathi [21] evaluated several macro steel fibre types with various aspect ratios of 50 and 80 dosage of 2.5% by binder weight affected the SCC's fresh characteristics. The study showed that, although using the same types of macro steel fibre, different aspect ratios can have different effects on the SCC's filling, passing, and segregation resistance. According to the study, SCC's filling, passing, and segregation resistance may all be adversely affected by macrofibers with a greater aspect ratio.

Similarly, it was found in this study that after gradually increasing the dosage of macrofibers to 48.0 mm (aspect ratio: 35) in the Mix-50c, the SCC's fresh properties become worse by the J-Ring and V-Funnel test method passing ability testing from V-Funnel test method, filling ability slight decreased from Mix-50c's 9.46 s until to no test result being achievable for 1.0% macro fibre dosage (Mix-50c-48MF100). Additionally, segregation resistance decreased from 2.74 s until to no value is obtained for test. This is due to the fact that a high aspect ratio and a high dosage of macro fiber are making it harder for new SCC mix to pass through the small orifice at the bottom of the V-Funnel, trapping it there and preventing it from flowing out. SCC's passing ability for the J-Ring test also declined, going from Mix-50c's 10.25 mm to 81.75 mm for the 1.0% doses of 48.0 mm macro fiber employed. Finally, the employed macro fiber's 48.0 mm length is longer than the J-ring apparatus's 40.0 mm space between its 10.0 mm steel bars. However, it was discovered that the 1-day compressive strength of the SCC increased along with an increased dose of 48.0 mm macro fiber, from 13.53 MPa at 0% dosage to 14.27 MPa in 0.1% dosage. Secondly, whenever the macro fibre dosages is increased by more than 0.1%, its 1-day compressive strength drops. At 1.0% dosage, the compressive strength is reduced to 13.49 MPa, which is significantly less than Mix-50c's compressive strength. Similar to this, 28-day compressive strength is raised from 60.48 MPa to 62.83 MPa at increased dosge from 0 to 0.1% of macro fibre, growing along with it. When the dosage of macrofiber is raised by more than 0.1%, the compressive strength after 28 days gradually decreases. At a dosage of 1.0%, the compressive strength has decreased to 57.41 MPa, which is less than Mix-50c's. Additionally, the compressive strength of SCC is affected similarly by the dosage of macro fibers in Rao and Ravindra [20]'s study.

Therefore, it can be concluded that in order for SCC to attain superior fresh state performance, the aspect ratio in macro fiber need to be decreased. By cutting the fibers into approximately 24.0 mm length, which is half of the original macro fiber length, the aspect ratio of the macro fiber is decreased to 17.5. Table 7 shows the dosages of 24.0 mm macro fiber incorporated into SCC, which are tested at 0.1%, 0.2%, and 0.3% by the volume of concrete to see if it allows for the addition of macro fiber above 0.1% dosage.

Table 9 shows that SCC's ability to pass and segregation resistance have gradually improved as a result of the aspect ratio of macrofibers being reduced. The SCC's V-Funnel test filling ability has been enhanced from 11.56 to 10.47 s, which is below the maximum 12.0-s limit, and the segregation resistance is improved from 6.97 to 1.96 s, which is below the maximum 3.0-s limit, both at the same dosage of 0.1%. The aspect ratio decrease, which is 10.25 mm and is under the requirement's maximum 20.0 mm limit, has not changed, but the J-Ring test still requires it to pass. The filling ability by the V-Funnel test technique is improved from 17.82 to 15.73 s at the same dosage of 0.3% (Mix-50c-48MF30 against

Table 9 Properties of SCC using various dosages of 24 mm Macro fibre

Mix	Mix-50c	Mix-50c-24MF10	Mix-50c-24MF20	Mix-50c-24MF30
w/b ratio, SP and 24 mm Macro fiber				
w/b ratio	0.31	0.31	0.31	0.31
SP dosage (%)	0.6	0.6	0.6	0.6
24 mm Macro fibre (%)	0.0	0.1	0.2	0.3
Fresh properties				
J-Ring test				
Filling ability				
T500 (3.5–6.0 s)	3.90	4.71	5.38	6.14
Daverage (600–750 mm)	770.0	745.0	730.0	690.0
Passing ability (≤ 20 mm)	10.25	10.25	13.5	15.75
V-Funnel test				
Filling ability, T0min (6–12 s)	9.46	10.47	12.11	15.73
Segregation resistance (0–3 s)	2.74	1.96	2.83	3.65
Mechanical property				
1-day Comp. St. (MPa)	13.53	14.39	14.46	14.23
28-day Comp. St. (MPa)	60.48	63.32	61.82	60.49

Mix-50c-24MF30), and the segregation resistance is enhanced from 43.61 to 3.65 s, which is just beyond the maximum 3.0-s limit. The J-Ring test's passing ability has increased from 33.25 to 15.75 mm, which is less than the 20.0 mm maximum limit. SCC's fresh properties are discovered to be still within the acceptable range but almost at the limit of each requirement at 0.2% incorporation of short (24.0 mm) macro fiber dosage, as shown in Table 9.

Although the fresh qualities of SCC have improved due to the reduction in macro fiber aspect ratio, the fresh characteristics have deteriorated due to an increase in the dose of short macro fiber. On the other hand, the SCC's 1-day compression strength and 28-day compressive strength have marginally increased thanks to the reduction in the aspect ratio of macro fiber. The 1-day compressive strength is increased from 14.27 to 14.39 MPa at the same dosage of 0.1% (Mix-50c-48MF10 versus Mix-50c-24MF10), while the 28-day compressive strength is increased from 62.83 to 63.32 MPa. One-day compressive strength is increased from 13.85 to 14.23 MPa at the same dosage of 0.3% (Mix-50c-48MF30 against Mix-50c-24MF30), while 28-day compressive strength is increased from 59.23 to 60.49 MPa. In the work by Rao and Ravindra [20], a comparable impact of a modest increase in compressive strength at constant dosage with reduced macro fiber aspect ratio was also noted. Additionally, it was discovered that the SCC's compressive strength still diminishes when the dosage of included macro fiber with reduced aspect ratio is higher than the recommended dosage, regardless of the aspect ratio of the macro fiber. It is noted that when the dose of 24.0 mm macro synthetic fiber is increased from 0.1% (Mix-50c-24MF10) to 0.2% (Mix-50c-24MF20), the 28-day compression strength decreases from 63.32 to 61.82 MPa. When the dose of 24.0 mm macro synthetic fiber is increased to 0.3% (Mix-50c-24MF30), the compressive strength is further reduced to 60.49 MPa. The research conducted by Rao and Ravindra in 2010 also shown this trend of effect. Although the highest dosage of 0.2% of 24.0 mm macrofiber can be integrated, 0.1% dosage is thought to be more appropriate as the optimal dosage of macrofiber for SCC in this study.

3.5 Micro and macro fibre admission in SCC

Utilising Mix-50c-24MF10 as the basis mix, the micro fibre is tested with 0.01%, 0.02%, and 0.03% amount by volume of concrete, as indicated in Table 10. Although all dosages tried are less than the 0.06% dosage recommended by Sika Kimia Sdn. Bhd., the Mix-50c-24MiF20 and Mix-50c-24MiF30 trial mixtures failed to produce filling ability test results in the J-Ring test because the slumps did not flow to at least 500 mm diameter, as shown in Table 11. After the slump cone is lifted, it is noted that the fresh mixtures flow is unable or very slow to flow fluidly by J-Ring's bars, as shown in Fig. 2. Only Mix-50c-24MiF10's slump, which had a flow of at least 500 mm diameter, was able to produce result in the J-Ring test. Trial mix Mix-50c-24MiF10, Mix-50c-24MiF20, and Mix-50c-24MiF30 have passing abilities by the J-Ring test that range from 25.5 to 36.0 mm, which are higher than a maximum 20.0 mm limit. The passing ability test results were also at least twice as high as the passing ability for Mix-50c-24MF10, which was 10.25 mm before to the addition of micro fibre. The V-Funnel test method may still produce test results for segregation resistance and filling ability testing for all

Table 10 Mix proportions of SCC using different dosages of micro fiber

Mix	Binder (binder kept at 630 kg/m^3)		Filler			w/b ratio	SP (%)	24 mm Macro fibre (%)	Micro fibre (%)
	OPC (ASTM Type I)	Fly ash Class F	Fine aggregate		Coarse aggregate				
			Quarry dust	River sand					
Mix-50c-24MF10	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.10	–
Mix-50c-24MiF10	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.10	0.01
Mix-50c-24MiF20	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.10	0.02
Mix-50c-24MiF30	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.10	0.03

Table 11 Properties of SCC with various dosages of Micro fibre

Mix	Mix-50c-24MF10	Mix-50c-24MiF10	Mix-50c-24MiF20	Mix-50c-24MiF30
w/b ratio, SP dosage, Macro fiber and Micro fiber				
w/b ratio	0.31	0.31	0.31	0.31
Superplasticizer (%)	0.6	0.6	0.6	0.6
24 mm Macro fibre (%)	0.1%	0.1	0.1	0.1
Micro fibre (%)	0.0	0.01	0.02	0.03
Fresh properties				
J-Ring test				
Filling ability				
T500 (3.5–6.0 s)	4.71	10.53	Nil	Nil
Daverage (600–750 mm)	745.0	515.0	455.0	440.0
Passing ability (≤ 20 mm)	10.25	25.5	32.0	36.0
V-Funnel test				
Filling ability, T0min (6–12 s)	10.47	12.37	12.79	13.52
Segregation resistance (0–3 s)	1.96	2.41	4.31	5.04
Mechanical property				
1-day Comp. st. (MPa)	14.39	20.76	22.53	23.01
28-day Comp. st. (MPa)	63.32	65.35	68.72	70.93

Fig. 2 Slump flow test with J-Ring tested on Mix-50c-24MiF30

trial mixtures that microfiber. At 0.01% micro fibre percent (Mix-50c-24MiF10), filling the ability decreased from 10.47 to 12.37 s, slightly higher than12.0-s, and segregation resistance decreased from 1.96 to 2.41 s, nevertheless dropping below the maximum 3.0-s limit.

When the dosage of microfiber was raised to 0.02%, and 0.03% (Mix-50c-24MiF20 and Mix-50c-24MiF30), respectively, the filling ability further decreased to 12.79 s and 13.52 s, while the segregation resistance values have also decreased to 4.31 s and 5.04 s, respectively. The actual SCC's quantity of segregation may be misled by the improved segregation resistance values. Instead, it has been discovered that the SCC's high viscosity caused the mixture stiffer and slow to flow after 5 min of resting in the V-funnel before the gate is opened to let the SCC flow out. With some adjusting of the other material proportions, it can be concluded that 0.01% of micro fibre is the most that can be incorporated in this research's SCC.A similar impact of micro fibre dosage on SCC fresh characteristics was discovered in Oztekin et al. [18]'s study, which focused on the utilisation of micro steel fibre.

As microfibers are small in size, similar others fine materials, adding microfiber to concrete can also increase the overall surface area of the particles, which will increase the concrete's need for water for improved flow in SCC [23]. A fresh mix's reduced fluidity has caused it more challenging for it to flow under gravity, although a high viscosity can help to decrease segregation. To obtain satisfactory flowability with little segregation, SCC's fluidity and viscosity must be balanced. The compressive strength of SCC, on the other hand, was found to have increased with a higher microfiber dosage. With the addition of 0.01%, 0.02%, and 0.03% of microfiber, the compressive strength of Mix-50c-24MF10 is increased by one day from 14.39 to 20.76 MPa, 22.53 MPa, and 23.01 MPa, respectively. With 0.01%, 0.02%, and 0.03% of micro fibre added, the 28-day compressive strength increased from 63.32 to 65.35 MPa, 68.72 MPa, and 70.93 MPa, respectively. Oztekin et al. [18] similarly reported a similar increase in SCC's compressive strength by increasing microfiber dosage. The significant improvement in compressive strength may be attributable to the role microfibers contribute in reducing early-age shrinkage cracks and producing SCC denser. As a result, the problem of failure to attain the required fresh characteristics is given priority. In order to regain sufficient flowability, the water/binder ratio or superplasticizer dosage in SCC mixes has to be increased. However, higher mixing of micro fibre dosage will need higher water content or superplasticizer dosage. Consequently, it can have a negative impact on the early strength of concrete. As a result, it is decided that the optimum dosage of microfiber to be added to SCC is 0.01%.

3.6 Determining superplasticizer dosage and water/binder ratio in SCC

Utilising the Blend-50c-24MF10 mix design as a basis mix for integrating microfiber, the microfiber For maintaining fibre reinforced SCC workable, a sufficient water/binder ratio and superplasticizer dosage are needed. As previously observed, 0.10% macro fibre dosage and 0.01% micro fibre dosage are optimum fibre dosages in SCC mix design. The Mix-50c-24MiF10 mix design is utilised as a basis for additional adjustments on water/binder ratio and superplasticizer dosage to enhance the SCC's fresh characteristics. As illustrated in Table 12, modifications to the water/binder ratio, superplasticizer dosage, or both can be investigated in small increments. Table 13 shown that increasing the water/binder ratio and superplasticizer dosage enhanced the fresh characteristics of SCC. When the water/binder ratio of trial mix Mix-50c-24MiF10 is raised from 0.31 to 0.32 as trial mix Mix-50c-V, the filling ability by J-Ring test is enhanced from 10.53 to 8.07 s, and the filling ability by V-Funnel test method is improved from 12.37 to 12.15 s. Nonetheless, both have failed to achieve each of the requirements ranges mentioned in Table 13. The slump flow diameter of Mix-50c-V has increased from 515.0 to 610.0 mm, falling within required range of (600.0–750.0) mm. It also has enhanced passing ability from (25.5 to 17.0) mm, which is less than the 20.0-mm maximum limitation. Segregation resistance, on the other hand, increased slightly from 2.41 to 2.29 s, which is still less the maximum 3.0 s.

Table 12 Mix proportions of SCC based on binder with adjustment of w/b ratio and SP dosage

Mix	Binder (binder kept at 630 kg/m^3)		Filler			w/b ratio	SP (%)	24 mm Macro fibre (%)	Micro fibre (%)
	OPC (ASTM Type I)	Fly ash Class F	Fine aggregate		Coarse aggregate				
			Quarry dust	River sand					
Mix-50c-24MiF10	0.50	0.50	1.00	0.80	0.63	0.31	0.60	0.10	0.01
Mix-50c-V	0.50	0.50	1.00	0.80	0.63	0.32	0.60	0.10	0.01
Mix-50c-W	0.50	0.50	1.00	0.80	0.63	0.31	0.7	0.10	0.01
Mix-50c-X	0.50	0.50	1.00	0.80	0.63	0.32	0.7	0.10	0.01
Mix-50c-Y	0.50	0.50	1.00	0.80	0.63	0.33	0.7	0.10	0.01
Mix-50c-Z	0.50	0.50	1.00	0.80	0.63	0.32	0.8	0.10	0.01

Table 13 Properties of SCC with final adjustment of w/b ratio and SP dosage

Adjusted mix	Mix-50c-24MiF10	Mix-50c-V	Mix-50c-W	Mix-50c-X	Mix-50c-Y	Mix-50c-Z
w/b ratio, SP dosage, Macro and Micro fiber dosages						
w/b ratio	0.31	0.32	0.31	0.32	0.33	0.32
SP dosage (%)	0.6	0.6	0.7	0.7	0.7	0.8
24 mm Macro fibre (%)	0.10	0.10	0.10	0.10	0.10	0.10
Micro fibre (%)	0.01	0.01	0.01	0.01	0.01	0.01
Fresh properties						
J-Ring test						
Filling ability						
T500 (3.5–6.0 s)	10.53	8.07	7.55	3.59	3.68	3.59
Daverage (600–750 mm)	515.0	610.0	655.0	725.0	710.0	705.0
Passing ability (≤ 20 mm)	25.5	17.0	13.0	10.5	15.0	18.75
V-Funnel test						
Filling ability, T0min (6–12 s)	12.37	12.15	11.67	8.44	9.73	10.19
Segregation resistance (0–3 s)	2.41	2.29	2.44	2.78	3.98	4.62
Mechanical properties						
1-day Comp. St. (MPa)	20.76	23.09	23.69	22.81	20.16	21.14
28-day Comp. St. (MPa)	65.35	63.24	64.52	62.89	62.40	62.01
28-day Tensile split St. (MPa)	–	–	–	4.83	–	–
28-day Flexural St. (MPa)	–	–	–	10.53	–	–
28-day Modulus of Elasticity (GPa)	–	–	–	28.76	–	–

However, the 28-Day compressive strength of Mix-50c-V slightly dropped from 65.35 to 63.24 MPa as a result of the increasing water content. Mix-50c-24MiF10's filling ability enhanced from 10.53 to 7.55 s when the superplasticizer dosage is raised from 0.6 to 0.7% as trial blend Mix-50c-W, which is 0.52 s higher than trial mix Mix-50c-V has still failed to satisfy the maximum 6.0-s limitations. The V-Funnel test method's filling ability has increased from 12.37 to 11.67 s, which is just under the maximum 12.0-s restriction. The J-Ring is increased the slump flow diameter from 515.0 to 655.0 mm, which is 45.0 mm wider than Mix-50c-V's and falls within the desired range of 600.0 to 750.0 mm. Its passing capacity has increased from 25.5 to 13.0 mm, which is better than Mix-50c-V's and 4.0 mm lower. While its segregation resistance declined slightly from 2.41 to 2.44 s, Mix-50c-W's 28-day compressive strength decreased slightly from 65.35 to 64.52 MPa, which is still 1.28 MPa greater than Mix-50c-V's. When the water/binder ratio and superplasticizer dosage of Mix-50c-24MiF10 are both increased from 0.31 to 0.32 and 0.6–0.7%, respectively, as Mix-50c-X. Its J-Ring test filling ability gradually increased from 10.53 to 3.59 s, which is close to the minimum 3.5 s. Its V-Funnel test filling ability increased from 12.37 to 8.44 s, which is within the range limit of 6.0 s to 12.0 s. Slump flow diameter by J-Ring test increased from 515.0 to 725.0 mm, which to the maximum limit of 750.0 mm. Its passing ability is enhanced from 25.5 to 10.5 mm, its segregation resistance is decreased from 2.41 to 2.78 s which to maximum 3.0-s limit. The compressive strength was noted to also decrease from 65.35 to 62.89 MPa at 28 days.

In contrast, a slightly increase in water/binder ratio of higher than 0.32 and superplasticizer dosage of more than 0.7% for Mix-50c-Y and Mix-50c-Z caused the fresh SCC blends to increasingly segregate as illustrated in Table 13, despite fluidity of SCC mixes is significantly improved. Blend -50c-Y with w/b ratio increased from 0.32 to 0.33 had its segregation resistance decrease in from Mix-50c-X's 2.78 s to 3.98 s which is more than the maximum 3.0-s. While the superplasticizer dosage in Mix-50c-Z increased from 0.7 to 0.8%, the segregation resistance decreased from 2.78 to 4.62 s, which is also more than the acceptable maximum limit. As the segregation in SCC deteriorated, coarse aggregates have been found to be left behind in steel bars of the J-ring apparatus, while separated SCC's mortar liquid was observed to flow away on its own. The passing ability of Mix-50c-Y was observed to decrease from 10.5 to 15.0 mm, whereas Mix-50c-Z's decreased from 10.5 to 18.0 mm. As a result, the fluidity and viscosity of SCC must be adjusted in order to avoid excessive segregation and provide optimum flowability. This balance is found in Mix-50c-X, which has obtained adequate fresh characteristics within the specifications with a water/binder ratio of 0.32 and a superplasticizer dosage of 0.7%, as shown in Fig. 3. As a result, Mix-50c-X with the optimal water/binder ratio, superplasticizer dosage, macro fibre dosage, and micro fibre dosage has been determined as the optimum mix design of SCC in this study.

Fig. 3 Slump flow test with J-Ring on Mix-50c-X

The study observed that an increasing in micro fibre percentage has gradually reduced SCC mixes flexural strength. As indicated by Babaie et al. [5], Despite using a high fibre dosage, macro (or polymer) fibre performed less than steel macro fibre at improving SCC's flexural strength, with minor increase in strength. The decrease in strength in this study may therefore have negated the improvement in flexural strength caused by the use of macro synthetic fibre. It is to be found that SCC mixes microstructure testing is not a part of this study. Therefore, it may be recommended for future research to understand the factors effecting enhancement on SCC' mixes mechanical properties. Although integrating macro and micro fibre improved only the compressive strength of SCC, its incorporation of macro and micro fibre is known to have advantages such as resisting micro-cracking during the plastic state and controlling concrete parts cracking before overall failure of a structural. This allows precast SCC constructions to perform structurally higher than produced utilizing plain SCC constructions. In a nutshell, SCC's Mix-50c-X blend fulfilled the required specifications.

4 Conclusion

In conclusion, each ingredient utilised in the SCC mix design has the potential to influence SCC performance in a variety of ways, including viscosity, fluidity, and blocking tendency. A balance in SCC fluidity and viscosity is very important to maintain SCC flowing fluidly with the least amount of segregation. Therefore, the issue of failure to achieve the required fresh properties deserves high priority. Superplasticizer dosage or the water/binder ratio in mixtures of SCC has to be raised in order to regain adequate flowability. While reducing blocking tendency is necessary for allowing SCC to pass through gaps in steel reinforcement or small gaps especially in moulds, obtaining 1-day compression strength of at least 10.0 MPa is required to enable test specimens to be demoulded in 1 day after casting. In order fulfil these requirements, modifications have been implemented to the water/binder ratio, superplasticizer dosage, the ratio of fine to coarse aggregate, and the determination of the optimal fly ash replacement for cement, tiny macro fibre dosage, and micro fibre dosage. As a result, Mix-50c-X is a satisfactory mix design for hybrid fibre reinforcing self-compacting concrete. The Mix-50c-X's proportion of mix includes 50% substituted cement by fly ash (by weight of binder), 630.0 kg/m^3 of binder, 2.85 of the ratio of fine to coarse aggregate, 1538.0 kg/m^3 of total aggregate, 55.0% of the fine aggregate substitution by quarry dust, 0.32 of w/b, By 0.70% of the superplasticizer dosage, 0.10% of the concrete volume for the 24 mm macrofiber, and 0.01% of the concrete volume for the microfiber.

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Data availability All data available in this paper.

Declarations

Competing interests The authors declare no conflict of interest for this study.

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