Laboratory Investigation of Underwater Concreting

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16. Abstract:

Concrete and grout with minimal washout are required for underwater placements from both a structural and environmental perspective. Resistance to washout and consolidation are factors difficult to achieve underwater using conventional concretes or grouts. Cohesive and self-consolidating concrete and grouts could provide the needed washout resistance and omission of consolidation efforts with mechanical vibration.

Cohesive concrete and grout mixtures with high flowability that have satisfactory strength and durability would satisfy both the structural and environmental needs of underwater placement. This study investigated the performance of both concrete and grout mixtures with and without self-consolidation in addition to various types of viscosity modifying admixtures for cohesiveness in an underwater environment. The laboratory study investigated concrete and grout mixtures resistant to washout and segregation underwater.

The study found that mass loss can be reduced through the choice of mixture ingredients, especially viscosity modifying admixtures; proper mixture proportions; use of grout bags; and the lowering of the slump or slump flow of the mixture. However, reduction of mass loss was not directly related to reduction of pH. To reduce the pH that is harmful to aquatic life, alternative cementitious materials—such as rapid set cements or magnesium phosphate binders—can be used. In addition, the increase of pH underwater mainly occurs while concrete is still plastic; thus, reducing the setting time would limit the pH exposure. The study recommends that the Virginia Department of Transportation update existing special provisions on underwater concreting to include the findings of this study.

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FINAL REPORT

LABORATORY INVESTIGATION OF UNDERWATER CONCRETING

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In Cooperation with the U.S. Department of Transportation
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FINAL REPORT

LABORATORY INVESTIGATION OF UNDERWATER CONCRETING

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INTRODUCTION

Based on several cost estimates for construction and scour restoration/rehabilitation for several Virginia Department of Transportation (VDOT) concrete structures in water, the cost of performing the work in the dry (e.g., within a cofferdam) is just over double that of performing the same work in the wet (underwater). Therefore, during new construction or in preservation/rehabilitation of existing structures in water, less expensive underwater concreting may be required (Fitch, 2003; Yao and Gerwick, 2004a; 2004b; 2004c). Underwater placement can be performed by placing grout or concrete generally with small size aggregate (i.e., No. 8 aggregate or pea gravel) in a grout bag or depositing them by tremie or pump generally behind a form in the water. Underwater placement requires a mix design that flows easily to provide proper consolidation while staying cohesive to prevent the washout, i.e., mass loss, of paste (Yao and Gerwick, 2004c). Excessive washout of paste reduces the strength of the grout and concrete and causes the pH of the stream to rise to levels that are harmful to organisms in the ecosystem; therefore, it is environmentally unacceptable (Fitch, 2003). A rise in pH is caused by the hydration of the cementitious materials, which results in high concentrations of hydroxyl ions being released into the water surrounding the concrete and grout. If at any time the pH reading in the water next to the concrete placement exceeds 9.0, VDOT requires that the contractor cease operations immediately to allow the stream to return to its baseline pH (Fitch, 2003).

Conventional concrete used underwater usually has high slump for easy consolidation of the material without any equipment since mechanical vibration deep in the water and under the foundation of existing structures is not possible (Yao and Gerwick, 2009). Self-consolidating concretes (SCCs) and grouts have high flow rates. SCC is made with conventional concrete materials and contains admixtures for workability and stability (American Concrete Institute, 2007). SCC mixtures generally have a reduced volume of coarse aggregate, an increased volume of cement paste, and an increased volume of fine material compared to concretes with conventional slump to provide the workability and the stability (Morgan Girgis and Tuan, 2005). They include a high dosage of high-range water reducing admixture (HRWRA) for workability. These changes lead to a high flowability, which helps the concrete move around any reinforcement used in construction and consolidate without the use of vibration.

Mixtures with high flowability or fluidity are prone to segregation and lead to a higher mass loss in underwater concreting (Khayat et. al., 1996). For stability (resistance to segregation), cohesive mixtures are prepared using high fines from fine aggregate and cementitious material and a reduced water–cementitious material ratio, as is typical in SCC. In Virginia, concretes regularly include supplementary cementitious materials (SCMs) such as fly ash, slag cement, and silica fume, which provide cohesion, stability, and durability. In order to make the SCC mixture more cohesive, a viscosity modifying admixture (VMA) can also be added. It increases the viscosity and controls the rheological properties of the concrete. This improved cohesiveness could result in minimal washout of the fresh concrete and grout in water.

To reduce mass loss, grout bags can also be used; they act as formwork containing the cementitious material. However, paste could still seep out of the grout bags, increasing the pH (Yao et al., 1999). Grout bags are often used in tandem with turbidity curtains, which form a barrier that is not impermeable but still restricts the flow of water from one side of the curtain to the other (Yao et al., 1999). In hydraulic cement concretes, portland cement contributes to increases in pH; therefore, alternative cementitious material that has less of an effect on the pH would be beneficial to use in underwater concretes.

PURPOSE AND SCOPE

The purpose of this study was to investigate concretes and grouts that have reduced mass loss in underwater placement and exhibit minimal pH spikes to avoid harm to aquatic life. Concrete and grout using portland cements with different slump or slump flow and ingredients such as cementitious material, fibers, and admixtures at varying amounts were investigated with and without a grout bag. Cementitious material other than portland cement such as rapid set cement and magnesium phosphate (MGP)—including prepackaged material—was also investigated to determine if a lower mass loss and pH spike than with portland cement could be achieved. The mass loss of a mixture was determined in the laboratory using the U.S. Army Corps of Engineers (USACE) washout test procedure (USACE, 1985). The pH of the water was determined using a digital meter. Concretes and grouts with high flowability, especially those that are self-consolidating, were studied for ease of placement where consolidation using mechanical equipment is not possible.

METHODS

Concrete and grout mixtures with different cementitious materials were prepared in the laboratory and tested in water for mass loss and pH increase in the water. The amount of water in the column used in the USACE test was about 1.7 ft^3. For the mass loss test, a given amount of material was placed in a basket (Figure 1) and dipped into a column of water 3 times. Some of the tests were also done without the basket but with a grout bag (Figure 1). Mass loss is considered to be the difference between the original mass of the material and that remaining after the third dipping. At the end of the test, 1 ft above the bottom of the water column, the water solution was sampled and tested for pH. Each test comprised dipping the sample 3 times into the same water. In the beginning of each test, fresh water was used and had a pH value ranging from 7.1 to 7.5. Compressive strength was tested using 4 x 8-in cylinders for the concrete samples and 2-in mortar cubes for the mortars and prepackaged materials.

Figure 1. Underwater Column, Basket, and Grout Bag

Concrete with Type I/II portland cement was prepared as the control mixture using the mix design included in the USACE test procedure (USACE, 1985). Then, concretes were prepared with two types of portland cement (Type I/II and Type III) including supplementary cementitious material (SCM), fibers, and varying amounts of HRWRA and VMA for varying consistency and stability. The 3/4 in and 3/8 in nominal maximum size coarse aggregates were used in the concrete mixtures.

After the concrete testing, grouts without coarse aggregate but with portland cement and SCMs and VMAs were prepared and tested to determine the resistance to washout. The concretes and grouts did not contain an air entraining admixture since they were designed to be used underwater where freezing is not expected in the Virginia climate. If the concrete application would have had exposure to a freezing environment, air entraining admixture would have been added.

Then, concretes and grouts containing rapid set cements with and without portland cements were cast and tested. Tests also included two prepackaged cementitious repair materials prepared in accordance with the recommendations of the manufacturer. One of these prepackaged materials was expected to have strength loss underwater; therefore, testing was conducted to determine the extent of the loss with time.

Concretes and Grouts With Portland Cement and SCM

Concrete and grout mixtures with portland cements with the proportions shown in Table 1 were prepared and tested for mass loss and pH values. Except for the B1, B3, and B9 mixtures, the mixtures also contained SCM. The fly ash met the Class F specifications of ASTM C618. The effect of cement fineness was investigated by including Type III portland cement.

Table 1. Concrete and Grout Mixture Proportions (lb/yd^3)

Material	B1 (Control)	B2[a]	B3[b]	B4[c]	B5[d]	B6[e]	B7[f]	B8[g]	B9	B10
	8/3/16	**8/11/16**	**8/3/16**	**10/4/16**	**8/16/16**	**8/30/16**	**1/10/17**	**10/18/16**	**10/12/17**	**10/12/17**
Cement (Type I/II) (lb)	600	560	600	600	600	645	480	640	-	-
Cement (Type III) (lb)	-	-	-	-	-	-	-	-	800	640
Silica fume (lb)	-	35	-	-	32	35	-	-	-	-
Fly ash (lb)	-	105	-	150	151	120	120	160	-	160
Total cementitious material (lb)	600	700	600	750	783	800	600	800	800	800
w/cm	0.49	0.38	0.6	0.38	0.38	0.35	0.45	0.46	0.46	0.46
Coarse aggregate (lb)	1,696	1,485	1,696	1,485	1,485	1,535	1,485	-	-	-
Coarse aggregate size (in)	3/4	3/8	3/4	3/8	3/8	3/8	3/8	-	-	-
Sand (lb)	1,388	1,435	1,388	1,340	1,340	1,307	1,515	2,529	2,540	2540

w/cm = water–cementitious materials ratio; - = not used.

[a] Three batches with different amounts of high-range water reducing admixture and viscosity modifying admixture.

[b] Two batches, 1 with viscosity modifying admixture for increased viscosity.

[c] Six batches: 3 with different amounts of high-range water reducing admixture and 3 with different amounts of viscosity modifying admixture.

[d] Three batches with different amounts of high-range water reducing admixture.

[e] Three batches with different amounts of high-range water reducing admixture and viscosity modifying admixture.

[f] Two batches with different amounts of high-range water reducing admixture and viscosity modifying admixture.

[g] Eight batches: 4 with viscosity modifying admixture and 4 with different amounts of high-range water reducing admixture.

Concretes and Grouts With Rapid Set Cements and Portland Cements

In this series, rapid set cement alone or in combination with a reduced amount of portland cement was prepared and tested. The concretes and grouts were tested in the grout bags. The mixture proportions for this series of tests are given in Table 2.

In the batches with rapid set cement, which inherently have short setting times, the effect of setting time on pH increase was studied. Short setting times are desirable for pH control since set concretes exhibit a low pH increase. However, too short a setting time would make placement difficult and raise concerns with setting of material in the pump.

Table 2. Mixture Proportions for Concrete and Grout With Rapid Set Cement (lb/yd^3)

Material	**B11** **10/10/17**	**B12** **10/3/17**	**B13**[a] **9/26/17**	**B14**[b] **10/12/17**	**B15** **9/19/17**
Cement (Type III) (lb)	-	-	280	-	-
Cement (Type I/II) (lb)	-	-	-	-	401
Rapid set cement (lb)	800	658	329	640	197
Fly ash (lb)	-	-	49	160	60
Total cementitious material (lb)	800	658	658	800	658
w/cm	0.46	0.4	0.35	0.46	0.35
Coarse aggregate (lb)	-	1,804	1,804	-	1,272
Maximum coarse aggregate size (in)	-	1	1	-	1
Sand (lb)	2,530	1,188	1,270	2,529	1,804

w/cm = water–cementitious materials ratio; - = not used.

[a] Two batches; the second one has the same total amount of cementitious material but with 50% rapid set cement.

[b] Three batches with different amounts of viscosity modifying admixture and high-range water reducing admixture.

Prepackaged Materials

One of the two prepackaged materials prepared and tested was a quick setting cementitious patching material composed of portland and rapid set cements, graded and washed silica aggregates, accelerating additives, and workability and water reducing admixtures. The set time was expected to be 20 to 30 min. The other repair material tested was MGP mortar, which is a rapid-setting, rapid-hardening, material. Compared with portland cement, MGP mortar has a rapid setting, high early strength, the ability to set and harden at low temperatures, and high bonding strength. The set time was expected to be 30 to 45 min. Previous work has shown that MGP mortar loses strength underwater; however, adding metakaolin or silica fume was shown to reduce the strength loss (Lu and Chen, 2016; Orlov and Chernykh, 2016). In this study, both silica fume and Class F fly ash were used to determine the extent of strength loss reduction underwater.

pH Change in Fresh and Hardened Concrete

To investigate the effect of fresh and hardened concrete on pH increase, samples containing portland cement were made with the same mix design as for Batch B8. The sample was placed in the grout bag and submerged in the water column in accordance with the USACE test procedure, and the pH of the water was measured immediately after submersion. Then, another sample from the same mixture was kept moist for 1 day and this set concrete sample was submerged in the freshwater column; the pH of the water was measured and recorded at 1 day. Then, the sample stayed in water for an additional 2 days for a test on the third day.

RESULTS AND DISCUSSION

Concretes With Portland Cement and SCM

Figures 2 and 3 summarize the results of mass loss for concrete mixtures with varying consistency and the presence of a VMA. Figure 2 summarizes the concretes with conventional slump, and Figure 3 summarizes the concretes that are self-consolidating or have high flowability. The results indicated that slump or slump flow and the presence of the VMA affected the mass loss. The low slump or slump flow mixtures had low mass loss. The addition of VMA appeared to reduce the mass loss.

Figure 4 displays the relationship between the mass loss and the slump flow for different cementitious material contents. The results indicated that with a slump flow of more than 20 in, the mass loss increased and there was the tendency of higher mass loss with higher amounts of cementitious material.

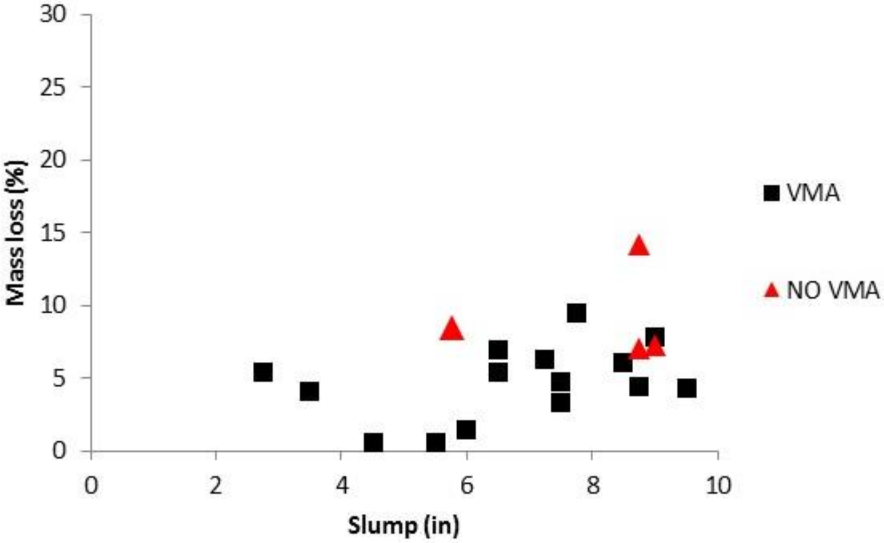

Figure 2. Conventional Concrete Mass Loss vs. Slump Using the Basket Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers; VMA = viscosity modifying admixture.

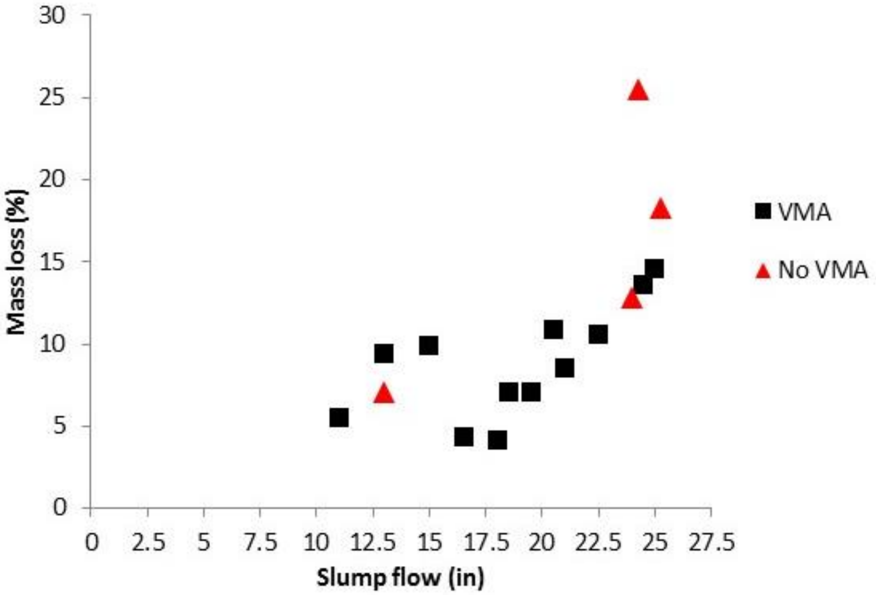

Figure 3. Self-Consolidating Concrete Mass Loss vs. Slump Flow Using Basket Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers; VMA = viscosity modifying admixture.

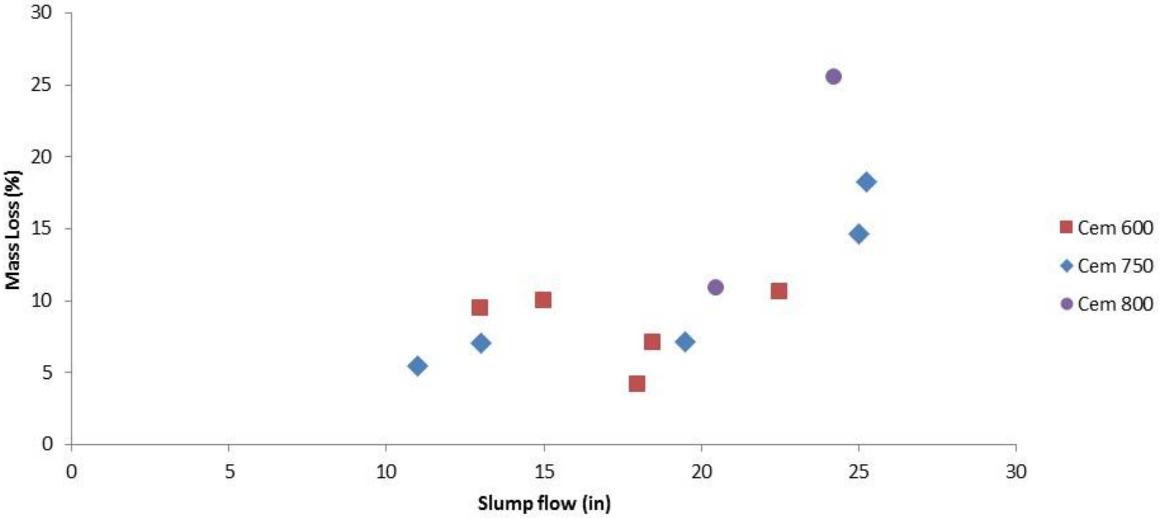

Figure 4. Concrete Mass Loss vs. Slump Flow for Mixtures With Different Amounts of Cementitious Material. Cem = portland cement content (lb/yd^3).

Figure 5 shows data comparing concretes tested in a basket or in the grout bag for Batch 7. Results indicated that with the grout bag, mass loss was less than with the basket. The grout bag retains the larger particles and enables a mass loss reduction of less than 5%. Figure 6 shows the concrete samples after immersion into the water column with a basket and a grout bag.

The results of pH testing are displayed in Figure 7. The pH values ranged between 11.1 and 11.6.

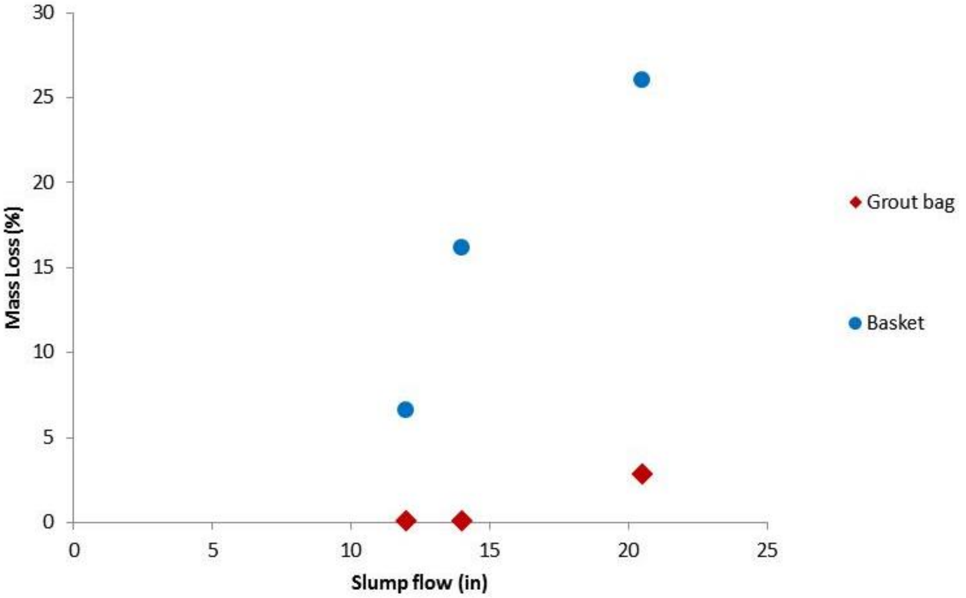

Figure 5. Concrete Mass Loss vs. Slump Flow Determined With Either a Grout Bag or a Basket as Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers.

Figure 6. Concrete Mass Loss After Immersion. The two left samples had a slump of 7.75 in: the top left sample was from the basket; the bottom left sample was from the grout bag. The two right samples had a slump flow of 22 in: the top right sample was from the basket; the bottom left sample was from the grout bag.

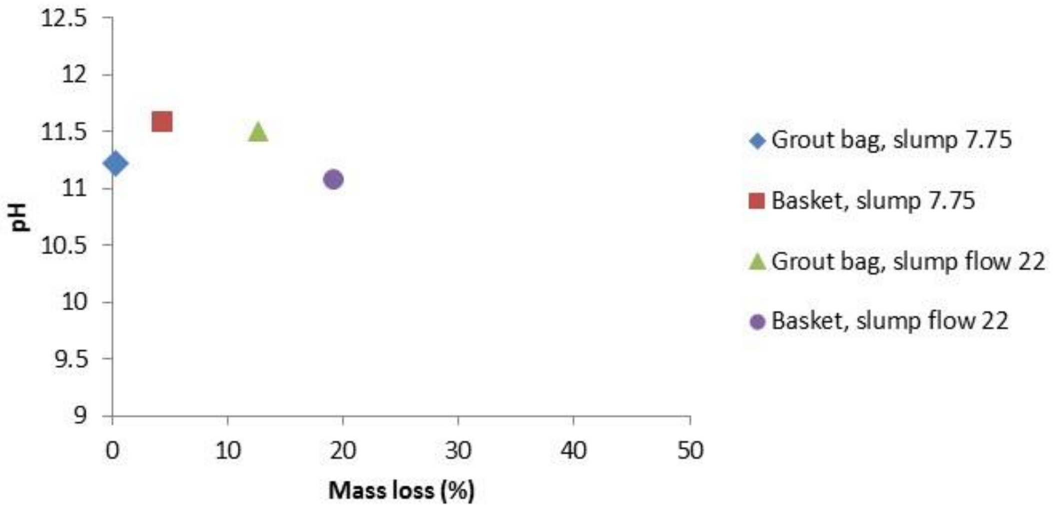

Figure 7. Concrete Mass Loss Using Grout Bag and Basket Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers.

Figure 8 shows the sample of solutions obtained for pH testing after the concrete mass loss test with a basket. Samples were darker when obtained after submerging concrete with high slump or slump flow. The darkness is attributed to the fine aggregate particles washing out of the basket. These particles affected the color change in the solution and mass loss.

Figure 8. Solutions Obtained After Submerging the Concrete in a Basket as Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers.

Grout Mixtures

Figure 9 shows the results for mass loss for varying slump values of grout mixtures with and without VMA. Figure 10 shows the relationship of the slump flow values.

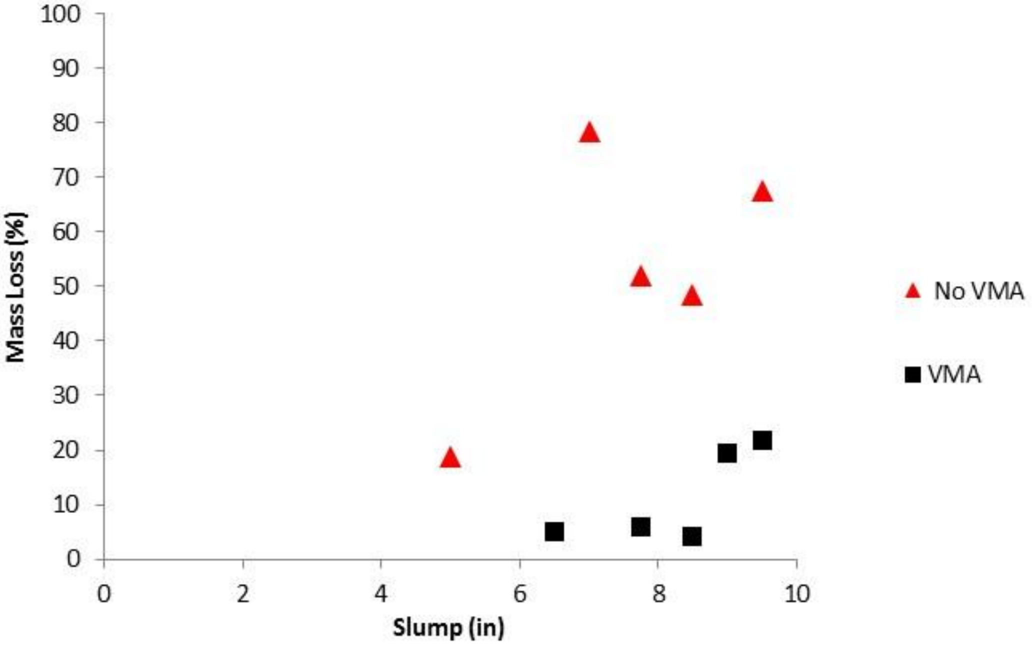

Figure 9. Grout Mass Loss vs. Slump Using Basket Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers; VMA = viscosity modifying admixture.

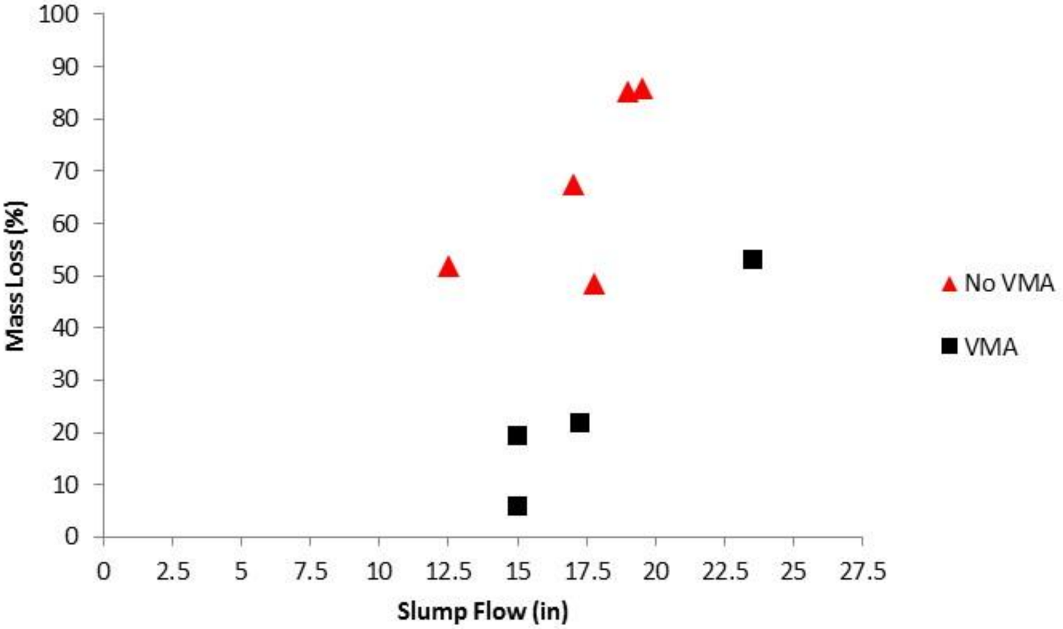

Figure 10. Grout Mass Loss vs. Slump Flow Using Basket Specified in the USACE Test Procedure. USACE = U.S. Army Corps of Engineers; VMA = viscosity modifying admixture.

The results indicated that the mass loss in grouts was higher than in concrete mixtures when the basket was used but followed the same trend; mass loss was higher with increased flowability and was reduced with the addition of a VMA.

Figure 11 shows data comparing grout tested with the basket and grout tested in a grout bag for Batch B8. Results indicated that grout bags reduced the mass loss. The results of pH testing for the grouts are displayed in Figure 12. The pH values ranged from 11.4 to 12.0.

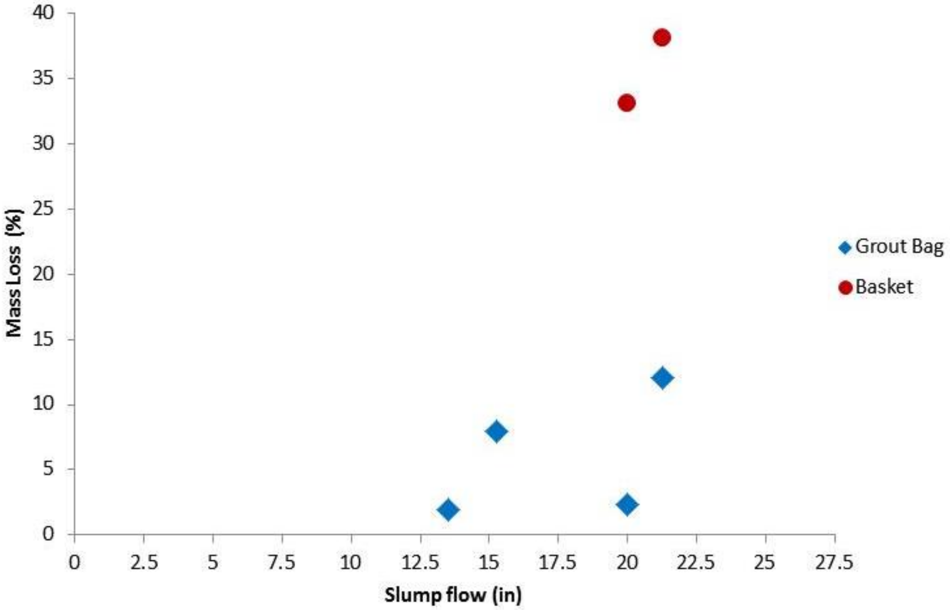

Figure 11. Grout Mass Loss vs. Slump Flow for Batch B8

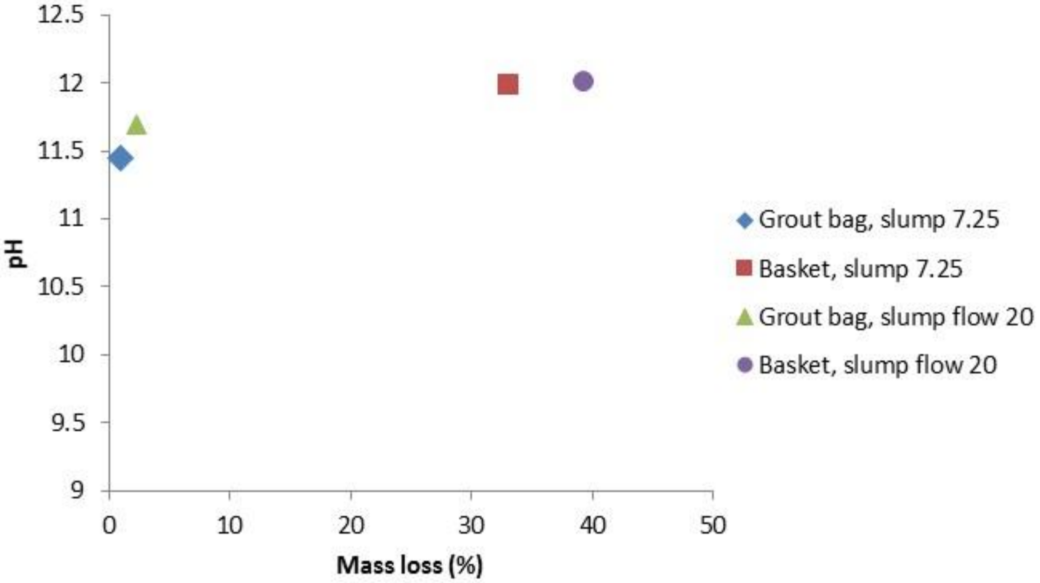

Figure 12. pH Values vs. Grout Mass Loss

As shown in Figures 7 and 12, grout mass loss from the basket was much higher than concrete mass loss from the basket. Fine grout material in the basket is able to mix with water and flow out the openings of the basket easily, which causes the higher mass loss.

The 7-day compressive strength of the grouts and concretes ranged from 3,860 to 5,460 psi, and the 28-day compressive strength ranged from 4,880 to 7,410 psi. All strengths were greater than the 2,500 psi specified for the underwater concrete.

Concretes and Grouts With Rapid Set Cements and Portland Cements

The relationship between the mass loss and pH in mixtures using rapid set cement is displayed in Figure 13. The mass loss ranged from 2.2% to 9.3%, and the pH from 9.9 to 11.3. The results indicated that the mass loss and pH of mixtures with rapid set cement were lower than for the mixtures with only the portland cements. However, in the underwater applications, a larger amount of water will reduce the pH compared to that observed in the column test. The column test values could indicate a ranking system that could suggest the likelihood of damage to marine life before the field placement.

Rapid set cement has a different chemical formulation than portland cement, contributing to the lower pH values. It also has a reduced setting time, which ranges from 20 min to 40 min. The cementitious material stiffens fast and therefore the mass loss is reduced, and the pH increase occurs in a short time period.

In all mixtures with rapid set cement, the 3-hr compressive strength ranged from 4,210 to 4,390 psi. The 1-day compressive strength ranged from 5,510 to 6,270 psi, and the 28-day compressive strength ranged from 6,820 to 7,080 psi.

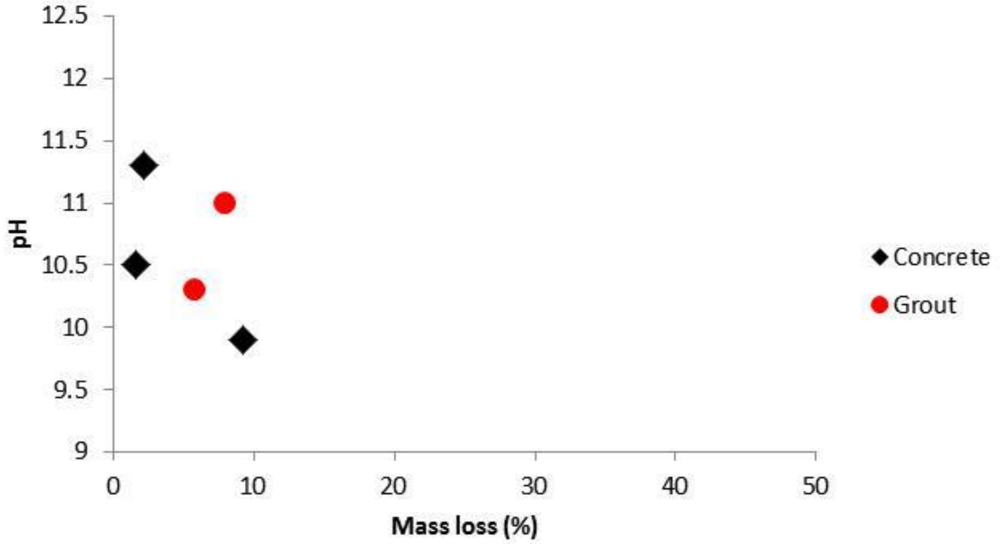

Figure 13. Concrete and Grout pH Values vs. Mass Loss for Mixtures With Rapid Set Cement

Prepackaged Material

The first prepackaged material tested had very high viscosity and low workability and was not suitable for underwater applications. The workability was minimally improved by adding an HRWRA recommended by the manufacturer, but the mixture was still not suitable.

The second prepackaged material was MGP mortar. It was a workable mixture, and the mass loss from the grout bag was low, at 3%. The set time was 30 min, and the pH of the water tested using the USACE test column was 8.0. Table 3 indicates the cube compressive strength of the MGP mortar under different methods of curing, in air and in water, to determine the water sensitivity. The decrease in strength at 28 days did occur for cube specimens stored in water for all mixtures; however, the use of fly ash and silica fume reduced the decrease in strength loss. Even with a reduction in strength, the compressive strengths were very high, much higher than the 28-day strength of 2,500 psi generally specified for the underwater concrete. In actual structures, a large amount of MGP mortar material would be used and the strength loss effect of the water would be less since the penetration of water to the core of the large element would be minimal.

In the next trial, longer curing times of 3 months were used for the mixtures with and without 30% fly ash added to the MGP mortar. The compressive strength of the cubes at different ages with air and water curing is summarized in Table 4.

The compressive strength test results were similar between the two batches, indicating that the compressive strengths of the MGP mortar with or without fly ash were lower when the samples were kept in water; however, the mortars had very high strengths compared to the 2,500 psi generally specified.

Table 3. Cube Compressive Strength Results at Different Ages With Different Supplementary Cementitious Materials

	MGP		**MGP and 30% Fly Ash**		**MGP and 10% Silica Fume**	
Age	**In Air**	**In Water**	**In Air**	**In Water**	**In Air**	**In Water**
3 hr (psi)	4,440	-	5,520	-	5,750	-
1 day (psi)	7,950	6,700	8,230	10,160	6,420	6,860
7 days (psi)	10,960	11,650	7,390	12,840	9,880	10,320
28 days (psi)	14,140	8,960	16,520	12,050	14,820	12,330

MGP = magnesium phosphate; - = no data.

Table 4. Cube Compressive Strength Results at Different Ages With Fly Ash

	MGP		**MGP and 30% Fly Ash**	
Age	**In Air**	**In Water**	**In Air**	**In Water**
At the time of set (1.5 hr) (psi)	720	-	2,390	-
3 hr (psi)	3,360	2,400	3,550	3,650
1 day (psi)	5,050	5,720	6,460	6,690
7 days (psi)	9,220	7,610	6,770	6,560
28 days (psi)	11,170	8,410	9,890	7,800
3 months (psi)	10,950	7,780	10,210	8,640

MGP = magnesium phosphate; - = no data.

pH Change in Fresh and Hardened Concrete

As shown in Table 5, the pH of the water containing fresh concrete with portland cement was high, as expected.

However, concretes that had started to set and started to gain strength (hardening) had low pH values, as shown in Table 5. Thus, once they have set, the contribution of concretes to the pH rise is minimal.

Table 5. pH Values for Batch B8

Age	pH
2 min (fresh)	11.9
1 day	7.6
2 days	8.9
3 days	8.4

CONCLUSIONS

- *Concretes and grouts with portland cements have high mass loss when tested in accordance with the USACE test procedure using a basket. Grouts can have higher mass loss than concretes when tested in the basket. The addition of a VMA or a reduction in the slump or slump flow of the concrete can reduce mass loss. The mass loss includes both cement and aggregates.*

- *The addition of VMA in concretes and grouts and the use of grout bags can reduce mass loss to less than 5% as measured in the USACE test.*

- *pH increases in the water in the USACE test when concrete is in the fresh state. Hardened concretes have a negligible or small effect on pH in the surrounding water.*

- *When Type I/II cements or Type III cements were used with varying cementitious contents or with SCMs, high pH values ranging from 11.4 to 12.0 were obtained when the water was tested 1 ft above the bottom of the USACE test column after the determination of mass loss.*

- *The use of rapid set cement reduces the pH of the water used in the USACE test compared to the use of only portland cements. The pH values ranged from 9.9 to 11.3. Mixtures with a higher percentage of rapid set cement and a lower percentage of portland cement had lower pH values. With rapid set cements, pH is lower in the surrounding water and the set is faster, limiting the exposure time since the pH rise mainly occurs in the water when concrete is in the fresh state.*

- *The use of MGP prepackaged material can result in the lowest pH values in the USACE column test, about 8.0.*

- *The compressive strength of the MGP prepackaged material varies with curing type: water curing can result in reduced compressive strength; however, the addition of fly ash and/or silica fume can reduce the weakening effect of water curing. The use of the MGP prepackaged material can result in high compressive strengths even when cured in water. The strength reduction was minimal, and the strengths were much higher than the 2,500 psi generally specified.*

RECOMMENDATIONS

1. *VDOT's Materials Division, Structure and Bridge Division, and Environmental Division should work with the Virginia Transportation Research Council to update the existing VDOT special provisions for underwater concreting based on the results of this study.*

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, VDOT's Materials Division, Structure and Bridge Division, and Environmental Division, working together, will update the existing VDOT special provisions to provide one consolidated special provision within 1 year from the publication of this report to address concerns of the Virginia environmental regulatory agencies regarding underwater concreting.

Benefits

An updated special provision will provide environmentally sound options for varying site conditions that will make it easier and more cost-effective to repair underwater scour on bridge substructures, which is a serious problem on some Virginia bridges. The updated special provision will be beneficial in reducing risk to aquatic life potentially resulting from bridge scour repair.

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