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Original research article

Effects of Polysaccharide-Based Viscosity-Modifying Agent on Properties of Self-Compacting Concrete

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ABSTRACT

To address the high cost of self-compacting concrete (SCC) in Thailand, this research examines the use of viscosity-modifying agents (VMAs) to enhance sustainability and promote cost effectiveness and carbon dioxide (CO_2) reduction. Encouraging the study of polysaccharide-based viscosity-modifying agents (PVMAs), particularly locally available starch, this research investigated various SCC mixtures. The analysis included properties such as slump flow, T50cm time, V-Funnel time, L-box filling ability, bleeding, setting times, and compressive strength. The concrete mixtures were made with water-to-binder ratios (w/b) of 0.28, 0.32, and 0.37. The cement/fly ash ratio was kept constant at 0.50 for all concrete mixtures. The results revealed that the addition of starch to the concrete decreased slump flow and L-Box filling ability while it increased T50cm and V-funnel times. Moreover, a delay in strength development at early ages was also found, but no effect was seen at later ages. Additionally, the binder content was reduced from 580 kg/m³ to 500 kg/m³, resulting in a cost reduction from 4.90% to 5.64% and CO_2 relative emission-reduction of 6.15% to 12.30%, marking a decrease of 5.64% for cost and 12.30% for CO_2 emission, while maintaining the properties of SCC. In conclusion, starch as a locally-sourced polysaccharide-based VMA offers potential benefits for manufacturing SCC with desirable properties, aligning with SCC criteria and showing promise for the construction industry.

Keywords: Binder content and CO_2 reduction; PVMAs; SCC; Starch; SCC Properties

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1. Introduction

SCC is a high-performance concrete which is well-known for its cohesiveness, greater workability, and ability to flow effortlessly into restricted spaces, making it ideal for complicated construction projects such as heavily reinforced buildings [1–4]. Isik and Ozkul [5] reported that the key properties of SCC are its resistance to segregation and excellent deformability and several techniques have been employed to obtain these properties. The first technique is to utilize a high content of fine materials to improve the deformability and stability of SCC. The second technique proposed by Shindoh and Matsuoka [6], is to utilize VMA in SCC with a low w/b ratio to improve the stability of concrete and the third technique is a combination of fine materials and VMA. However, the amount of cementitious materials used in the third technique is minimal in comparison to the previous two techniques [7–10]. According to Ouchi and Attachairywuth [11], the fourth technique for obtaining SCC is to introduce highly stable air bubbles to design the SCC mix proportions. However, the utilization of VMA in SCC is the most practical at present so it is emphasized in this study.

VMAs are chemical additives used to enhance the viscosity and stability of fluid systems, improving their flow properties. In concrete, VMAs are added to improve mix stability, particularly in SCC. They help reduce segregation and bleeding by increasing the viscosity, ensuring a cohesive and uniform mix during placement. This allows for better flowability without compromising the structural integrity of the concrete. VMAs can be obtained from natural polymers such as cellulose or starch, synthetic polymers such as polyethylene oxides, or biopolymers such as alginates derived from seaweed. These materials are processed to create agents that control viscosity in concrete [7, 9, 12].

Using VMAs in SCC is essential for ensuring stability and cohesion in concrete mixtures. While by-product materials such as limestone powder, silica fume, and fly ash have been utilized to improve SCC properties, their inconsistent composition and limited availability in the concrete industry make VMAs a preferred option for robust mix designs [13]. To meet the growing demand for SCC in Asian and European markets, cost-effective solutions are essential as rising VMA prices and high binder volumes are making current SCC expensive [12].

Polysaccharides viscosity modifying agents (PVMAs) can be obtained from plants (e.g., starch, cellulose), algae (e.g., alginates, carrageenan), animals (e.g., glycogen, chitin), and microorganisms (e.g., xanthan gum) [5, 12] are ideal for SCC as they form a non-free-draining molecule that flows uniformly with the solid core, enhancing stability and minimizing bleeding and segregation after casting, as well as having a low price. This makes them a valuable choice for improving SCC properties in construction [5]. PVMAs have been shown in several studies to have a positive effect on fresh and hardened properties of concrete. I. E. Isik and M. H. Ozkul (2014) conducted a study which found that the incorporation of PVMAs into concrete resulted in a notable improvement in fresh properties of concrete. They utilized three distinct types of PVMA and concluded that starch was the most efficient at mitigating slump flow, T50cm and V-Funnel times, and bleeding of concrete mixtures [5]. In another study by S. Rols, J. Ambroise, and J. Péra (1998), the use of precipitated silica, welan gum, and starch as viscosity agents in self-leveling concrete was investigated. The study concluded that starch could be a good alternative compared to welan gum as a viscosity agent, as its use produced concrete with excellent resilience to segregation and low bleeding [9]. U. Neupane (2016) also used starch from 1.7%

to 2.5% and obtained good results in terms of slump flow, bleeding and compressive strength of concrete mixtures [14]. Generally, the addition of PVMA in concrete has been found to have a positive effect on fresh and hardened properties of concrete. However, the effectiveness of VMA can depend on several factors including the type of VMA used, the dosage, and the concrete's mix design [7]. Therefore, this study addresses the limited adoption of SCC in Thailand, which is primarily due to high costs related to its high binder content, as well as sustainability issues, especially elevated carbon dioxide emissions. The research aims to produce SCC with reduced binder content to alleviate cost and environmental concerns, thereby promoting wider acceptance of SCC in construction practices despite the prevailing preference for traditional concrete.

2. Experimental Program

2.1 Materials

The binders used for SCC were fly ash and Type 1 ordinary Portland cement having blaine fineness of 2506 cm^2/g and 3054 cm^2/g and specific gravity of 2.57 and 3.15, respectively. The cement was an ordinary Portland cement complying with ASTM C150 [15] while the fly ash was obtained from Mae Moh Power Plant in Lampang province and was utilized to replace cement. The ASTM C618 [16] standard classified the fly ash as Class C and TIS-2135 [17] classified it as Class 2b. The chemical compositions of the binders measured by XRF are listed in Table 1. The fine aggregate was natural river sand having specific gravity of 2.60 and water absorption of 1.10%, while the coarse aggregate was crushed limestone with a maximum size of 20 mm, specific gravity of 2.76, and water absorption of 0.40%. Both sand and coarse aggregates met the ASTM C33 [18] standards. According to the ASTM C494 [19] standard, the water reducer employed in the current study was a Type F naphthalene-based superplasticizer known as Mighty MX-T having a specific gravity of 1.15 and liquid content of 62.62%. A polysaccharide-based starch was collected from Siam Modified Starch (SMS). The starch was in white powder form and was labeled as EXCELCON C250.

Table 1. Chemical compositions of cement and fly ash.

Chemical compositions (%)	CaO	SiO_2	SO_3	MgO	K_2O	Fe_2O_3	Al_2O_3	Na_2O	LOI
Cement	65.34	18.98	2.65	1.15	0.21	3.16	5.33	0.16	2.54
Fly ash	18.74	36.18	3.74	2.69	2.29	13.89	20.21	1.14	0.25

2.2 Mix proportions and tested properties for preparing the SCC

The concrete mixtures were manufactured with w/b ratios of 0.28, 0.32, and 0.37. All mixtures contained 50% cement and 50% fly ash. In this study, a 50:50 ratio of fly ash to cement was employed, reflecting the common SCC mix proportions observed in the Thai market. The starch was in powder form. The weights of starch and SP were taken as a percentage of the binders. The weights of sand and limestone were kept constant for all mixtures. Table 2 represents the mix proportions of all the tested mixtures.

An inverted slump cone (Abram's cone) was used to assess concrete mixture's slump flow without obstruction. At the same time T50cm time was also measured with a stop watch starting when the cone was lifted.

V-Funnel time was also measured by using a stop watch. Passing ability was measured through L-Box.

The EFNARC (2005) guidelines were adopted to measure these properties [20]. Moreover, the compressive strength of cylindrical concrete specimens was tested using the compression testing machine according to ASTM C39 [21] at the ages of 3, 7, 28 and 91 days. The study employed the ASTM C403 [22] standard penetration test to measure setting times. Furthermore, SCC bleeding behavior was assessed by placing fresh samples in a cylindrical container using the ASTM C243 tamping procedure [23]. Bleeding, calculated as a percentage of unit water content, was measured every 10 minutes for the first 40 minutes and then at 30-minute intervals until cessation, using Eq. (2.1) [14].

$$b(t) = w(t) / \mathrm{WAH}. \tag{2.1}$$

Table 2. Mix proportions for preparing SCC mixture.

Mix ID	Cement (kg/m^3)	Fly ash (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	SP/b (%)	Starch/b (%)
Mix-0.28-1	290	290	850	880	160	0.20	0
Mix-0.28-2	290	290	850	880	160	0.40	0
Mix-0.28-3	290	290	850	880	160	0.60	0
Mix-0.28-4	290	290	850	880	160	0.70	0
Mix-0.28-5	290	290	850	880	160	0.75	0
Mix-0.28-6	290	290	850	880	160	0.75	0.01
Mix-0.28-7	290	290	850	880	160	0.75	0.03
Mix-0.28-8	290	290	850	880	160	0.75	0.05
Mix-0.28-9	290	290	850	880	160	0.75	0.07
Mix-0.28-10	290	290	850	880	160	0.75	0.08
Mix-0.28-11	290	290	850	880	160	1.0	0.07
Mix-0.28-12	290	290	850	880	160	1.15	0.07
Mix-0.28-13	290	290	850	880	160	1.30	0.07
Mix-0.32-1	270	270	850	880	174	0.9	0.07
Mix-0.32-2	270	270	850	880	174	1.0	0.07
Mix-0.32-3	270	270	850	880	174	1.10	0.07
Mix-0.32-4	270	270	850	880	174	1.15	0.07
Mix-0.37-1	250	250	850	880	188	0.60	0.07
Mix-0.37-2	250	250	850	880	188	0.75	0.07
Mix-0.37-3	250	250	850	880	188	0.85	0.07
Mix-0.37-4	250	250	850	880	188	0.90	0.07

Note: SP/b: SP is superplasticizer and b is binder

Where, $w(t)$ represents the weight of bleeding water (kg) at time t (minutes), W represents the unit water content of the mixtures (kg/m^3), A represents the cross-sectional area of the sample (m^2), and H represents the height of the sample (m).

Furthermore, the carbon dioxide (CO_2) emission was calculated using Eq. (2.2) [24, 25].

$$\begin{aligned} EF_{\mathrm{mix}} = (W_{\mathrm{C}} \times EF_{\mathrm{C}}) + (W_{\mathrm{G}} \times EF_{\mathrm{G}}) \\ + (W_{\mathrm{S}} \times EF_{\mathrm{S}}) + (W_{\mathrm{FA}} \times EF_{\mathrm{FA}}) \\ + EF_{\mathrm{plant}}, \end{aligned} \tag{2.2}$$

where EF_{mix} is the CO_2 emission of a produced concrete mixture ($t\text{-}CO_{2eq}$), W_C is the weight of cement per $1m^3$ of concrete (kg), W_G is the weight of coarse aggregate per $1m^3$ of concrete (kg), W_S is the weight of fine aggregate per $1m^3$ of concrete (kg), W_{FA} is the weight of fly ash per $1m^3$ of concrete (kg), EF_C is the emission factor of cement ($kg\text{-}CO_2$/t-cement), EF_G is the emission factor of coarse aggregate ($kg\text{-}CO_2$/t-coarse-aggregate), EF_S is the emission factor of fine aggregate ($kg\text{-}CO_2$/t-fine aggregate), EF_{FA} is the emission factor of fly ash ($kg\text{-}CO_2$/t- fly ash), and EF_{plant} is the emission factor for manufacturing a cubic meter of concrete by an industrial batching-mixingplant ($kg\text{-}CO_2/m^3$ concrete) [24].

3. Results and Discussions

3.1 Slump flow test results

The aim was to achieve SCC mixtures with a targeted slump flow of 650±30 mm for all the tested mixtures. The study extensively examined the slump flow of the concrete mixtures, with and without starch addition, focusing on a concrete mix with a w/b ratio of 0.28, which consisted of three phases. In the initial phase, concrete mixtures were produced using SP only to evaluate its effect on slump flow. Results demonstrated that the added SP, ranging from 0.20% to 0.75% (Mix-0.28-1 to Mix-0.28-5), increased [26] slump flow from 415 to 680 mm, as shown in Fig. 1. In the second phase (Mix-0.28-6 to Mix-0.28-10), the study evaluated the impact of starch on concrete mixtures by maintaining the same proportions as Mix-0.28-5. Starch was added at dosages ranging from 0.01% to 0.08%. Results in Fig. 1 show that the added starch within the 0.01% to 0.07% range decreased slump flow from 680 to 410 mm until it was difficult to determine the slump flow for the Mix-0.28-10 (starch content = 0.08%). The decrease in slump flow can be attributed to an increase in the viscosity of the paste. However, when the starch content exceeded 0.07%, such as at 0.08%, very high SP dosage was expected, resulting in an overdose and higher concrete costs. So, it was important to strike a balance between starch and SP to avoid unnecessary expenses while ensuring concrete quality.

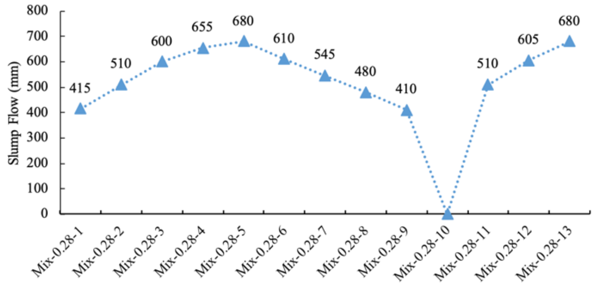

Fig. 1. Slump flow test results of concrete mixture for w/b ratio 0.28.

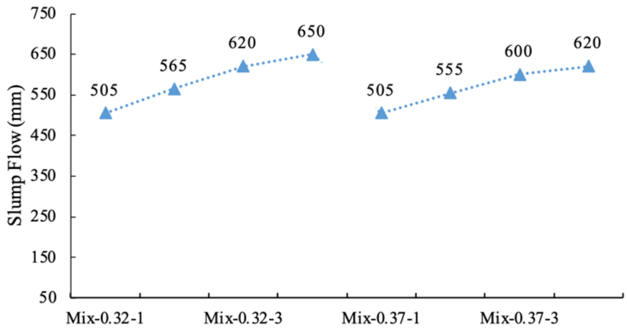

Fig. 2. Slump flow test results of the concrete mixtures for w/b ratios 0.32 and 0.37.

Moreover, starch dosages below 0.07% demonstrated unsatisfactory segregation resistance. Thus, a 0.07% starch dosage was selected for further study. In the final phase, the target slump flow of 650±30 mm was restored by using the mix proportion of Mix-0.28-9 (starch content = 0.07%) and increasing SP dosage from 0.[illegible]5% to 1.30% (Mix-0.28-11 to Mix-0.28-13). The combination of 1.30% SP and 0.07% starch (Mix-0.28-13) successfully achieved the desired slump flow, as shown in Fig. 1. Similarly, the w/b ratio was increased from 0.28 to 0.32, and with a fixed starch dosage of 0.07% and varying SP dosages ranging from 0.9% to 1.15%, the mixtures Mix-0.32-1 to Mix-0.32-4 were tested to achieve the target slump flow of 650±30 mm for w/b ratios of 0.32. While the main objective was to reduce the binder content, the w/b ratio was further increased from 0.32 to 0.37 with the aim of achieving the target slump flow of 650±30 mm. To achieve this purpose, a fixed dosage of starch of 0.07% was used, and only SP was added in the range of 0.60% to 0.90% for Mix-0.37-1 to Mix-0.37-4. Results showed that adjusting SP dosage with 0.07% starch for w/b ratios of 0.32 and 0.37 approached the target of 650±30 mm, as shown in Fig. 2. According to EFNARC (2005), slump flow values ranging from 660 to 700 mm fall under the SF2 classification, which is usually ideal for normal applications such as columns and walls. While slump flow between 550 and 650 mm falls under SF1, which is used for unreinforced or slightly reinforced concrete, e.g., housing slabs [20].

3.2 T50cm time, V-Funnel time, and L-Box test results

In addition to slump flow, T50cm time was recorded as an indicator of concrete viscosity. T50cm time represents the duration for fresh concrete to spread to a diameter of 500 mm, with higher values indicating higher viscosity [19, 27]. The results of the T50cm time for concrete mixes with SP only and starch are shown in Fig. 3. Results revealed that with the addition of SP in the range of 0.4%–0.75% for the mixtures from Mix-0.28-2 to Mix-0.28-5, the T50cm times decreased. While the added starch in the range of 0.01% to 0.07% for the mixtures Mix-0.28-6 and Mix-0.28-9 increased the T50 cm time, indicating higher viscosity, as shown in Fig. 3. According to EFNARC (2005) [20], a T50cm time higher than 2 seconds can be classified as VS2, whereas VS1 is defined as a T50cm time shorter than or equal to 2 seconds. Similarly, the results for the V-Funnel test with SP only and with starch dosage are shown in Fig. 3, where SP in the range of 0.4% to 0.75% for the mixtures from Mix-0.28-2 to Mix-0.28-5 decreased the V-Funnel time, while the added starch in the range of 0.01% to 0.07% for the mixtures from Mix-0.28-6 to Mix-0.28-9 prolonged it. According to EFNARC (2005) [20], V-Funnel times higher than 8 seconds can be classified as VF2, whereas VF1 is defined as a V-Funnel time shorter than 8 seconds. The L-Box filling ability, according to EFNARC (2005) [20], should range between 0.8 and 1.0. Results of L-Box for the concrete mixtures with SP only for the mixtures from Mix-0.28-2 to Mix-0.28-5 and with starch for the mixtures from Mix-0.28-6 to Mix-0.28-9 are shown in Fig. 3, where SP increased the passing ratio but starch addition decreased it when SP dosage was kept constant.

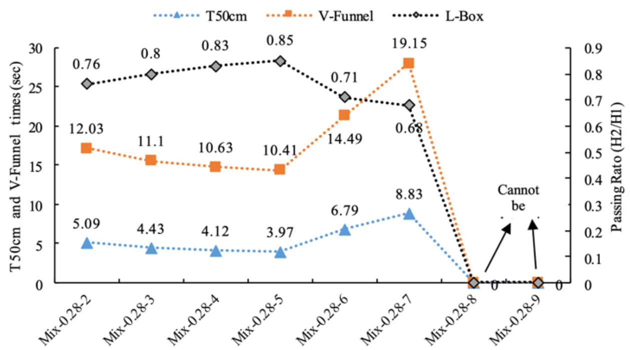

Fig. 3. T50cm time, V-Funnel time, and L-Box test results of the concrete mixtures.

3.3 Setting times

Setting times of concrete mixtures with and without the incorporation of starch are displayed in Fig. 4. The findings reveal that the initial and final setting times of the SCC mixture Mix-0.28-5 without starch were 198 and 255 minutes, respectively. The addition of 0.05% starch to the SCC mixture (Mix-0.28-8) raised the initial and final setting times to 300 and 380 minutes, respectively. Further raising the starch content to 0.07% for the mixture Mix-0.28-9 resulted in 310 and 390-minute initial and final setting times, respectively. In the current study, the incorporation of starch increased the setting times of the concrete mixtures. According to Neupane (2016) and Khayat (2012), when VMA is introduced into the concrete mixture, its polymer chain can adsorb onto cement grains. This interaction affects the hydration rate of the cement particles and consequently delays the setting times of the concrete [23, 28]. Therefore, the delaying influence on setting time in this study is attributed to the presence of starch.

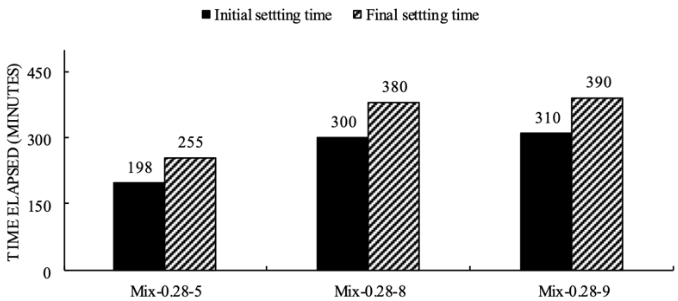

Fig. 4. Setting time test results of the SCC mixtures with and without starch.

3.4 Bleeding

Fig. 5 depicts the impact of SP and starch on the bleeding behavior of the SCC mixture Mix 0.28-13. It can be concluded that the bleeding percentage for the SCC mixture Mix-0.28-13 without starch was 3.12%. However, when 0.07% starch was added to the SCC mixture Mix-0.28-13, the bleeding percentage at 180 minutes of the mixture was significantly reduced to 0.271%. The finding suggests that the incorporation of starch in concrete mixtures has the ability to reduce bleeding. In a study by Neupane et al., starch can absorb free water, leading to a rise in the viscosity of the mortar or paste. This increase in viscosity results in a reduction in the probability of bleeding in SCC mixtures [14]. This study further emphasizes that bleeding behavior is influenced by the dosage of SP and VMA combinations. To achieve excellent bleeding resistance, it is necessary to carefully choose the dosage of the VMA-SP combination in VMA-type SCC [9, 29].

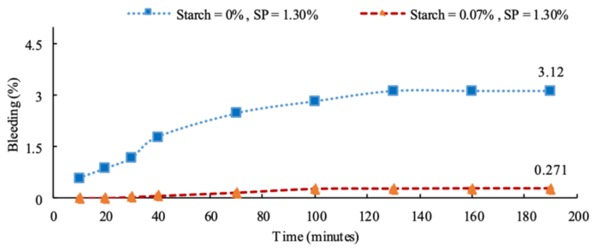

Fig. 5. Bleeding test results of the SCC mixtures with and without starch.

3.5 Compressive strength

Fig. 6 shows the compressive strength test results of the concrete mixtures with and without starch. The concrete mixtures from Mix-0.28-1 to Mix-0.28-5 were prepared without starch, while the mixtures from Mix-0.28-6 to Mix-0.28-13 were prepared with the addition of starch. The compressive strength of the concrete mixtures from Mix-0.28-1 to Mix-0.28-5 without starch is higher than concrete mixtures Mix-0.28-6 to Mix-0.28-13 with starch at early ages (3 and 7 days), but the starch has little influence on compressive strength at the age of 28 days and the strength is almost the same at later ages. For comparison, the compressive strengths of the concrete mixture (Mix-0.28-5) with SP only at the ages of 3, 7, 28, and 91 were 44 MPa, 50 MPa, 66 MPa, and 75 MPa, respectively. However, when the starch was added from 0.01 to 0.07% (Mix-0.28-6 to Mix-0.28-13), some changes were noticed, and the compressive strength development of the concrete mixtures was lower compared to concrete mixtures without starch. For comparison, the compressive strengths of the Mix-0.28-9 with 0.07% starch at the ages of 3, 7, 28, and 91 were 38 MPa, 44 MPa, 62 MPa, and 75 MPa, respectively. Though holding the same compressive strength at 91 days, the compressive strength at 3, 7, and 28 days is lower than those without starch when compared at the same ages. It means that the incorporation of starch delayed the early compressive strength, i.e., at 3 and 7 days. However, little influence was noticed at the age of 28 days, and almost no effect was noticed at the age of 91 days. The addition of starch to the SCC mixes alters the hydration process of the cementitious materials [12, 13, 28, 30] resulting in a delay in the development of early-age compressive strength. This delay was noticed at 3 and 7 days after casting. However, as the curing period progresses, the effects of starch on compressive strength become less significant.

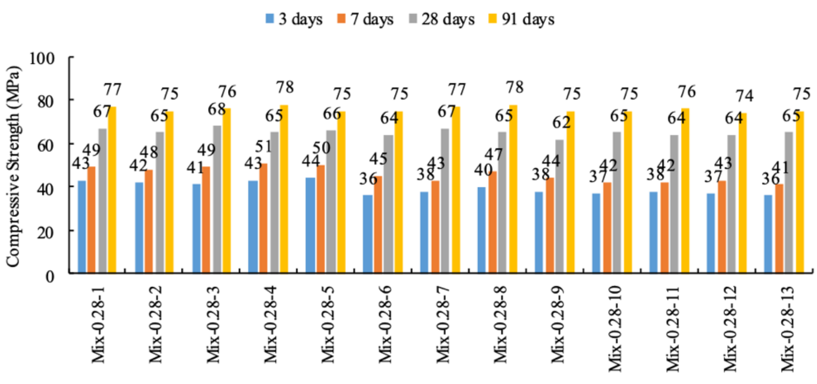

Fig. 6. Compressive strength test results with and without starch.

4. Potential of Reducing Binder Content

In Thailand, the cost of SCC has been identified as a significant drawback, particularly when powder-based SCC requiring a high binder content is predominantly used. To address the cost issue, this study explored the possibility of reducing the binder content while still maintaining the desired properties of SCC. Three distinct w/b ratios of 0.28, 0.32, and 0.37 were tested. The mixtures were designed to achieve a target slump flow of 650±30 mm. Various mix proportions were evaluated to identify the best amount of starch that could be utilized at all three w/b ratios. After conducting multiple trial mixes with and without starch at a w/b ratio of 0.28, it was determined that a starch dosage of 0.07% yielded the desired results for this study. This dosage resulted in a target slump flow of 650±30 mm, meeting all the requirements for SCC in fresh state. As the primary objective of the study was to decrease binder content, the w/b ratio was subsequently increased from 0.28 to 0.32, and 0.37 (Mix-0.32-4 and Mix-0.37-4), respectively. Even with this increase in w/b ratio, the 0.07% starch dosage continued to produce SCC mixtures meeting the target slump flow requirement and other SCC properties in fresh state. The 0.07% starch dosage consistently meets SCC performance standards across various w/b ratios, supporting the study's objectives of reducing binder content. Therefore, incorporating this 0.07% starch dose reduced binder content from 580 kg/m^3 to 500 kg/m^3 without compromising SCC properties, as illustrated in Table 3. This also suggests that larger cost savings can be accomplished even by further reducing the binder level without affecting SCC performance.

Table 3. Binder reduction in SCC by using 0.07% starch dosage.

Mix ID	w/b	SP/b (%)	Starch/b (%)	Binder content (kg./m^3)
Mix-0.28-13	0.28	1.30	0.07	580
Mix-0.32-4	0.32	1.15	0.07	540
Mix-0.37-4	0.37	0.90	0.07	500

5. Cost Comparison

In this study, the unit prices of materials used for calculating the price/m^3 of SCC consist of 660 Baht/m^3 for limestone, 560 Baht/m^3 for sand, 1400 Baht/ton for fly ash, 2500 Baht/ton for cement, 25 Baht/m^3 for water, 30 Baht/liter for SP, and 95 Baht/kg for starch [31]. The cost comparison per cubic meter for different mixtures, particularly focusing on the incorporation of SP and starch, is presented in Fig. 7. At a w/b ratio of 0.28 and without starch, the price for Mix-0.28-5 is 2319 Baht/m^3. However, incorporating starch in Mix-0.28-13 resulted in a slight price increase from 2319 Baht/m^3 to 2454 Baht/m^3 with a percentage increase of 5.79%. Notably, raising the w/b ratio from 0.28 to 0.32 and 0.37 led to significant cost reductions, with expenses dropping to 2333 Baht/m^3 and 2202 Baht/m^3 and with percentage reductions of 4.90% and 5.64%, respectively. The addition of 0.07% starch demonstrated promise for cost-effective SCC production while meeting strength requirements since SCC with starch addition surpassed 40 MPa compressive strength at 28 days, exceeding the strength of about 80% of conventionally used ready-mixed concrete in Thailand [32]. This highlights substantial potential for cost reduction while maintaining performance standards in SCC production in Thailand. Comparing costs, traditional SCC with SP additives may be more expensive due to material costs, while incorporating starch offers a more economical alternative while meeting necessary strength requirements, particularly evident at certain w/b ratios. This cost difference suggests that incorporating starch can offer a cost-effective solution for producing SCC while meeting the required strength of the majority of ready-mixed concrete consumed in Thailand, which is lower than 40 MPa.

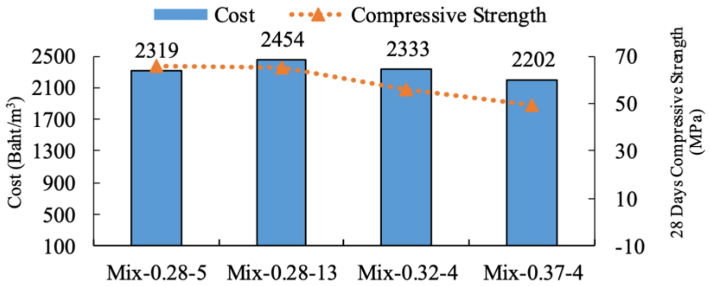

Fig. 7. Cost comparison of SCC mixtures with and without starch.

6. Carbon Dioxide (CO_2) Reduction

Decreasing the binder concentration by using starch helps to reduce CO_2 emissions from SCC mixes. The reduction in environmental effect is consistent with sustainability objectives, making the SCC mixture with starch a more ecologically friendly alternative. In this research, the mixtures shown in table 3 and Fig. 7 were used as the reference mixture for the evaluations of CO_2 emission and cost-effectiveness of the tested concrete mix proportions while Table 4 shows the CO_2 emissions in obtaining a cubic meter of a concrete mixture. They include materials like cement, coarse aggregate, fine aggregate, and fly ash, and concrete production. Hence, to compute the CO_2 emissions of the selected mix proportions in this research, the CO_2 emission data of the concrete's raw materials were collected from literature review. From 2001 to 2014, the Thailand Greenhouse Gas Management Organization (Public Organization) reported [24, 33, 34] that the average value of CO_2 emission is about 0.7935 t-CO_2/tonne for cement. The CO_2 emission per tonne of sand is 0.0046 t-CO_2/tonne. The CO_2 emission per tonne of coarse aggregate is 0.0290 t-CO_2/tonne. The emission factor of fly ash production is estimated to be about 0.0196 t-CO_2/tonne. The report shows that the CO_2 emission for manufacturing 1m^3 of ready-mixed concrete is about 0.0012 t-CO_2/m^3 [24, 25]. Table 4 shows the cost-effectiveness and mitigation of CO_2 of each mix proportion. For cost-effectiveness, the results indicate that Mix-0.37-4 has the lowest cost, which is 5.64% cheaper than Mix-0.32-4. The next lower cost is of Mix-0.32-4 at 4.90% cheaper than Mix-0.28-13, While for mitigation of CO_2, Mix-0.37-4 shows the highest performance at 87.70% of Mix-0.28-13, which is followed by Mix-0.32-4 at 93.85% of the Mix-0.28-13 mixture.

Table 4. Cost-effectiveness and mitigation of carbon dioxide emission of each mix proportion

Mix ID	Cost (Baht/m^3)	Relative cost (%)	CO_2 emission (t-CO_{2eq}/m^3)	Relative Emission (%)
Mix-0.28-13	2454	100	0.264498	100
Mix-0.32-4	2333	95.06	0.248236	93.85
Mix-0.37-4	2202	89.73	0.231974	87.70

7. Conclusions and Recommendations

The study's findings led to the following conclusions:

1) The addition of starch in SCC decreased slump flow and L-Box filling ability while increasing T50cm and V-funnel times.
2) The starch used in this research reduced bleeding and delayed the setting times of concrete mixtures.
3) The incorporation of starch in SCC delays early-age compressive strength but has no effect on later-age compressive strength.

4) The price of every SCC mixture containing starch is lower than that of the conventional SCC mixture without starch, while satisfying the strength requirement of 80% of the concrete consumed in Thailand.
5) In terms of CO_2 emission, Mix-0.37-4 shows the highest performance at 87.70% of the Mix-0.28-13, which is followed by Mix-0.32-4 at 93.85% of the Mix-0.28-13 mixture.
6) It is revealed that with 0.07% starch dosage, it is possible to lower the binder content of SCC while its properties meet SCC specifications in terms of slump flow, T50cm time, V-Funnel time, and L-Box passing ability.

Future studies could investigate the long-term performance of SCC with local starch as a VMA, alongside exploring other local VMAs. Evaluating the sustainability of locally sourced VMAs in SCC would offer insights into their environmental impacts.

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