Development of an Anti-washout Underwater Concrete for an Undersea Concrete Structure Repair

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Abstract

This paper aims to develop an anti-washout underwater concrete (here-in-after called underwater concrete) that can be cast in water without washout of powder particles by water. The underwater concrete was developed following self-compacting concrete (SCC) method. For preliminary study, the underwater concrete was investigated from the anti-washout ability of cement-only mortars and cement mortars with fly ash by visual method with sand to mortar ratios (S/M) of 0.3 to 0.35, water to binder ratios (w/b) of 0.3 to 0.4. For viscosity modifying agent (VMA), this study used 2 components of extra high-performance thickeners (VMA) which were Mighty VT100A&B as VMA component 1 and Mighty VT200 as VMA component 2 with dosages of 4 to 9% and 2 to 5%, respectively and a superplasticizer (PC based) with the dosages of 1.5 to 2%. The mortars achieving anti-washout ability were used to design concrete mixes with the same sand to mortar ratios (S/M) and water to binder ratios (w/b) but the amounts of both VMAs and superplasticizer (SP) were increased (Mighty VT100A&B with a dosage of 10 %, VT200 with a dosage of 7 % and SP with dosages of 2 to 2.5 %) in order to achieve anti-washout ability and workability (slump flow of 650 to 750 mm, V-funnel time of 60 to 80 sec) and to achieve static segregation resistance before setting time (22 - 24 hrs.) and L-box tested with water filled in the box (passing ability under water). This underwater concrete was developed for a repair project of the port authority of Thailand at Samut Prakan province where marine environment conditions such as chloride resistance, sulfate resistance and non-shrink ability must be considered, and these were achieved by applying 10 % of fly ash and 30 kg/m^3 of expansive agent in the concrete. As mixing process of the concrete caused entrapped air of about 8-12 %, a de-air admixture was used to reduce the entrapped air to prevent viscosity loss and settlement of the concrete due to the high content of entrapped air.

Keywords: Underwater concrete, Self-compacting concrete, Viscosity modifying agent (VMA), Anti-washout

1. Introduction

Underwater concrete is a challenge for engineers both during mix design, construction and supervision, due to the fact that many cautions must be taken for the success of the casting process. The most important precaution is to prevent the fresh concrete during casting process from wash-out of binder particles and segregation under water since the start until the completion of the concrete pouring as well as hardening of the concrete. Concrete can be placed underwater successfully by implementing a good mix design and a suitable method for placing. There are wide ranges of methods for underwater concrete placing which include traditional methods such as bagwork method, skips method, tremie method and pumping method. There are also some new and uncommon methods such as grouted aggregate method which is known as the two-stage concrete method as described below [1].

Bagwork was probably one of the oldest and simplest techniques of placing concrete underwater. A common application of bagwork was the construction of retaining walls to act as formworks for mass concrete pouring. The type of bags was normally made from an open-weave material such as hessian. The half-filled bag with plastic concrete is sealed and then taken under water and placed by a diver. Partial filling allowed concrete to be molded into shape and given concrete good contact areas with adjacent bags. Grout from the mix seeped through the open textured material allowing bond to be established with adjacent bags. For additional stability the bags can be spiked together with small-diameter reinforcing bars.

Skips are more suitable for thin pours, although it is possible to bury the mouth of the skip in previously poured concrete to produce deeper pours. The skip should be fully charged in the dry and covered with a pair of flexible and overlapping covers. These prevent washout during lowering and also during discharge because they stay in contact with the top surface of the concrete as it flows out of the bottom.

Tremie is one of the traditional techniques used for the placing of concrete underwater. The tremie consists of a steel pipe mounted vertically in the water. To the top of the pipe is a fixed hopper, to receive the fresh concrete. It also acts as a reservoir for the supply of fresh concrete. Tremies are best used for thick pours of any area. For large area pours, multiple tremies can be used, spaced at about 4–6 m apart, depending on the flatness required for the top level.

For the pumping method, the principal advantage is that concrete can be delivered to the pour site quickly and continuously. Using static pipe runs, concrete can be pumped over distances of up to 1000 m and the hydraulic boom on most mobile units permits great versatility in placing. The placement of concrete can be carried out using either a tremie or direct pumping to the underwater site.

The two-stage concrete method, also known as preplaced aggregate method, is suitable for underwater work. The technique is particularly applicable in conditions where there is limited access to the work, in situations where high water velocities exist or where the site is subjected to wave action, which would normally prohibit the use of conventional placement methods. The method consists of filling a form with aggregate and then injecting a grout to fill the voids. The study about this method and the advantages of the two-stage concrete are given in ref [1].

The above-mentioned methods are some examples of techniques for working mostly with equipment while the efforts to design mix proportions of concrete to prevent washout (anti-washout property) by water were not really successful in the past.

Self-compacting concrete (SCC) was first developed in Japan in 1980's, in order to solve the construction problems of lacking of skill workers. SCC is a concrete that can fill into every corner of formworks by means of its own self weight without needs of vibration. The main key of this unique workability is to have high deformability, segregation resistance, and passing ability [2, 3]. SCC can be classified into 4 types based on the ingredients as follows;

1) Powder based: It could be achieved by use of high binder content (500-600 kg/m^3), low water to binder ratio (0.25-0.35) and high superplasticizer dosage (0.5-1.0% for polycarboxylate based superplasticizer). It has high durability due to its high strength and low porosity.

2) Viscosity modifying agent (VMA) based: VMA is a viscosity modifying agent with the main function to modify rheological properties of cement paste so that its plastic viscosity is increased. Due to modification on viscosity, the binder content could be reduced to around 400-500 kg/m^3, which is lower when then that of powder-based SCC. The water to binder ratio of this SCC is around 0.35-0.45.

3) Entrained air based or Aired SCC: High stability entrained air is incorporated into the SCC to increase paste but reduce binder. The high stability air can behave as lubricating particles in the mixture. The binder content of this type of SCC can be reduced to 350-400 kg/m^3 which is extremely low for SCC.

4) Combined based: This is the hybrid between the above 2 or 3 types of SCC [2]-[6].

There were some literatures on development of anti-washout underwater concrete since the last few decades [7]-[8]. However, they were not so successful to achieved anti-washout performance and all of them utilized viscosity additives which are different from that used in this study.

The objective of this research is to develop and design an underwater concrete by a concept of viscosity modifying agent (VMA) based SCC. The VMAs used are extra high-performance thickeners (Alkyl aryl sulfonate + Alkyl ammonium salt) such as Mighty VT100A&B (VMA component 1) and Mighty VT200 (VMA component 2) that are anti-washout agent for this concrete.

Tests with simple equipment such as slump cone and V-funnel were used to identify underwater concrete properties. In addition, as this concrete was developed for use in a repair project of the port authority of Thailand at Sumut Prakan, so sea environment must be taken in to consideration. Figure 1 shows the site condition with the details of the rock infilled column to be repaired. The conditions that must be considered were such as chloride resistance, sulfate resistance and also non-shrink ability which were achieved by adding 10 % of fly ash (from BLCP power plant) and 30 kg/m^3 of expansive agent.

Figure 1 Structure to be repaired and its site location at Samut Prakan

2. Research Scope

The scope of this project is to develop an underwater concrete and describe measuring techniques for underwater concrete for self-compacting ability, anti-washout ability, anti-segregation ability (static segregation) by slump flow test and V-funnel test and design the underwater concrete for undersea condition.

3. Materials and Methods

3.1 Materials

In this study, binders used for conducting concrete trial mixes include OPC type 1 and fly ash from BLCP power plant. Two components of extra high-performance thickeners (Alkyl aryl sulfonate + Alkyl ammonium salt) which were Mighty VT100A&B (VMA component 1) and Mighty VT200 (VMA component 2) were used as the viscosity modifying agent (VMA). A Type F polycarboxylate based (HW) superplasticizer was used. River sand complying with ASTM C33 and crushed limestone having a maximum size of 9 mm were used as fine and coarse aggregates, respectively.

3.2 Methods

3.2.1 Mortar tests

Underwater mortars were studied for the effect of extra high-performance thickeners (Alkyl aryl sulfonate + Alkyl ammonium salt) such as Mighty VT100A&B (VMA component 1) and Mighty VT200 (VMA component 2) and a Type F polycarboxylate based (HW) superplasticizer tested by 1) Mini cone slump and 2) V-funnel test, whereas anti-washout ability was tested by casting the fresh mixtures in water and visualize the condition via video recording underwater.

Mortars made from cement only and cement with fly ash were formulated by varying sand to mortar ratios (S/M) and water to binder ratios (w/b) of 0.3 to 0.35 and 0.3 to 0.4, respectively. Superplasticizer dosages of 1 % to 2.5 %, Mighty VT100A&B and Mighty VT200 with dosages of 4 to 10 % and 2 to 5 %, respectively were used. For undersea condition, 10 % of BLCP fly ash replacement was applied. The replacement percentage of fly ash was intended not to be high in order to prevent excessive delay of setting and hardening of the concrete as high dosages of VMA and superplasticizer were used in the concrete.

Mortar mixes that passed workability criteria (flow diameter of 250 mm, and funnel flow time of 5 seconds) and anti-washout ability, were identified and used to prepare SCC by adding coarse aggregate with the same sand to mortar ratio (S/M), water to binder ratio (w/b), Mighty VT100A&B and Mighty VT200 dosages and Type F polycarboxylate based (HW) superplasticizer dosage.

3.2.2 Concrete tests

3.2.2.1 Workability (slump flow, V-funnel)

Selected test methods from EAFNAC, Specification and Guidelines for Self-Compacting Concrete [3], were used to measure initial concrete workability. The workability loss of all concrete mixes was also measured.

3.2.2.2 Anti-washout ability test

V-funnel [2] was used to indicate appropriate viscosity of the concrete that achieved the required anti-washout ability, confirmed by video visualizing under water.

3.2.2.3 Segregation resistance test

Segregation resistance was tested by 2 methods which are;

1) V-funnel test (by the same procedure as workability and anti-washout ability tests) [3]

2) Cast concrete cylinder specimens (150 x 300 mm) and split the cylinder specimens with the same method as that conducted for the splitting tensile test (see Figure 2), then take a photo of the split specimens' surfaces and visualized the segregation condition.

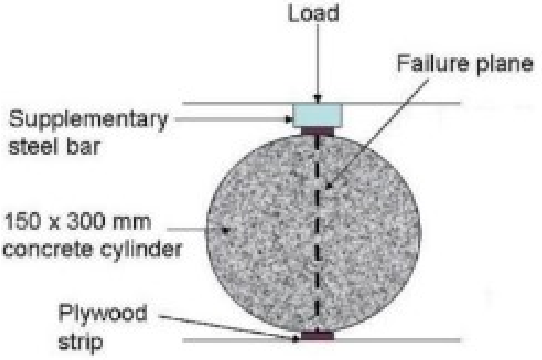


Figure 2 Splitting tensile strength test [11]

3.2.2.4 Passing ability (L-Box)

Passing ability (L-Box) test for self-compacting concrete is based on a Japanese design for underwater concrete and is described by RILEM technical committee 174-SCC [9]. The test assesses the flow of the concrete and also the extent to which it is subjected to blocking by reinforcement. The apparatus is shown in Figure 3.

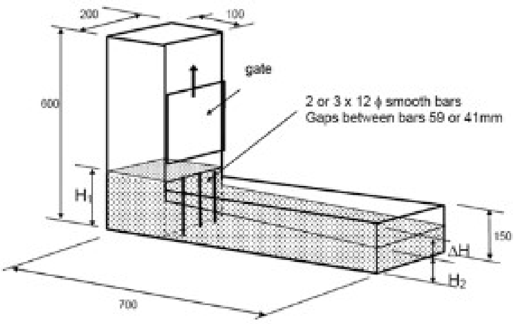


Figure 3 Passing ability (L-Box) apparatus [3]

3.2.2.5 Compressive strength

Compressive strength of concrete according to ASTM C39 was conducted. The strength development of underwater concrete was examined by collecting specimens both underwater and in the air for comparison and investigation according to requirement of each mix (at the ages of 7, 14, 28 days).

3.2.2.6 Setting time

Setting time of concrete according to ASTM C403 was investigated.

3.2.2.7 Shrinkage

Free shrinkage of the obtained underwater concrete was measured on prism specimens according to ASTMC878.

4. Results

4.1 Mortar test results

4.1.1 Slump flow and V-funnel time

The mini cone slump flow and V-funnel tests of mortar samples were used to test deformability and viscosity of mortar mixtures in order to obtain relationships between their indices Γm and Rm. Γm and Rm [1] are defined as;

Deformability index:

$$\Gamma m = \frac{(d_1 d_2 - d_0^{2})}{d_0^{2}} \qquad (4.1)$$

Viscosity index: $Rm = \frac{10}{t}$ (4.2)

Where d_1 and d_2 are measured flow diameters measured from two perpendicular directions, mm (see Figure 1), d_0 is flow cone's bottom diameter, mm (see Figure 4), t is measured time to flow through V-funnel, sec (see Figure 5).

The mortar mixes that passed SCC criteria must have a flow diameter not less than 250 mm and funnel flow times equal or more than 5 seconds as shown in Table 1.

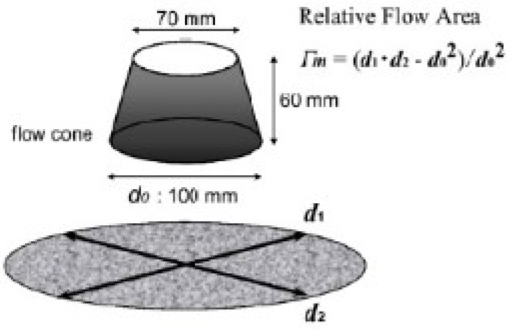


Figure 4 Flow test [3]

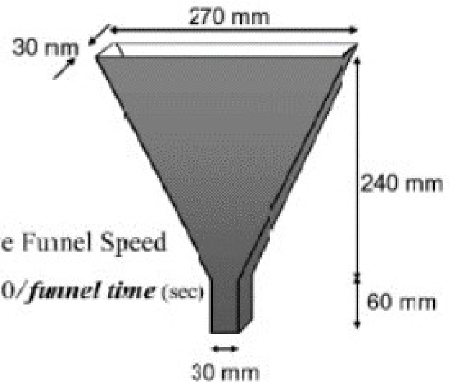


Figure 5 V-funnel test [3]

Table 1 Mortar mixes that pass SCC workability criteria

Mortar Mix.	VMA type	S/M	w/b	Sp/b (%)	VMA/w (%)	r_{fa} (%)
Cement-only	VT100A&B (1:1)	0.3	0.3	1.5	4	-
			0.35	1.75	6	-
			0.4	2	8	-
		0.35	0.3	1.75	5	-
			0.35	2	7	-
			0.4	2.25	9	-
	VT200	0.3	0.3	1.5	2	-
			0.35	1.75	4	-
			0.4	2	4	-
		0.35	0.3	1.75	4	-
			0.35	2	5	-
Cement + Fly ash (BLCP 10%)	VT100A&B (1:1)	0.3	0.3	1.5	4	10
			0.35	1.75	6	10
			0.4	2	8	10
		0.35	0.3	1.75	5	10
			0.35	2	7	10
			0.4	2.25	9	10
	VT200	0.3	0.3	1.5	2	10
			0.35	1.75	4	10
			0.4	2	4	10
		0.35	0.3	1.75	4	10
			0.35	2	5	10
			0.4	2.25	5	10

Remarks: S/M is sand to mortar ratio by volume, w/b is water to binder ratio, Sp/b is superplasticizer dosage (% by weight of binder), VMA/w is VMA dosage (% by weight of unit water content), r_{fa} is replacement ratio of fly ash.

4.1.2 Anti-washout test

The results were recorded underwater by a camera to prove that mortar mixes were not washed-out by water (as shown in Figure 6). The mortar mixes that pass the requirement as underwater concrete are as shown in Table 2.

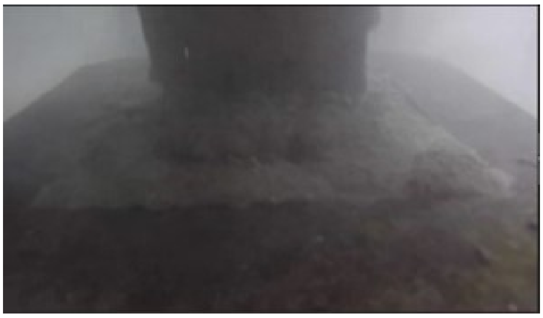


Figure 6 Casting mortar under water

4.2 Concrete test results

To reduce cost of concrete, it was decided to ignore the mixes that had S/M = 0.3 and w/b = 0.3 from the study. Cement-only concrete mixes were developed in laboratory by mixing with a pan mixer but for the mixes made from cement with BCLP fly ash, the concrete were mixed using a drum mixer and adjusted the concrete mixes to suit undersea environment. For chloride resistance, ACMC-L3 standard specifies that water to binder ratio (w/b) should not be higher than 0.45 in order to resist the highest severity of corrosive environment. BLCP fly ash at 10% replacement was also applied for sulfate resistance [10] as shown in Figure 7 and Figure 8, according to the requirement of the port authority.

Table 2 Mortar mixes that pass anti-washout ability

Mortar Mix.	VMA type	S/M	w/b	Sp/b(%)	VMA/w (%)	r_{fa} (%)
Cement-only	VT100A&B (1:1)	0.3	0.3	1.5	4	-
			0.35	1.75	6	-
		0.35	0.3	1.75	5	-
			0.35	2	7	-
	VT200	0.3	0.3	1.5	2	-
			0.35	1.75	4	-
		0.35	0.3	1.75	4	-
			0.35	2	5	-
Cement + Fly ash (BLCP 10%)	VT100A&B (1:1)	0.3	0.3	1.5	4	10
			0.35	1.75	6	10
		0.35	0.3	1.75	5	10
			0.35	2	7	10
	VT200	0.3	0.3	1.5	2	10
			0.35	1.75	4	10
		0.35	0.3	1.75	4	10
			0.35	2	5	10

Remarks: S/M is sand to mortar ratio by volume, w/b is water to binder ratio, Sp/b is superplasticizer dosage (% by weight of binder), VMA/w is VMA dosage (% by weight of unit water content), r_{fa} is replacement ratio of fly ash

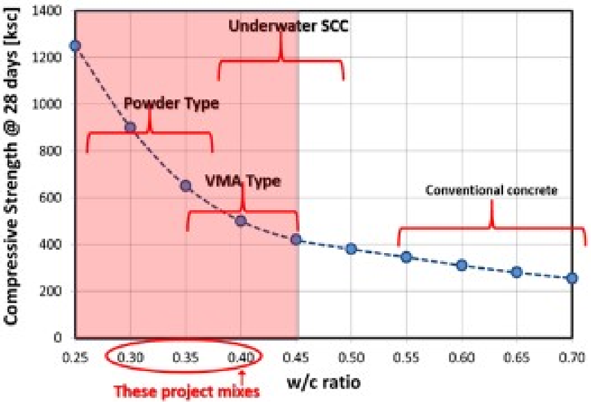


Figure 7 Allowable w/b ratio for highest severity of corrosive environment.

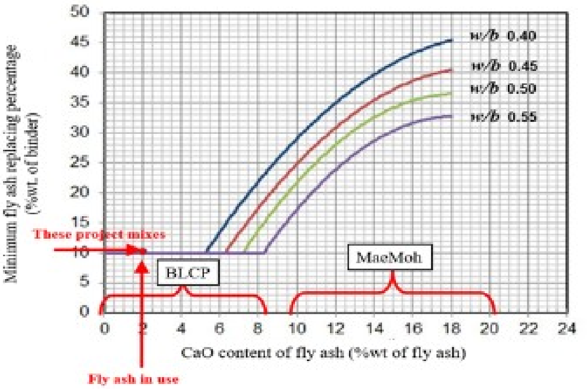


Figure 8 Minimum fly ash content % for sulfate resistance

4.2.1 Workability test results

The concrete mixes that pass underwater and undersea properties in Table. 3 and the test results of the concrete used for the repair are shown in sections 4.2.1 to 4.2.7.

For slump flow test [9] (see Figure 9 for the apparatus), slump flow was between 650 to 850 mm. Not only slump flow, V-funnel test [9] (see Figure 10 for the apparatus) was also conducted for other properties such as anti-washout, segregation resistance and passing ability (L-Box) [9].

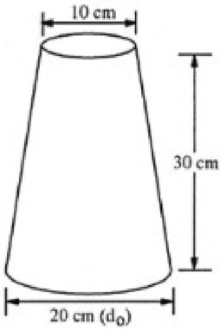


Figure 9 Slump flow apparatus [3]

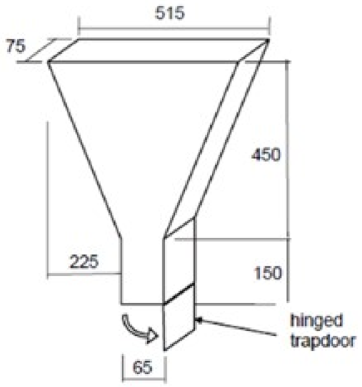


Figure 10 V-funnel apparatus [3]

4.2.2 Anti-washout test result

Anti-washout results were identified by pouring concrete into water. V-funnel time, which were equal or longer than 30 seconds, refers to viscosity of concrete that can pass anti-washout ability in this research. The passing zone is shown on Bingham's model graph in Figure 11, comparing V-funnel time of water and various types of concrete.

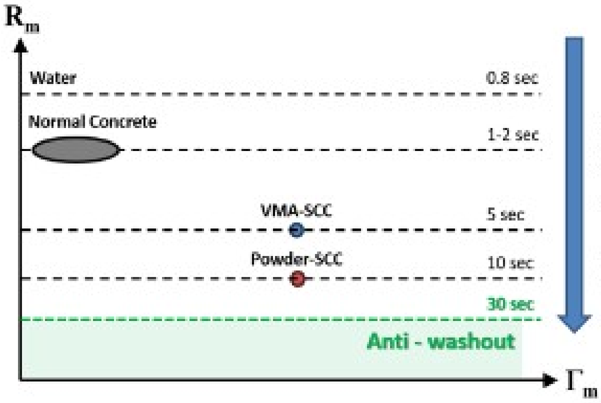


Figure 11 V-funnel test results (Anti-washout) on Bingham's model grap

Table 3 Concrete mixes that pass underwater and undersea properties.

Concrete Mix.	VMA type	S/M	w/b	Sp/b (HW)	VMA /w	r_{fa} %	Exp. (Kg/m^{3})	De-air agent (g/m^{3})
Cement only (Underwater Condition)	VT100A&B (1:1)	0.35	0.3	1.5	6	-	-	-
			0.35	1.75	8	-	-	-
			0.38	2	10	-	-	-
			0.40	2	10	-	-	-
	VT200	0.35	0.3	1.75	4	-	-	-
			0.35	2	5	-	-	-
			0.38	2.25	6.5	-	-	-
			0.4	2.25	6.5	-	-	-
Cement + Fly ash (BLCP 10%) (Undersea Condition)	VT100A&B (1:1)	0.35	0.3	1.75	6	10	30	300
			0.35	2	8	10	30	300
			0.38	2.25	10	10	30	300
			0.4	2.25	10	10	30	300
	VT200	0.35	0.3	2	4	10	30	300
			0.35	2.25	6	10	30	300
			0.38	2.5	7	10	30	300
			0.40	2.5	7	10	30	300

*Concrete mix for repair Port authority of Thailand.

Remarks: S/M is sand to mortar ratio by volume, w/b is water to binder ratio, Sp/b is superplasticizer dosage (% by weight of binder), VMA/w is VMA dosage (% by weight of unit water content), r_{fa} is replacement ratio of fly ash

4.2.3 Segregation test result

In this study, static segregation condition of underwater concrete was investigated by visualizing the split concrete surfaces of cylinder specimens as an example in Figure 12, as well as by V-funnel time which had to be equal or more than 60 seconds to prevent static segregation as shown in Figure 13.

Figure 12 Split concrete cylinder section that has static segregation.

Figure 13 V-funnel test results (static segregation) on Bingham's model graph

4.2.4 Passing ability (L-Box)

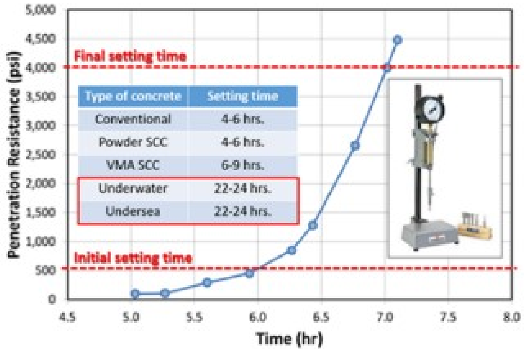
Passing ability was tested by casting concrete into the L-Box filled with water which can also check anti-washout ability after concrete has passed obstacles as shown in Figure 14. The poor passing ability was achieved by V-funnel time which was equal or more than 120 seconds as shown in Figure 15.

Figure 14 L-Box testing with water

Figure 15 Graph showing V-funnel results of Anti-washout, Anti segregation and poor passing ability

4.2.5 Setting time

For underwater concrete, final setting time of all concrete mixes were 22-24 hours which were very long when compared to other concretes as shown in Figure 16.



Type of concrete	Setting time
Conventional	4-6 hrs.
Powder SCC	4-6 hrs.
VMA SCC	6-9 hrs.
Underwater	22-24 hrs.
Undersea	22-24 hrs.

Figure 16 setting time of underwater concrete compare to other concretes

4.2.6 Compressive strength

The compressive strength of the concrete required by port authority of Thailand for the repair condition in this project was 350 kgf/cm^2. The concrete samples were cast in the air and underwater to compare their compressive strength at 7, 14 and 28 days as shown in Figure 17. It is shown that the compressive strength of the concrete cast in air and underwater are equivalent. This means that casting underwater does not have any effect on strength of the developed concrete.

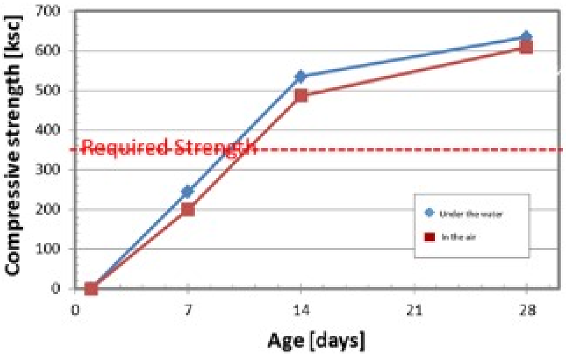


Figure 17 Comparison of compressive strength between concrete cast in air and underwater

4.2.7 Shrinkage

Because the repair structure, which was a thin concrete structure, was cast continuously without contraction joint provision. An expansive additive, manufactured by DENKA, co., Ltd such as CSA Type-S (30 kg per 1 m^3 of concrete) was applied for shrinkage cracking prevention. The results of shrinkage, tested according to ASTM C157, were investigated by measuring free expansion of related mixes as shown in Figure 18 at water to binder ratio (w/b) equal to 0.4. The measured free expansion was lower than 150 microstrain at 28 days which was still lower than the normal cracking strain of concrete.

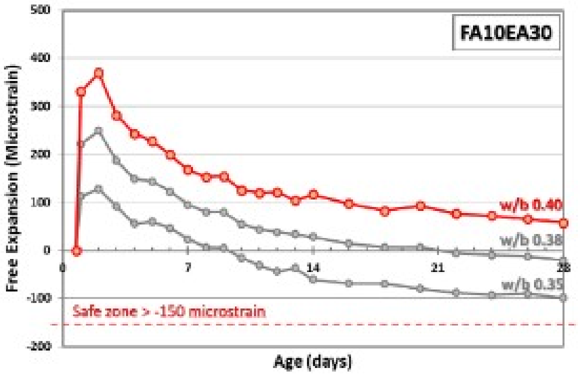


Figure 18 Free expansion of the tested mixes

5. Discussions

For both concretes made from cement only and cement with BLCP fly ash at sand to mortar ratio (S/M) equal to 0.35, when increasing water to binder ratio, both the VMA to water ratio and superplasticizer to binder ratio (Sp/b) should be increased to obtain the underwater concrete performances.

For V-funnel time which indicates viscosity of concrete, all concrete mixes passed anti-washout ability by 30 seconds of V-funnel time. However, when comparing air content of cement-only concrete mixes mixed with pan mixer and cement with BLCP fly ash concrete mixed with drum mixer (tested following ASTM C231) as shown in Figure 19, cement with BLCP fly ash concrete mixed with drum mixer had air content of 8-12% (entrapped air) which was much higher than cement-only concrete mixes that had air content of only 2-3%.

Figure 19 Air content of concrete mixed with pan and drum mixer

For the same mix proportion, if air content increased, V-funnel time would decrease, causing anti-washout ability to decrease. As an example, in this study, with the same mix proportion but changing from mixing with pan mixer (air 2%) to drum mixer (air 12%), the V-funnel time changed from 60 seconds to 20 seconds. The air content in concrete should be controlled. Large air content such as 12% will cause floating of the air to the surface and volume loss when the concrete hardens as shown in Figure 20.

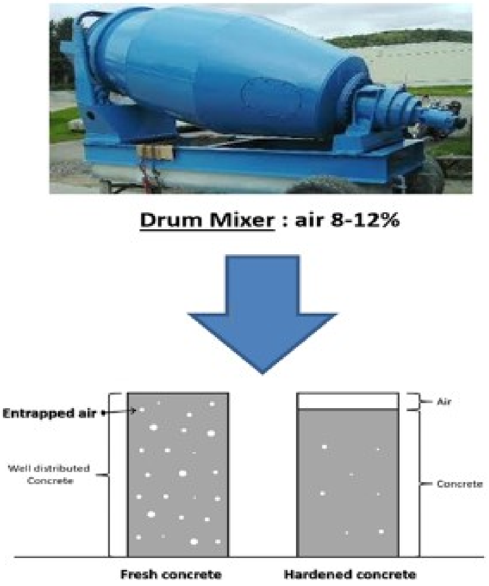


Figure 20 Volume loss of hardened of concrete because entrapped air

The setting time of underwater and undersea concrete were 22-24 hours that may cause static segregation because of long setting time. Coarse aggregate can sink by its own weight as shown in Figure 21. So, to prevent static segregation, the concrete should have sufficiently high viscosity (V-funnel should be equal to or more than 60 seconds according to the results in this study).

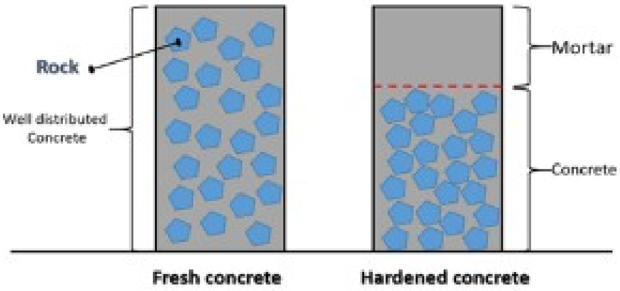


Figure 21 Segregation in form of settlement due to long setting time

For passing ability, the results showed that V-funnel time equal or more than 120 seconds would cause poor passing ability.

The compressive strength at 7,14 and 28 days of the developed underwater concrete cast underwater were equal to 250, 530 and 620 kg/cm^2, respectively, which were much higher than that required by the port authority of Thailand of 350 kg/cm^2 at 28 days.

For undersea environment, 10 % of BLCP fly ash was used to replace cement to improve sulfate resistance, chloride penetration resistance and reduce shrinkage. Expansive additive at 30 kg/m^{3}of concrete and water to binder ratio (w/b) of 0.4 were selected to provide shrinkage cracking resistance and chloride attack, following ACMC Lv3[7].

6. conclusion

An anti-washout underwater concrete for the undersea repair project was successfully developed. The underwater and undersea concrete should have workability such as slump flow diameter between 650 mm to 850 mm and V-funnel time between 60 to 80 seconds as shown in Figure 22, in comparison with those of other concrete plotted on a Bingham's model graph

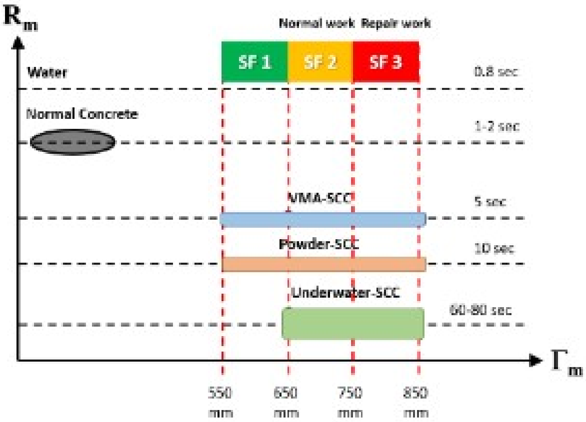


Figure 22 workability of other concrete and underwater concrete on Bingham's modal

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