Mathematical Modelling of Engineering Problems
Vol. 10, No. 4, August, 2023, pp. 1324-1332
Journal homepage: http://iieta.org/journals/mmep

Evaluating Fresh Properties of Non-Dispersive Reactive Powder Concrete: A Novel Approach

Doha M. Al-Saffar[1*], Basil S. Al-Shathr[1], Suhair K. Abed[2]

[1] Civil Engineering Department, University of Technology, Baghdad 10066, Iraq
[2] Building Research directorate, Ministry of Construction, Housing, Municipalities and Public Works, Baghdad 10011, Iraq

Corresponding Author Email: bce.20.05@grad.uotechnology.edu.iq

https://doi.org/10.18280/mmep.100426

Received: 12 February 2023
Revised: 10 March 2023
Accepted: 15 March 2023
Available online: 30 August 2023

Keywords:
viscosity-modifying additives, fluidizing, underwater construction, viscosity, non-dispersive concrete

ABSTRACT

A novel testing methodology was developed in this study to efficiently evaluate the non-dispersibility of Reactive Powder Concrete (RPC) that does not disperse (Non-Dispersive RPC or NDRPC) - a concrete variant derived from the amalgamation of RPC and non-dispersive concrete. To study the fresh behavior of NDRPC, a series of fourteen mixes were prepared, each incorporating an Anti-Wash Admixture (AWA) concentration ranging between 0.5% and 2%. Fresh state properties were identified through a series of Slump Flow, V Funnel, L-box, and Setting Time tests, while washout resistance was determined through modified Stream Test, Turbidity, and pH tests. The findings constitute the first efficient evaluation of the non-dispersibility of fresh Self-Compacted Mortar (SCM) or concrete mixtures when placed underwater, as ascertained by V Funnel and L-box tests under similar conditions. Experimental results indicated a synergistic effect between AWA and High Range Water Reducer Admixture (HRWRA) concentrations on the properties, which could be counterbalanced by increasing the incorporation of silica fume to 30%. Notably, a significant reduction in washout loss was observed when silica fume replacement was increased to 30%.

1. INTRODUCTION

Marine and hydraulic structures, particularly those damaged by abrasion-erosion, along with aging bridges, are a significant concern for construction experts. These structures often require underwater strengthening procedures to ensure their functional and structural safety [1-4].

The primary challenge with underwater concrete lies in its setting and curing process; the presence of water slows the chemical reactions that lead to hardening. To mitigate this challenge, construction professionals utilize special types of high early strength cements and admixtures that can set and cure rapidly, even in a water-rich environment.

One crucial property of underwater concrete is its resistance to chemical attack. Concrete can deteriorate upon exposure to various chemical agents, such as seawater, river water, and industrial effluents. Enhancing its chemical resistance involves the use of unique cements, such as sulfate-resistant Portland cement. Furthermore, pozzolanic materials like fly ash, slag, and silica fume are often included in the mix to bolster the concrete's resistance to chemical attack.

Workability and pumpability are critical aspects of underwater concrete. The presence of water can complicate handling the concrete mixture, and the pumping process can present its own set of challenges. To address these issues, admixtures like superplasticizers and air-entraining agents are employed, improving the concrete mixture's workability and pumpability.

Given the above, it's clear that cementitious materials significantly determine the properties and performance of underwater concrete. These special cements and admixtures help improve the concrete's strength, durability, and resistance to chemical attack. Therefore, the appropriate selection and use of these materials are vital for ensuring the long-term performance and durability of underwater structures.

In the quest to improve construction quality assurance and efficiency, several properties—like washout resistance, pumpability, low dispersibility, and viscosity—are primary considerations in the design of underwater concrete (UWC) [4-7]. Different UWC applications entail different fresh parameters. Recent research has improved the cohesiveness and viscosity of UWC by incorporating supplementary materials such as silica fume (SF), fly ash (FA), metakaolin, and ground granulated blast slag. SF, which boasts the highest specific surface area among other supplementary cementitious materials, has been proven to increase water resistance, densify the interfacial transition zone (ITZ), and enhance compressive strength through the pozzolanic reaction [8-10].

Conventional strengthening methods, while effective, are often time-consuming and costly [6, 7, 11-13]. Therefore, traditional strengthening and rehabilitation methods should ideally be performed without requiring dewatering and downtime. This study investigates the fresh performance of a novel type of concrete—non-dispersive reactive powder concrete (NDRPC). NDRPC is produced by combining reactive powder concrete and non-dispersive concrete. Reactive powder concrete (RPC) is composed of a precise blend of high-quality materials, including fine powders, micro silica, quartz powder, steel fibers, and chemical admixtures. These materials are carefully chosen for their unique properties and combined in specific proportions to achieve the desired performance characteristics.

Reactive Powder Concrete (RPC) is known for its high strength, with the capacity to achieve compressive strengths of up to 200 MPa (29,000 psi)—significantly higher than traditional concrete. Its durability properties are also impressive, with low permeability and high resistance to chemical and environmental degradation. Owing to its superior properties, RPC has found its way into several high-performance construction applications. These include bridge components, precast concrete elements, tunnel linings, and offshore structures. RPC is also used in creating intricate and visually pleasing architectural features, such as facades and sculptures [10, 14].

However, the inclusion of Silica Fume (SF) necessitates higher amounts of a viscosity agent, as SF reduces flowability and pumpability, consequently delaying the setting time [14-16]. Several studies have explored the effects of adding cementitious materials to Underwater Concrete (UWC). For instance, a UWC mix with a compressive strength of 435kg/m3, composed of 12% Fly Ash (FA) and 6% SF (as a replacement by cement weight) at 28 days, registered a strength of 62 MPa. This mix incorporated 0.08% welan gum by the mass of the binder material and recorded initial slumps of 250 and 275mm [17].

Other studies have experimented with SF replacements of 5%, 10%, and 15% alongside a high volume of class C FA to produce eco-friendly UWC. The primary conclusions related to the effect of SF involved a loss of workability and compressive strength as the SF percentage increased. Although this study focused on UWC, it did not record the type and doses of Anti-Wash Admixture (AWA) [18]. Another study explored the incorporation of 10% SF with two common AWAs: welan gum and a cellulose-based anti-washout. The test results reported increased washout resistance and water velocity, which led to losses in in-place strength [19].

From the literature mentioned above, it can be inferred that a UWC with adequate compressive strength and substantial washout resistance can be achieved by incorporating SF. Yet, the performance of Non-Dispersive Reactive Powder Concrete (NDRPC) remains unclear. This study aimed to determine how the gum-powder anti-wash influences the rheology of fresh concrete. Modifications to the properties of fresh concrete may enhance construction methods and concrete elements. To analyze the advantages and limitations of NDRPC, it is crucial to characterize its fresh properties.

Such a design approach is beneficial for advancing the engineering applications of UWC. Furthermore, this study sought to develop a new test to efficiently assess the non-dispersibility of a fresh Self-Compacted Mortar (SCM) or concrete mixture when placed underwater.

2. EXPERIMENTAL INVESTIGATION

Following the production of NDRPC, this study was implemented to investigate the fresh properties with different parameters. The fresh properties of NDRPC can include, flowability, filling ability, passing ability, washout resistance, and setting time with deferent AWA precents.

2.1 Materials and mix proportion

NDRPC mixtures investigated in the present study was prepared with ordinary Portland cement CEM I 42.5 with a 3267cm^2/gm fineness, replaced with15%, and 30% silica fume by mass with a 200,000cm^2/gm, to see how SF affects the fresh properties of NDRPC. According to the technical data sheet of AWA, cement with lower levels of tricalcium will increase the retardation. Chemical and physical properties of the binder materials are summarized in Table 1. Seven doses of AWA were 0.5%, 0.7%, 0.9%, 1.1%, 1.3%, 1.5% and 2% [20-22], natural welan gum in powdered form was used for the NDRPC, Figure 1 illustrates powdered materials were used to production NDRPC. A constant w/b of 0.25 was used for all NDRPC mixtures. A commercial silica sand <600 µm was used as fine powders have a fineness modulus 2.75 and specific gravity of 2.65 to increment particle packing and elimination of interparticle space and pores. Moreover, in the production of NDRPC a naphthalene based as a high range water reducer was used, complying with ASTM C494M-08 Type F, and the dose percentage was changed to eliminate vibration and to obtained slump flow 240-250 mm [12]. NDRPC composition details are presented in Table 2.

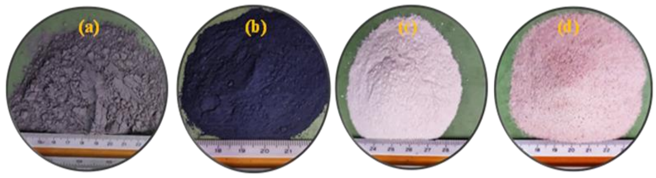

Figure 1. Powdered materials were used for NDRPC, (a) ordinary Portland cement; (b) micro silica fume; (c) anti-wash admixture; and (d) silica sand

Table 1. Chemical and physical properties of cementitious materials*

Oxides, %	OPC	SF
SiO_2	21.7	94
Al_2O_3	5.48	0.5
Fe_2O_3	3.17	2
CaO	63.03	0.8
MgO	3.41	0.9
Na_2O+K_2O	0.51	1
SO_3	2.22	0.2
Specific gravity	3.15	2.2
Blain fineness, cm^2/gm	3267	200000

*Note: OPC: ordinary Portland cement; SF: silica fume.

Table 2. NDRPC proportion mixtures*

Group No.	Unit weight, kg/m^3					
	OPC	SF	SS	AWA	HRWR	Water
GI	850	150	1100	4.6	22.7	230
	850	150	1100	6.44	27.6	230
	850	150	1100	8.28	32.2	230
	850	150	1100	10.12	36.2	230
	850	150	1100	11.96	38.7	230
	850	150	1100	13.8	44.9	230
	850	150	1100	18.4	46.2	230
GII	700	300	1100	4.6	23.3	228
	700	300	1100	6.44	28.6	228
	700	300	1100	8.28	33.6	228
	700	300	1100	10.12	37.8	228
	700	300	1100	11.96	40.3	228
	700	300	1100	13.8	46.9	228
	700	300	1100	18.4	48.7	228

*Note: SS: silica sand; AWA: anti-wash admixture; HRWR: high range water reducer.

2.2 Testing methods

To evaluate the rheological properties of NDRPC, two sets of tests were conducted in this study: the first set included indirect tests, such as the turbidity test and the pH factor test. The combination of UWC and RPC rheological properties was assessed based on the second set of tests, which were direct tests, such as setting time as defined by ASTM C191 [23], slump flow test, V funnel [24] filling ability, stream test [25], and L-box passing ability, as illustrated in Figures 2-5. Moreover, the current study aimed to develop a new test to efficiently evaluate the non-dispersibility of a fresh self-compacted mortar (SCM) or concrete mixture placed underwater. The principle of direct determination of the required properties of an SCM mixture was adopted for the V-funnel and L-box tests.

2.2.1 The basic principles of the method for modified V funnel test

This test was performed to assess one of the self-compacting requirements of RPC underwater. The same procedure was used as for a conventional V-funnel test, using about 1 liter of mortar. In addition, the tap gate was immersed in the water tank within 10 sec of filling, the trap gate was opened, and the mortar was allowed to flow underwater. The test result is the time needed to empty the mold, which was recorded by stopwatch. Figure 3 illustrates the principles of this test underwater.

Figure 2. Flowability test of NDRPC

Figure 3. Filling ability of NDRPC

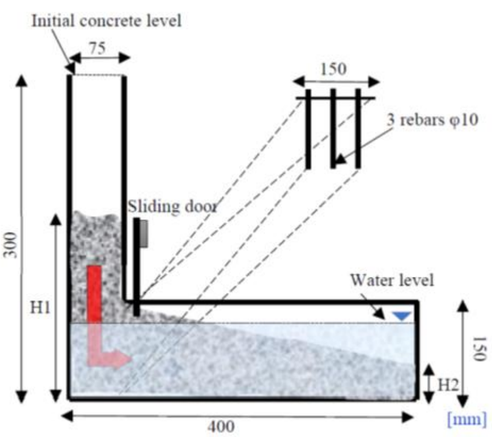

Figure 4. Passing ability test of NDRPC

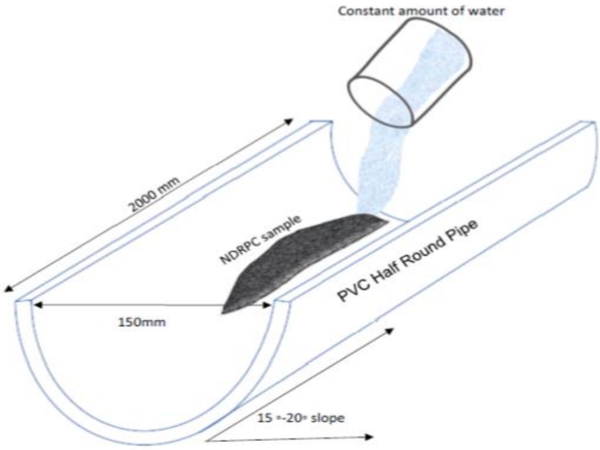

Figure 5. Stream test method

2.2.2 The basic principles of the method for modified L box test

This test was developed to evaluate the passing ability of mortar underwater; it can be applied to a concrete L-box. The test apparatus consists of a box with a rectangular section in the shape of an "L", with a 75×150×300 mm vertical and a 150×150×400 mm horizontal section, separated by a movable gate, as shown in Figure 4. The dimensions were adopted so that the SCM had a maximum range of slump flow between 200-300 mm [26, 27]. About 7 liters of NDRPC was needed to perform the test. The vertical section is filled with mortar; however, the horizontal section is filled with water. The sample is left to stand for 10 seconds; the sliding gate is lifted to allow the fresh mixture to flow into the water in the horizontal section through three reinforced bars. The distances H1 and H2 are measured for all series on different types of NDRPC. The final results are the ratio between H2 and H1, referred to as the NDRPC height after free fall.

2.2.3 The basic principles of the method for modified stream test

A stream test is a visual inspection test used to inspect the washout resistance of UWC. Although the plunge test is not suitable for determining the washout resistance of NDRPC, the washout resistance of NDRPC can be evaluated simply by the modified stream method, presented in Figure 5. The test measurements consist of a 2-m long half PVC pipe with a 150-200 mm diameter fixed at a 15-20° slope covered with plastic sheet for 300 mm to facilitate raising the sample after washout to measure the weight (w2). A 2,000 g (w1) sample of the fresh mixture is placed 300 mm from the upper end of the pipe, and a constant amount of water poured on the NDRPC samples. The washout loss of NDRPC was calculated using Eq. (1).

$$WOL = \frac{w1 - w2}{w1} \times 100 \qquad (1)$$

2.3 NDRPC mixtures preparation

Two groups consisting of fourteen NDRPC mixtures were designed, the first one used 15% SF and consists of seven mixtures with two variables AWA and HRWRA concentrations as presented in Table 2. NDRPC incorporation with 30% SF was used for the second group it also contains the same variables as the first group, which is also presented in Table 2. For the best performance, it is preferred to add the

AWA admixture as a thick slurry by mixing the powdered AWA with one quarter of the mixing water, followed by 15 minutes of rest. As well as to accelerate the hydration of AWA in the dry phase could mix it with warm water to 75-95 degrees Celsius. All concrete mixes were mixed using an electrical laboratory mixer. First, all dry powders were mixed at low speed for approximately 3 minutes until a uniform mixture was obtained. Subsequently, with the mixer still in operation, a liquid mix consisting of the remaining three-quarters of mixing water and HRWRA was added gradually within approximately 6 minutes at a high speed. Afterwards, with the equipment still in operation, and the mixture reached better consistency, the hydrated AWA in the aqueous phase was added, remaining for five minutes. The total mixing time ranged from 15-20 minutes.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Flowability and washout resistance of NDRPC

Table 3 and Figure 6 present the slump flow results for a different amount of AWA made with 15% and 30% SF replacement. For constant w/b, Figure 7 shows the HRWRA needed to give a slump flow between 244-248 mm. The first impression with increment of AWA dosage, the percentage of HRWRA required increased. The addition of HRWRA was necessary at high levels of AWA to secure the target flowability, between 240-250 mm. As expected, 30% SF incorporation prevents the need for increased HRWRA; overdosages were added for 0.9%. The percentage of increased HRWRA due to increasing SF to 30% ranged between 4%-5%. This is partially attributed to the gel action of AWA, which contains long-chain polymer molecules that fix and adhere to some of the water present. In the presence of high levels of AWA, this action increased significantly [28, 29].

Moreover, the superior fineness of SF effectively enhances the cohesiveness and increases the internal friction due to flocculation action on other solid particles [30]. The levels of washout loss of the NDRPC mixtures determined by stream test are given in Table 3. As represented in Figure 8, regardless of the added AWA, the mixtures prepared with 30% SF have dramatically improved anti-dispersion. For example, dispersions of 41%, 53%, 64%, and 76% were recorded for mixtures made with 0.9%, 1.1%, 1.3%, 1.5%, and 2% AWA, respectively.

Figure 9 plots the inverse relationship between flowability and washout resistance. A strong positive correlation of 0.955 and 0.973 was established for 15% SF and 30% SF. It is interesting to note the strength effect of washout loss (WOL) on the degree of flowability. Similarly, a correlation has been established by mathematically modeling WOL and slump flow after a series of experimental results [13]. This linear relationship between slump flow and WOL% has been reported for conventional UWC previously [30], which are expressed in Eq. (2) and Eq. (3) for NDRPC mixtures made with 15% SF and 30% SF, respectively.

$$Slump_{mm} = 0.47WOL_{\%} + 238 \quad (2)$$

$$Slump_{mm} = 0.41WOL_{\%} + 239 \quad (3)$$

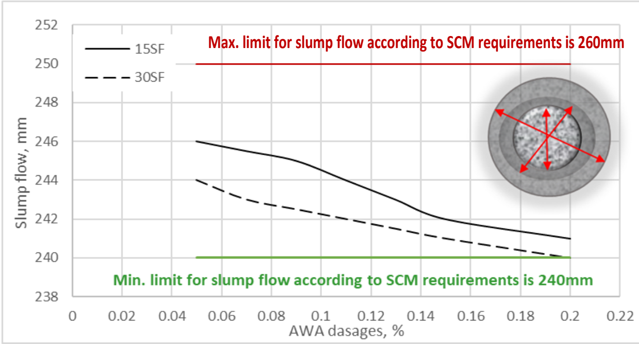

Figure 6. Flowability behavior of NDRPC with different percentage of AWA and SF

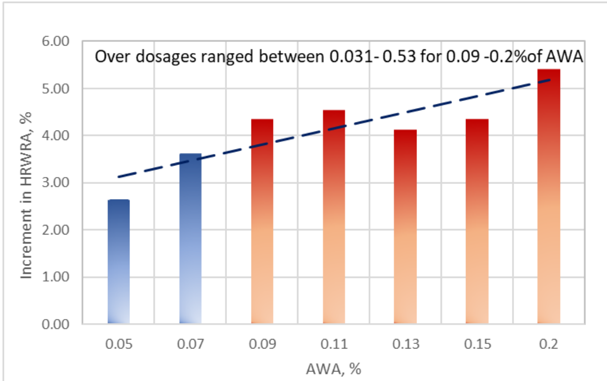

Figure 7. Effect AWA dosages on HRWR content

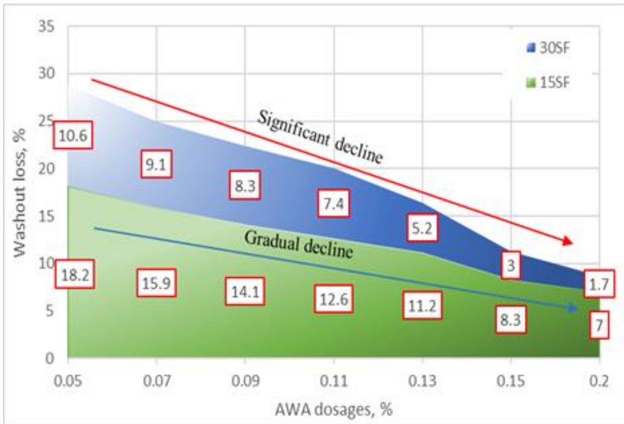

Figure 8. Washout loss of NDRPC

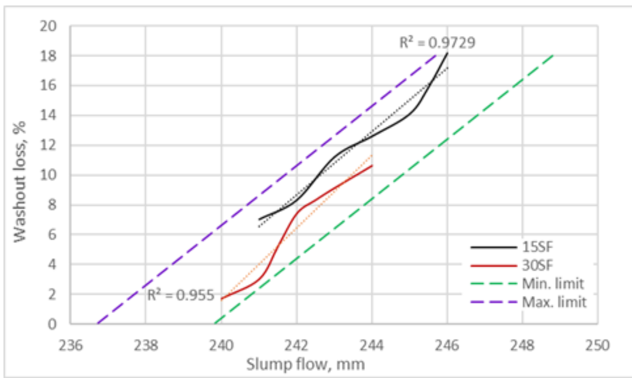

Figure 9. Relationship between slump flow and washout resistance of NDRPC

Table 3. Flowability, filling ability passing ability and viscosity of NDRPC

Mix ID	Slump Flow, mm	Time Through V Funnel, Min.: Sec.		Passing Ability by L Box, %		
		Conventional V Funnel	Under Water V Funnel	H1, mm	H2, mm	H2/H1
MI	246	00:08	00:12	60	57	0.95
MII	246	00:09	00:16	64	58	0.91
MIII	245	00:11	00:20	72	61	0.85
MIV	244	00:14	00:30	78	58	0.74
MV	243	00:18	00:38	88	51	0.58
MVI	242	00:25	00:51	94	46	0.49
MVII	241	00:30	01:05	96	42	0.44
MI	244	00:11	00:17	63	58	0.92
MII	243	00:13	00:19	66	56	0.85
MIII	243	00:18	00:26	70	54	0.77
MIV	242	00:23	00:45	81	49	0.60
MV	242	00:32	01:26	91	46	0.51
MVI	241	00:55	01:29	97	42	0.43
MVII	240	01:09	02:05	105	41	0.39

3.2 pH factor and turbidity tests of NDRPC

The pH and turbidity tests are methods commonly used to investigate the washout resistance of underwater concrete [31, 32]. Figures 10 to 13 illustrate the values of pH and turbidity with time over 24 hours. A 100-ml sample of NDRPC was placed in a beaker containing 500 ml of tap water. The first reading was taken instantaneously, and the second was taken after 15 minutes. After that, readings were taken every 30 minutes until 6 hours had elapsed. The pH values were monitored every 2 hours for 24 hours, with an average of three test values used as the final result, Hanna pH meter have been used. The results show that MV, MVI, and MVII have the same pH, which indicates high washout resistance, high cohesiveness, and good stability.

In contrast, despite using a high level of AWA, the first group of NDRPC samples incorporating 15% SF had high alkalinity, ranging between 9-9.3. The second group showed a slight increase in alkalinity. This is attributed to the physicochemical effect of the extremely fine surface area of SF. This significantly enhances the action of AWA and improves the packing density of underwater concrete, at the same time as an earlier chemical effect of SF related to its reaction with calcium hydroxide to form calcium silicate hydrate [30].

A previous study has used X-ray diffraction to determine that adding high doses of powdered AWA gum can reduce the formation of calcium hydroxide and, thus, cement hydration [29]. Despite the water beaker remaining clear at a high level of AWA for approximately 1-2 hours, a pH of 8 indicates zero washouts. However, the degree of purity rapidly changed afterward for MI, MII, and MIII in the first group. These results are considered excellent compared with other studies that have investigated the addition of nano SiO_2 and nano MgO to underwater concrete, in which the pH values ranged between 11.1 and 11.9 [2].

From the above, it is worth monitoring the turbidity for the first 24 hours. A Hach 2100N turbidimeter was used to measure the turbidity of NDRPC. The pH and turbidity of the samples are shown in Figure 12. The experimental results of the turbidity test for NDRPC samples incorporating 15% and 30% SF are illustrated in Figure 13 and Figure 14, respectively. Adding AWA appears to decrease the turbidity values. In general, the results show an approximately symmetric probability distribution, which suggests the turbidity is somewhat constant because each AWA dose has an equal chance of affecting the outcome. This proves the inefficiency of instantaneous turbidity inspection for indirectly indicating the washout resistance.

Otherwise, previous studies [2, 28-30] have used this test to predict the washout resistance of underwater concrete. Samples of NDRPC incorporating 15% SF showed that 58 to 258 NTU at 1 minute became 85 to 569 NTU at 15 minutes. However, samples of NDRPC incorporating 30% SF showed an effective reduction in turbidity at 15 minutes, ranging from 25 NTU to 56 NTU. This effective influence of SF on turbidity values was continuous for 24 hours. The maximum turbidity value in the second group at 2 hours was approximately equivalent to the minimum value in the first group at 1 minute. For example, MI from GII showed 249 NTU at 2 hours while form GI showed 260 NTU at 1 minute.

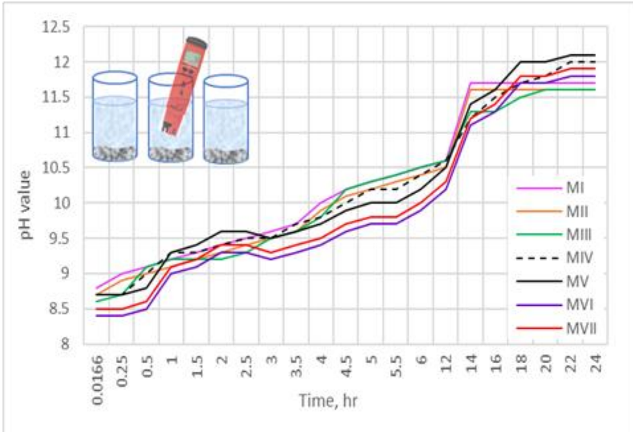

Figure 10. pH values for water contains 0.2 NDRPC mixtures with 15% SF through 24 hrs

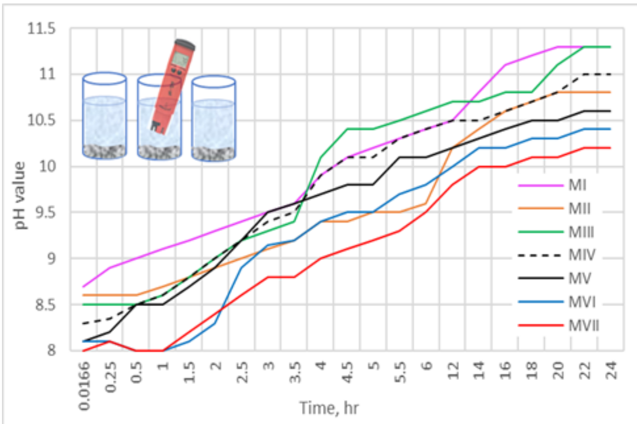

Figure 11. pH values for water contains 0.2 NDRPC mixtures with 30% SF through 24 hrs

Figure 12. Turbidimeter instrument and samples

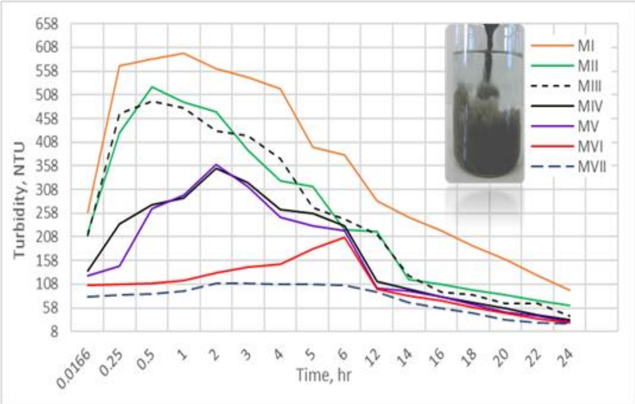

Figure 13. Turbidity results of NDRPC incorporating with 15% SF through first 24 hrs

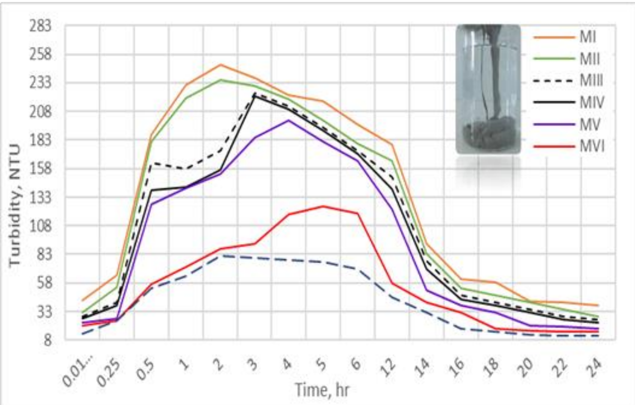

Figure 14. Turbidity results of NDRPC incorporating with 30% SF through first 24 hrs

3.3 Filling ability of NDRPC

Underwater concrete must easily flow out of the tremie, fill the placement area, and consolidate under its weight. Therefore, V-funnel and L-box tests have been performed for underwater concrete, and the results are given in Table 3. The filling required time limitations for SCM (using the V funnel), which were achieved at a low level of AWA ranging between 0.5% and 0.7%. In contrast, NDRPC resists the thrust of water using the force of gravity, and the surface tension starts at the tap gate, as shown in Figure 3. When V-funnel test have been conducted in conventional condition (in air) and underwater condition, the casting period takes approximately twice as long underwater as conventional tests in air. As expected, the addition of 30% SF increased the time to empty the V funnel due to the high degree of cohesiveness, as mentioned before. This is plotted in Figures 15 and 16 for mixtures from group I incorporating 15% SF and group II incorporating 30% SF. It is interesting to note that the decrease in variation in filling ability with increase SF contents. The variance in the filling ability for group I was increased from approximately 50%-116%. However, the significance reduction in variance ranged between 35% and 81% approximately.

Nevertheless, contrary to the previously stated effects of AWA and SF replacement on flowability, this was observed despite the overdosages of HRWRA used to reach the target flowability and satisfy SCM requirements. This effect is mainly related to the high internal friction and collision of grain particles in NDRPC, which increases the binding capacity and cohesiveness due to the high amount of cementitious materials [31, 33-36]. Thus, it is practical to use pumps for consolidated concrete underwater or at high levels of underground water containing 0.9%-1.5% of AWA.

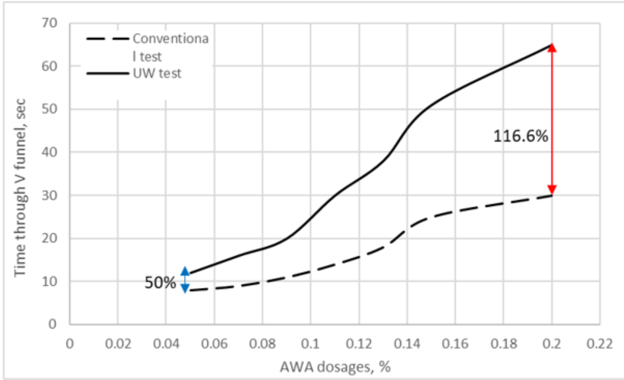

Figure 15. Variation of filling ability of NDRPC with 15% SF

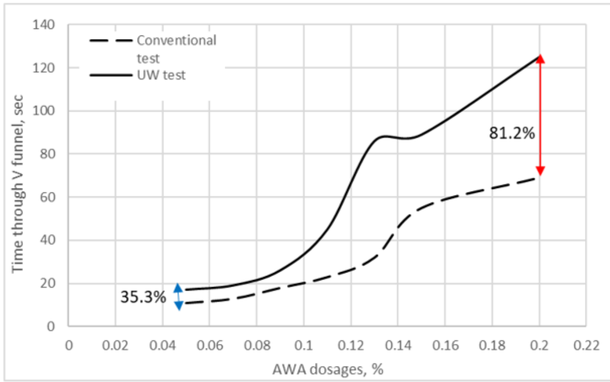

Figure 16. Variation of filling ability of NDRPC with 30% SF

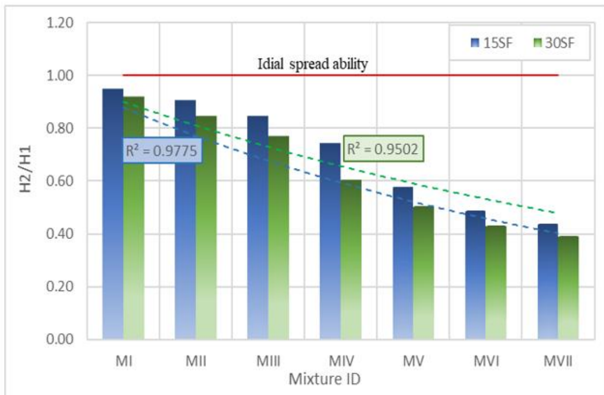

Figure 17. Spread ability of NDRPC incorporation with 15% and 30% SF

The passing ability has been investigated through two types of barrier steel reinforcement bars and thrusts of water; this was specifically realistically simulated. Figure 17 shows the ratio of H2/H1 for each NDRPC mixture. The proper passing ability was obtained when 0.5% AWA was added to 0.95 and 0.92 for 15% SF and 30% SF, respectively. The incorporation of 30% SF resulted in a slight reduction in the passing ability of approximately 3%. However, a significant reduction in the passing ability was observed due to 30% SF replacement at high levels of AWA (7%, 9%, 19%, 13%, 12%, and 11% for MII, MIII, MIV, MV, MVI, and MVII, respectively). Moreover, H2/H1 became very small, as low as 0.4, at overdosages of AWA for MVII. This drop in H2/H1 values occurred for two reasons: first, the extra cohesiveness due to the addition of 1.3%-2% AWA and second, friction between the NDRPC and the reinforced bars. MV, MVI, and MVII were confirmed to meet the requirements for underwater casting exposed to crushing water because the lowest H2/H1 could be lower than 0.4.

3.4 Effect AWA dosage and SF content on setting time of NDRPC

A standard Vicat apparatus was used according to ASTM C953 to determine the setting time of mixtures with and without AWA. Table 4 and Figures 18 and 19 present the initial and final setting times of NDRPC samples incorporating 15% and 30% SF. Generally, adding powdered AWA caused a significant delay in the setting time. However, replacement with 30% SF produced dramatic reductions in the delay in setting time. From the experimental results, the mechanism of the chemical additives is presumed. When admixtures with high absorptivity, such as HRWRAA or a water reducer, are used, the AWA is adsorbed by SF or the fine aggregate, leaving a reduced amount to be adsorbed by the supplementary materials, resulting in a shorter delay in setting time, especially for the initial setting time [8, 34]. The synergistic effect between AWA and HRWRA from the side and SF incorporation from the other side have been observed to counterbalance the setting time delay, especially for 30% SF replacement.

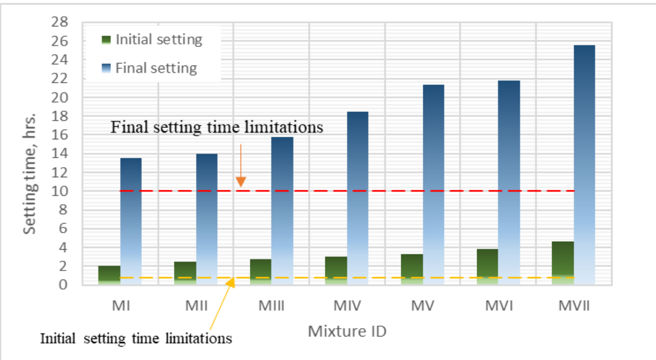

Figure 18. Setting time of NDRPC incorporating with 15%SF

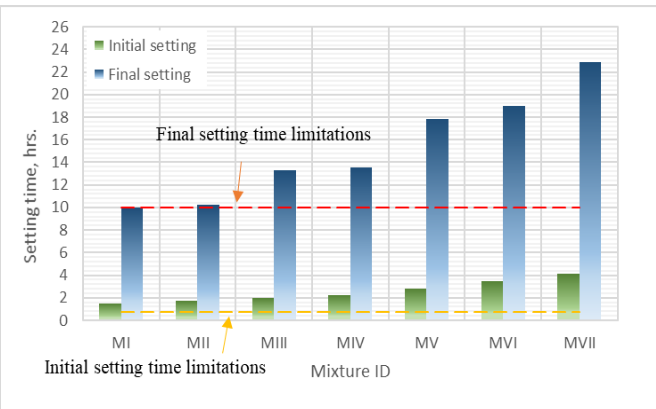

Figure 19. Setting time of NDRPC incorporating with 30%SF

The experimental results showed a slight delay in the initial setting time ranging from 15 minutes to approximately 3 hours. However, the retardation was increased for 15% SF replacement, and the setting time ranged from 45 minutes to approximately 4 hours. A setting time similar to the control mix was observed for MI and MII from the second set of mixtures. Generally, the initial setting time should be less than 45 min, while the final setting time should be not more than 10 hours [37]. The high concentration of HRWRA, which was required for workability enhancement, contributed substantially to promoting the setting time retardation. This could be due to the adsorbing action on cement grains or the dispersing action of HRWRA retarding the initial setting time and binder hydration, which can reduce cementitious hydration products [2]. Another reason that has been reported is that AWA molecules become adsorbed on cement grains initially in alite and particularly C3A [8].

Table 4. Setting time and washout resistance of NDRPC*

Mix ID	Mass after Test, gm	WOL%	Mix ID	Mass after Test, gm	WOL%
	GI			GII	
MI	1636	18.2	MI	1788	10.6
MII	1682	15.9	MII	1818	9.1
MIII	1718	14.1	MIII	1834	8.3
MIV	1748	12.6	MIV	1852	7.4
MV	1776	11.2	MV	1896	5.2
MVI	1834	8.3	MVI	1940	3
MVII	1860	7	MVII	1966	1.7

*Note: Mass before test was 2000 gm.

4. CONCLUSIONS

The influence of various AWA concentrations on NDRPC samples made with a constant w/b of 0.25 was investigated. The following conclusions are presented in this paper based on the experimental results:

(1) The slump flow of NDRPC is influenced, in order of significance, by AWA concentration, HRWRAA concentration, and SF incorporation. NDRPC mixtures have been achieved that meet SCM flowability requirements.

(2) The WOL of NDRPC can be enhanced significantly by increased AWA and SF contents despite the HRWRA overdosages required to ensure satisfactory flowability and passing ability.

(3) The reliance on instantaneous pH measurements for underwater concrete is not sufficient for indirect washout resistance evaluation. Therefore, pH value monitoring every 2 hours for at least 6 hours is more approachable, logical, and realistic. For the turbidity test, the results proved the inefficiency of instantaneous turbidity inspection at indirectly indicating the washout resistance.

(4) The resistance of the thrust water and surface tension are the main factors responsible for decreases in the filling ability of NDRPC. The filling ability of NDRPC underwater takes approximately twice as long as conventional filling in air, as investigated by the V-funnel test.

(5) Two types of barrier steel reinforcement bars and thrust of water were used to investigate the passing ability of NDRPC with the L-box test. Some mixes had acceptable H2/H1 results between 0.85-0.95 for the MI, MII, and MIII NDRPCs made with 15% SF; and MI and MII NDRPCs made with 30% SF.

(6) The coupled effect of AWA and HRWRAA concentrations on initial and final setting time was counterbalanced using NDRPC with 30% SF. A similar setting time to the control mix has been reported for MI and MII NDRPCs with 30% SF.

(7) It is worth noting the experimental work is still continuing to complete the investigation of hardened and long-term properties of NDRPC, as a second part of this line of research.

REFERENCES

[1] Zhu, J.H., Su, M.N., Huang, J.Y., Ueda, T., Xing, F. (2018). The ICCP-SS technique for retrofitting reinforced concrete compressive members subjected to corrosion. Construction and Building Materials, 167: 669-679. https://doi.org/10.1016/j.conbuildmat.2018.01.096

[2] Jeon, I.K., Woo, B.H., Yoo, D.H., Ryou, J.S., Kim, H.G. (2021). Evaluation of the hydration characteristics and anti-washout resistance of non-dispersible underwater concrete with nano-sio2 and mgo. Materials, 14(6): 1328. https://doi.org/10.3390/ma14061328

[3] Wang, J., Jiang, S.F., Cui, E.J., Yang, W.J., Yang, Z.X. (2022). Strength gain monitoring and construction quality evaluation on non-dispersible underwater concrete using PZT sensors. Construction and Building Materials, 322: 126400. https://doi.org/10.1016/j.conbuildmat.2022.126400

[4] Nasr, A.A., Chen, S.G., Wang, Y., Jin, F., Qiu, L.C. (2022). Influence of water currents velocity on the strength of a new underwater concrete approach. Construction and Building Materials, 356: 129236. https://doi.org/10.1016/j.conbuildmat.2022.129236

[5] Parghi, A., Alam, M.S. (2016). Seismic behavior of deficient reinforced concrete bridge piers confined with FRP-a fractional factorial analysis. Engineering Structures, 126: 531-546. https://doi.org/10.1016/j.engstruct.2016.08.011

[6] Ren, W., Sneed, L.H., Gai, Y., Kang, X. (2015). Test results and nonlinear analysis of RC T-beams strengthened by bonded steel plates. International Journal of Concrete Structures and Materials, 9: 133-143. https://doi.org/10.1007/s40069-015-0098-3

[7] Lehman, D.E., Gookin, S.E., Nacamuli, A.M., Moehle, J.P. (2001). Repair of earthquake-damaged bridge columns. Structural Journal, 98(2): 233-242. https://doi.org/10.14359/10192

[8] Khayat, K.H. (1995). Effects of antiwashout admixtures on fresh concrete properties. Materials Journal, 92(2): 164-171. https://doi.org/10.14359/9767

[9] Grzeszczyk, S., Jurowski, K., Bosowska, K., Grzymek, M. (2019). The role of nanoparticles in decreased washout of underwater concrete. Construction and Building Materials, 203: 670-678. https://doi.org/10.1016/j.conbuildmat.2019.01.118

[10] Mayhoub, O.A., Nasr, E.S.A., Ali, Y.A., Kohail, M. (2021). The influence of ingredients on the properties of reactive powder concrete: a review. Ain Shams Engineering Journal, 12(1): 145-158. https://doi.org/10.1016/j.asej.2020.07.016

[11] Nasr, A.A., Chen, S.G., Wang, Y., Jin, F., Qiu, L.C. (2022). Strength evaluation of a new underwater concrete type. Case Studies in Construction Materials, 16: e00884. https://doi.org/10.1016/j.cscm.2022.e00884

[12] Otsuki, N., Hisada, M., Nagataki, S., Kamada, T. (1996). An experimental study on the fluidity of antiwashout underwater concrete. ACI Materials Journal, 93(1): 20-25. https://doi.org/10.14359/9792

[13] Sonebi, M., Tamimi, A.K., Bartos, P.J.M. (2000). Application of factorial models to predict the effect of anti-washout admixture, superplasticizer and cement on slump, flow time and washout resistance of underwater concrete. Materials and Structures, 33: 317-323. https://doi.org/10.1007/BF02479702

[14] Sanjuán, M.Á., Andrade, C. (2021). Reactive powder concrete: durability and applications. Applied Sciences, 11(12): 5629. https://doi.org/10.3390/app11125629

[15] Heniegal, A.M., Maaty, A.A.E.S., Agwa, I.S. (2015). Simulation of the behavior of pressurized underwater concrete. Alexandria Engineering Journal, 54(2): 183-195. https://doi.org/10.1016/j.aej.2015.03.017

[16] Hasan, N., Faerman, E., Berner, D. (1993). Advances in underwater concreting: st. lucie plant intake velocity cap rehabilitation. Symposium Paper, 140: 187-214. https://doi.org/10.14359/3910

[17] Ali, T., Buller, A.S., Abro, F.U.R., Ahmed, Z., Shabbir, S., Lashari, A.R., Hussain, G. (2022). Investigation on mechanical and durability properties of concrete mixed with silica fume as cementitious material and coal bottom ash as fine aggregate replacement material. Buildings, 12(1): 44. https://doi.org/10.3390/buildings12010044

[18] Kumar, B.G., Muthu, M., Chajec, A., Sadowski, Ł., Govindaraj, V. (2022). The effect of silica fume on the washout resistance of environmentally friendly underwater concrete with a high-volume of siliceous fly ash. Construction and Building Materials, 327: 127058. https://doi.org/10.1016/j.conbuildmat.2022.127058

[19] Sonebi, M., Khayat, K.H. (1999). Effect of water velocity on performance of underwater, self-consolidating concrete. Materials Journal, 96(5): 519-528. https://doi.org/10.14359/653

[20] Plank, J., Sakai, E., Miao, C.W., Yu, C., Hong, J.X. (2015). Chemical admixtures-Chemistry, applications and their impact on concrete microstructure and durability. Cement and Concrete Research, 78: 81-99. https://doi.org/10.1016/j.cemconres.2015.05.016

[21] Lu, H., Sun, X., Ma, H.Y. (2022). Anti-washout concrete: an overview. Construction and Building Materials, 344: 128151. https://doi.org/10.1016/j.conbuildmat.2022.128151

[22] Wang, Y., Chen, S.G., Qiu, L.C., Nasr, A.A., Liu, Y. (2023). Experimental study on the slump-flow underwater for anti-washout concrete. Construction and Building Materials, 365: 130026. https://doi.org/10.1016/j.conbuildmat.2022.130026

[23] ASTM, C. (2021). Standard test methods for time of setting of hydraulic cement by vicat needle. ASTM International: West Conshohocken, PA, 4: 1-8. https://doi.org/10.1520/C0191-21

[24] Concrete, S.C. (2005). The European guidelines for self-compacting concrete. BIBM, CEMBUREAU, ERMCO, EFCA, 22: 563.

[25] Ceza, M., Bartos, P.J.M. (1996). Development of apparatus for testing the washout resistance of underwater concrete mixtures. Symposium Paper, 163: 111-126. https://doi.org/10.14359/1347

[26] Baluch, K., Baluch, S.Q., Yang, H.S., Kim, J.G., Kim, J.G., Qaisrani, S. (2021). Non-dispersive anti-washout grout design based on geotechnical experimentation for application in subsidence-prone underwater karstic formations. Materials, 14(7): 1587. https://doi.org/10.3390/ma14071587

[27] Lombardi, G. (1985). The role of cohesion in cement grouting of rock. Cong Large Dams.

[28] Abid, S.R., Hilo, A.N., Ayoob, N.S., Daek, Y.H. (2019). Underwater abrasion of steel fiber-reinforced self-compacting concrete. Case Studies in Construction Materials, 11: e00299. https://doi.org/10.1016/j.cscm.2019.e00299

[29] Khayat, K.H. (1996). Effects of antiwashout admixtures on properties of hardened concrete. ACI Materials Journal, 93(2): 134-146. https://doi.org/10.14359/1412

[30] Khayat, K.H., Assaad, J. (2003). Relationship between washout resistance and rheological properties of high-performance underwater concrete. ACI Materials Journal, 100(3): 185-193. https://doi.org/10.14359/12618

[31] Song, B.D., Park, B.G., Choi, Y., Kim, T.H. (2017). Determining the engineering characteristics of the Hi-FA series of grout materials in an underwater condition. Construction and Building Materials, 144: 74-85. https://doi.org/10.1016/j.conbuildmat.2017.03.101

[32] Rizwan, S.A., Gul, S., Bier, T.A. (2019). Self-consolidating paste systems containing acacia nilotica gum powder. ACI Materials Journal, 116(1) 5-14. https://doi.org/10.14359/51706841

[33] Zhang, M., Chen, L.K., Wang, X.F., Ge, W.J., Huang, J. (2015). Effect of main compositions of anti-washout admixture on paste. Materials Research Innovations, 19: S1-191-S1-194. https://doi.org/10.1179/1432891715Z.0000000001402

[34] Ghio, V.A., Monteiro, P.J.M., Gjorv, O.E. (1995). Effect of polysaccharide gums on fresh concrete properties. Materials Journal, 91(6): 602-606. https://doi.org/10.14359/1381

[35] Sonebi, M., Khayat, K.H. (2001). Effect of mixture composition on relative strength of highly flowable underwater concrete. ACI Materials Journal, 98(3): 233-239. https://doi.org/10.14359/10278

[36] Abdulqader, S.S., Al-Shathr, B.S., Hasan, A.K. (2018). Experimental behavior of self compacting concrete corbels strengthened with external CFRP. Engineering and Technology Journal, 36(2A): 154-162. https://doi.org/10.30684/etj.36.2A.6

[37] Al Saffar, D.M., Al Saad, A.J.K., Tayeh, B.A. (2019). Effect of internal curing on behavior of high performance concrete: an overview. Case Studies in Construction Materials, 10: e00229. https://doi.org/10.1016/j.cscm.2019.e00229