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Laboratory Investigation of Workable and Durable Concretes for Bridge Repair

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Concretes for bridge repair that attained 3,000 psi compressive strength within 10 hours, 1 day, and 7 days and had high workability and durability were investigated in the laboratory. Supplementary cementitious materials (SCMs) were used in concrete with portland cement to make the mixture resist the penetration of harmful solutions and chemical attack. These concretes were air entrained for proper resistance to cycles of freezing and thawing. When high early strength was needed, high amounts of portland cement and low water–cementitious materials ratios were used in these concretes that made them prone to cracking. However, fibers were investigated to control the cracking. Mixtures with rapid setting cement were also tested for high early strengths.

Test results indicated that with high amounts of portland cement with an SCM or the use of rapid setting cement, desired strength can be achieved within 10 hours. To achieve 3,000 psi in 1 day and 7 days, lower amounts of portland cement with an SCM and overall lower paste contents were used, making them less prone to cracking.

The study recommends that high amounts of portland cements with SCMs be used to achieve 3,000 psi within 10 hours with setting times long enough for mixing and delivery by truck mixers and placement. These concretes may need to be insulated at the jobsite to retain heat to ensure early strengths are achieved. If shorter setting times can be accommodated using on-site mobile mixers, rapid setting cement can be used to achieve a 3,000 psi compressive strength within a few hours, i.e., much less than 10 hours. For longer times, more than 1 day, to attain 3,000 psi, portland cements containing SCMs with a low cementitious materials content should be used; they are cost-effective, easier to make, and have less cracking potential than the high early strength mixtures with portland cement with an SCM. If cracking is anticipated, fibers can be added. In the laboratory, an efficient pan type mixer was used to obtain uniform blending of ingredients and good distribution of fibers. In future field work, large quantities of material would be mixed and delivered in ready mixed concrete trucks or mobile mixers, which are not as efficient as laboratory mixers. Use of ready mixed trucks and mobile mixers to provide the recommended mixtures needs to be investigated to identify any issues and to streamline the implementation of the mixtures.

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FINAL REPORT

LABORATORY INVESTIGATION OF WORKABLE AND DURABLE CONCRETES FOR BRIDGE REPAIR

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ABSTRACT

Concretes for bridge repair that attained 3,000 psi compressive strength within 10 hours, 1 day, and 7 days and had high workability and durability were investigated in the laboratory. Supplementary cementitious materials (SCMs) were used in concrete with portland cement to make the mixture resist the penetration of harmful solutions and chemical attack. These concretes were air entrained for proper resistance to cycles of freezing and thawing. When high early strength was needed, high amounts of portland cement and low water–cementitious materials ratios were used in these concretes that made them prone to cracking. However, fibers were investigated to control the cracking. Mixtures with rapid setting cement were also tested for high early strengths.

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INTRODUCTION

In bridge repairs, very early strength is generally needed and is achieved using special rapid setting cements (RSCs). Concretes containing RSC attain 3,000 psi within 2.5 hours to limit lane closures and minimize inconvenience to the traveling public (Sprinkel, 1999; Sprinkel, 2006). Concretes with RSC have short setting times, about 15 minutes, and are produced in mobile mixers at the jobsite. They are used in bridge repairs with a latex modifier to reduce permeability and provide better adhesion to the existing concrete for improved durability. With concretes containing portland cement, setting times are longer, about 3 to 5 hours, enabling them to be produced and delivered in ready mixed concrete trucks.

Because of the long setting times and the different chemical composition of portland cement, strength development takes longer when portland cements rather than RSC are used. Currently, the Virginia Department of Transportation (VDOT) specifies concretes for pavement and bridge repairs with an early strength of 2,000 psi at 6 hours; typically, only portland cements are used. These mixtures have a cementitious material content as high as 800 lb/yd^3, and they can be classified as high early strength (HES) mixtures. The early temperature rise with these mixtures enables the early strength development. Sometimes, 3,000 psi is required within 24 hours, and such mixtures can be classified as early strength (ES) mixtures. When longer setting and strength gain times are possible and specifications require 3,000 psi in 7 days, regular strength mixtures (RSMs) with low paste contents can be used.

HES repairs made with portland cement alone have high cement contents and are typically not durable (Sprinkel et al., 2019). However, this problem is commonly solved by using supplementary cementitious materials (SCMs) such as fly ash and slag cement in paving and bridge concretes to increase durability. SCMs provide low permeability (Ozyildirim, 1998) and resistance to chemical attack such as alkali-silica reaction, which increases the durability of concrete. SCMs are commonly used as a partial replacement for portland cement and have a tendency to reduce the early strength development since less portland cement is used. However, if the proper amount of portland cement and SCM were used, the concrete mixtures could develop high early strength.

Reduced cementitious material content and paste contents minimize cracking in bridge decks (Darwin et al., 2016). The paste content is the amount of paste (mixture of cementitious material and water) expressed as a volume percent of the concrete mixture. VDOT encourages the use of low cracking bridge deck concretes, which control the amount of cementitious material content by specifying a maximum amount to use in a mixture (VDOT, 2016). HES and sometimes ES concretes have high cement, water, and paste contents that make them prone to cracking caused by temperature rise, moisture loss, and chemical attack such as alkali-silica reaction (Lane and Ozyildirim, 1995). Wide and deep cracks reduce durability since they facilitate the intrusion of solutions to the level of the reinforcement (Balakumaran et al., 2017). In addition to proper mixture proportioning and good construction practices, fibers can be added to reduce the potential for wide and deep cracking.

VDOT has experimented with fiber reinforced concretes (ACI Committee 544, 2009) with polyvinyl alcohol, polypropylene (PP), or steel fibers to control cracking (Ozyildirim and Nair, 2017). Fiber reinforced concretes with the proper type and amount of fibers can exhibit strain and deflection hardening, enabling an increase in load-carrying capacity with further deformation after the first crack, which results in multiple tight cracks (Naaman, 2007). When cracks are tight (less than 0.1 mm in width), the penetration of water and harmful solutions is negligible (Lawler et al., 2002; Wang et al., 1997), again contributing to a more durable concrete.

Entrapped air voids in concrete are minimized through proper consolidation to ensure proper strength and permeability (Ozyildirim, 2005a). Concrete with high workability, such as self-consolidating concrete (SCC), does not require mechanical energy to consolidate (ACI Committee 237, 2007). SCC has been used in Japan and Europe advantageously since the 1990s (Okamura and Quchi, 1999). VDOT has been using SCC in structures since 2001 to improve workability and eliminate consolidation problems (Ozyildirim, 2005b; Ozyildirim and Moruza, 2015). It would be useful to explore the use of SCC in delivery and placement operations for repairs.

Although VDOT has done much research with regard to producing concretes that are durable and less prone to cracking, problems exist with the workability and durability of the repairs, especially when portland cements alone are used. There is still a need to produce and use concretes that have setting times that are long enough for the convenience of delivery and placement operations and that have high workability for ease of placement and high durability for extended service life with minimal maintenance. Rapid setting concrete is another viable option for high early strengths to be explored to improve cracking resistance. These concretes must meet the needs of traffic constraints. Sometimes, high early strengths are needed if the lane closure times are limited; however, there are occasions when lane closure times are not limited and concretes with lower cementitious materials and paste contents that are more cost-effective and less prone to cracking can be used. Fibers should also be investigated in concretes with high cementitious material contents and a high cracking potential to minimize cracking and increase durability.

PURPOSE AND SCOPE

The purpose of this study was to investigate workable and durable concretes for bridge repair. Mixtures with portland cement and SCMs that reach compressive strengths of 3,000 psi within 10 hours (HES), 1 day (ES), and 7 days (RSM) were prepared in the laboratory. Concretes with special cement such as RSC that achieved 3,000 psi strength in less than 10 hours (HES) were also investigated. The RSC used in this study was a calcium sulfoaluminate cement that enables rapid hardening or strength gain in concrete. To control cracking in mixtures with a high cementitious material content, fibers were also investigated.

METHODS

This section explains the ingredients and proportions of HES mixtures, ES mixtures, and RSMs.

Concretes containing commonly used Type I/II portland cement, RSC, and the combination of the two were prepared in the laboratory. The materials were mixed in an efficient pan type laboratory mixer that enabled uniform blending of the ingredients and good distribution of the fibers. In field work, small amounts of materials can be mixed in mortar mixers, which also provide efficient mixing. However, larger amounts of material would be mixed and delivered in ready mixed concrete trucks or volumetric mobile mixers, which are not as efficient as the mortar or pan type mixers for uniformity and fiber distribution and would require further investigation.

The specific gravity of portland cement is 3.15 and of RSC is 2.98. Concretes with portland cements also contained SCMs for durability. In some of the rich mixtures with high amounts of cementitious material, synthetic PP fibers and steel fibers were added to control cracking. The fresh concrete properties were tested for air content (ASTM C231), slump (ASTM C143), and density (ASTM C138). The hardened concrete tests used are summarized in Table 1.

The time to reach 3,000 psi compressive strength was estimated by the maturity method in accordance with ASTM C1074. The temperature of HES specimens kept in an insulated box to retain heat was recorded continuously for 1 day. At 1 day, the specimens were demolded and kept in the moist room at room temperature. The time of initial setting was estimated from the temperature data and checked by indenting the tamping rod into the concrete specimens. When the concrete sets, the rod no longer penetrates the surface. With regard to the temperature data, setting takes place as the temperature rise occurs: the intersection of a line following the initial part of the temperature curve with the line from the rising part of the curve indicates the initial setting time (Taylor, 2018).

Table 1. Hardened Concrete Tests

Test	Test Standard	Specimen Size
Compressive strength	ASTM C39	4 x 8 in cylinder
Drying shrinkage	ASTM C157	3 x 3 x 11 1/4 in beam
Flexural strength	ASTM C1609	4 x 4 x 14 in beam
Permeability (chloride ion)	ASTM C1202	4 x 2 in cylinder
Splitting tensile strength	ASTM C496	6 x 12 in cylinder

Ingredients and Proportions of HES Mixtures

Initially, the HES mixtures with portland cement summarized in Table 2 were prepared. Batches HES-1 through HES-7 had different amounts of portland cement and SCMs (silica fume and Class F fly ash). Air-entraining, workability-retaining, and high-range water-reducing (HRWR) admixtures were added to the mixtures. The HES mixtures with portland cement have a high paste content, exceeding 30%, and a low water–cementitious materials ratio (w/cm), 0.27 to 0.29. The HES mixtures investigated are prone to cracking because of the high cementitious material content, ranging from 825 to 1,020 lb/yd^3, and the high paste content. Specimens were cured in insulated curing boxes for 1 day and then demolded and kept in a moist room. In some batches, different types and amounts of fibers were added to investigate crack control. Batch HES-4 contained 2-in-long PP fibers. Batches HES-6, HES-7, HES-11, HES-12, and HES-13 had different amounts of hooked end steel fibers. They were 1.2 in long, glued to prevent balling, and had an aspect ratio (length/diameter) of 55. Fibers were well mixed and dispersed in the pan type mixer without any clumping.

Batches HES-8 through HES-13 in Table 2 had RSC or a combination of RSC and portland cement. RSC is fast setting and has high early strength and very low shrinkage. The w/cm for these mixtures, 0.40, was higher than for the mixtures with HES with portland cement, and the paste content was 28% when only RSC was used. The paste content of mixtures when portland cement and RSC were used together were 43% or 46%; these are very high paste contents. The concretes with portland cement have delayed setting time and slower strength development in comparison to concretes with RSC. Combining portland cement with RSC could enable setting times between those achieved by portland cement and RSC mixtures to meet the needs of a given project. Long setting times enable the preparation of mixtures in ready mixed concrete trucks. Citric acid or cold water can be added to extend the setting time of RSC; however, the setting time even with citric acid will be much less than that achieved in mixtures with portland cement, alone or in combination with RSC.

Table 2. High Early Strength (HES) Mixtures

Batch No.	PC (lb/yd^3)	RSC (lb/yd^3)	SCM (lb/yd^3)	Total Cementitious Material (lb/yd^3)	Fiber (lb/yd^3)	w/cm	Paste Content (%)
HES-1	784	---	41 (SF)	825	---	0.29	30
HES-2	850	---	45 (SF)	895	---	0.27	32
HES-3	786	---	139 (FA)	925	---	0.29	34
HES-4	786	---	139 (FA)	925	PP/12	0.29	34
HES-5	850	---	150 (FA)	1,000	---	0.27	36
HES-6	786	---	139 (FA)	925	S/80	0.29	34
HES-7	786	---	139 (FA)	925	S/160	0.29	34
HES-8	714	306	---	1,020	---	0.40	46
HES-9	510	510	---	1,020	---	0.40	43
HES-10	918	102	---	1,020	---	0.40	43
HES-11	---	658	---	658	S/80	0.40	28
HES-12	---	658	---	658	S/160	0.40	28
HES-13	---	658	---	658	S/265	0.40	28

PC = portland cement; RSC = rapid setting cement; SCM = supplementary cementitious material; w/cm = water–cementitious materials ratio; --- = not used; SF = silica fume; FA = Class F fly ash; PP = polypropylene; S = steel.

Ingredients and Proportions of ES Mixtures

In the ES mixtures, paste content was kept lower than for the HES mixtures, 26% to 29%, and the w/cm was kept higher, 0.38 to 0.41. There were no fibers in these mixtures since cracking potential was expected to be low because of the lower paste content. Table 3 summarizes the ES mixtures. Portland cement, Class F fly ash, and air-entraining and HRWR admixtures were used. Two different types of curing were used. Specimens were cured in either insulated curing boxes or the laboratory environment for 1 day. Then, they were demolded and kept in a moist room.

Table 3. Early Strength (ES) Mixtures

Batch No.	PC (lb/yd^3)	SCM (lb/yd^3)	Total Cementitious Material (lb/yd^3)	w/cm	Paste Content (%)
ES-1	559	99 (FA)	658	0.38	28
ES-2	510	90 (FA)	600	0.41	27
ES-3	540	95 (FA)	635	0.38	27
ES-4	559	99 (FA)	658	0.41	29
ES-5	510	90 (FA)	600	0.40	26

PC = portland cement; SCM = supplementary cementitious material; w/cm = water–cementitious materials ratio; FA = Class F fly ash.

Ingredients and Proportions of RSMs

In the RSMs, the paste ratio was kept lower, 26% to 28%, and the w/cm higher, 0.43 to 0.45, than for the HES and ES mixtures. There were no fibers in these mixtures since cracking potential was expected to be low because of the low paste contents. Air-entraining and HRWR admixtures were also added. Specimens were cured in the mold at room temperature for 1 day and then demolded and kept in a moist room. Table 4 summarizes the mixtures.

Table 4. Regular Strength Mixtures (RSMs)

Batch No.	PC (lb/yd^3)	SCM (lb/yd^3)	Total Cementitious Material (lb/yd^3)	w/cm	Paste Content (%)
RSM-1	500	88 (FA)	588	0.45	28
RSM-2	479	85 (FA)	564	0.43	26

PC = portland cement; SCM = supplementary cementitious material; w/cm = water–cementitious materials ratio; FA = Class F fly ash.

RESULTS AND DISCUSSION

HES Mixtures

Fresh concrete properties and compressive strength results for HES mixtures are given in Table 5. The concretes were workable, and the workability was increased by the addition of more HRWR admixture, enabling self-consolidation. The initial setting time is also given in Table 5. The compressive strength results indicate that 3,000 psi can be obtained in 8.5 hours or less. HES-1 and HES-2 had silica fume as the SCM.

Table 5. Concrete Properties and Setting Time for High Early Strength (HES) Mixtures

Batch No.	Fresh Density (lb/ft^3)	Slump (in)	Air (%)	Initial Set Time (hr)	Time to Reach 3,000 psi (hr)	1-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)
HES-1	152	3.75	4.7	4.5	8.0	7,400	10,090
HES-2	145.6	3.75	8.5	4.5	8.5	5,930	8,900
HES-3	148.4	3.5	6.2	4.0	7.25	6,300	9,230
HES-4	148.4	3.5	6.4	4.5	8.5	6,150	8,740
HES-5	148	7.5	6.1	3.5	8.25	5,460	8,500
HES-6	153.8	2.0	3.8	1.5	---	6,850	9,550
HES-7	154.8	27[c]	3.3	1.75	---	6,270	11,520
HES-8[a, b]	---	---	---	0.75	5.5	4,300	8,550
HES-9[a, b]	---	---	---	0.5	2.25	5,830	7,740
HES-10[a, b]	---	---	---	4.0	8.25	6,500	8,990
HES-11[a]	---	---	---	0.4	---[d]	---	9,260
HES-12[a]	---	---	---	0.4	---[d]	---	9,310
HES-13[a]	---	---	---	0.4	---[d]	---	10,210

--- = no data.
[a] In mixtures with portland cement and/or rapid setting cement, slump, air content, and fresh density were not measured, mainly because of short setting times.
[b] These mixtures with portland cement and rapid setting cement were air entrained.
[c] Slump flow (ASTM C1611).
[d] Compressive strength at 3 hours for batches HES-11, HES-12, and HES-13: 5,530, 6,140, and 6,030 psi, respectively.

Silica fume helped to achieve the 3,000 psi in around 8.5 hours with a lower amount of cementitious material in the mixtures with portland cements.

Batches HES-8, HES-9, and HES-10 were designed with different amounts of RSC and portland cement, as shown in Table 6. The 3,000 psi compressive strength was achieved in 2.25 to 5.5 hours, depending on the amount of RSC and the setting time. The results summarized in Table 6 indicate that higher amounts of RSC resulted in shorter setting times and reduced the time to reach 3,000 psi compressive strength. Batches HES-11 through HES-13 had RSC only with different amounts of steel fibers. They had short setting times and reached very early and high 28-day strengths even at a w/cm of 0.40, as shown in Table 5.

Results for flexural tests for mixtures with fibers are given in Table 7 and Figure 1. The specimens exhibiting deflection hardening (Figure 1) had the highest amounts of steel fibers. PP fibers and low amounts of steel fibers led to lower residual strength. The addition of fibers provided for residual strength, and both deflection hardening and softening occurred (Naaman, 2007).

Table 6. Properties of Mixtures With Portland Cement and Rapid Setting Cement

Batch No.	Rapid Setting Cement (%)	Citric Acid / RSC (%)	Initial Set Time (hr)	Time to Reach 3,000 psi (hr)
HES-8	30	1.5	0.75	5.5
HES-9	50	1.5	0.5	2.25
HES-10	10	1.0	4.0	8.25

RSC = rapid setting cement; HES = high early strength.

Table 7. Flexural Test Data at 7 Days (psi)

Batch No.	Fibers (amount in lb/yd^3)	First-Peak Strength	Residual Strength at Span/600	Residual Strength at Span/300	Residual Strength at Span/150
HES-4	PP (12)	988	219	253	293
HES-6	S (80)	1,083	417	315	178
HES-7	S (160)	1,214	1,133	980	746
HES-11	S (80)	977	828	816	570
HES-12	S (160)	891	1015	902	632
HES-13	S (265)	976	1,331	1,218	1,050

HES = high early strength; PP = polypropylene; S = steel.

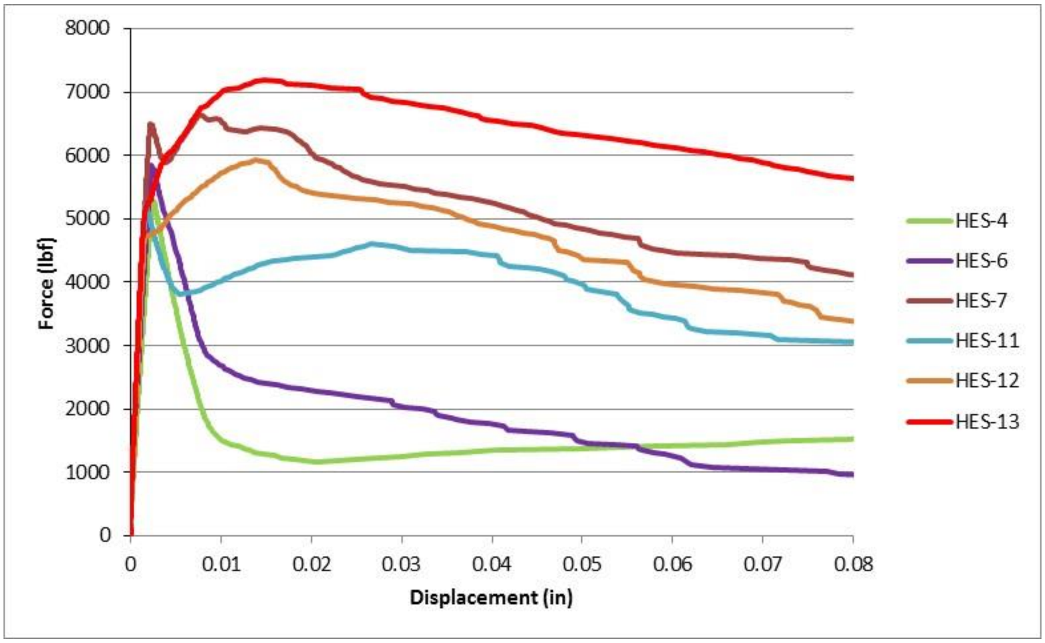

Figure 1. Load vs. Deflection at 7 Days for High Early Strength (HES) Mixtures

Deflection softening is indicated by lower residual strengths after the first crack. Deflection softening with a certain level of residual strength may be sufficient to keep cracks tight since there is primary reinforcement in the structures (Mobasher et al., 2015). However, if crack control is not achieved by deflection softening, higher levels of residual strength or deflection hardening may be needed. This can be accomplished by proper selection of the type and amount of fibers. PP fibers should be used with caution for structural applications since they have low elastic modulus and high creep values that would cause the cracks to widen with time under load.

Figure 1 displays load-deflection curves and shows, when read in conjunction with Table 7, that concretes with higher amounts of fibers have higher residual strengths. At high additions of steel fibers, Concretes HES-7, HES-12, and HES-13 exhibited deflection hardening. Cracked sections become stronger with the contribution of fibers than the uncracked sections. Thus, new cracks form near the initial crack, leading to multiple tight cracks.

Permeability specimens were tested at 28 days in accordance with ASTM C1202. Specimens were subjected to accelerated curing, i.e., moist cured 7 days at room temperature and

3 weeks at 100 ºF. The values ranged from 699 to 879 C for six specimens, two each from HES-1 through HES-3; they were less than 1000 C, indicating very low permeability. The low values are attributed to the use of SCM and the low w/cm. RSC modified with latex have also been found to achieve very low permeability (Ozyildirim and Nair, 2017).

Length change results after 28 days of drying for specimens from HES batches are displayed in Figure 2. They had high paste contents, and the shrinkage values ranged from 0.049% to 0.066% at 35 days of age. In VDOT specifications, low shrinkage bridge deck concrete is required to have a shrinkage value less than 0.035% when normal weight aggregates are used (VDOT, 2016). The test specimens were moist cured for 7 days and air dried for 28 days. Since the VDOT specification was not met, in the future, a shrinkage-reducing admixture (SRA) could be added to meet the specification (Nair et al., 2016). If cracking is because of shrinkage and loads imposed, fibers can be added to control the amount and width of cracks. RSC mixtures exhibit very low shrinkage values; in a previous study, values were less than 0.02% at 4 months (Ozyildirim and Nair, 2017).

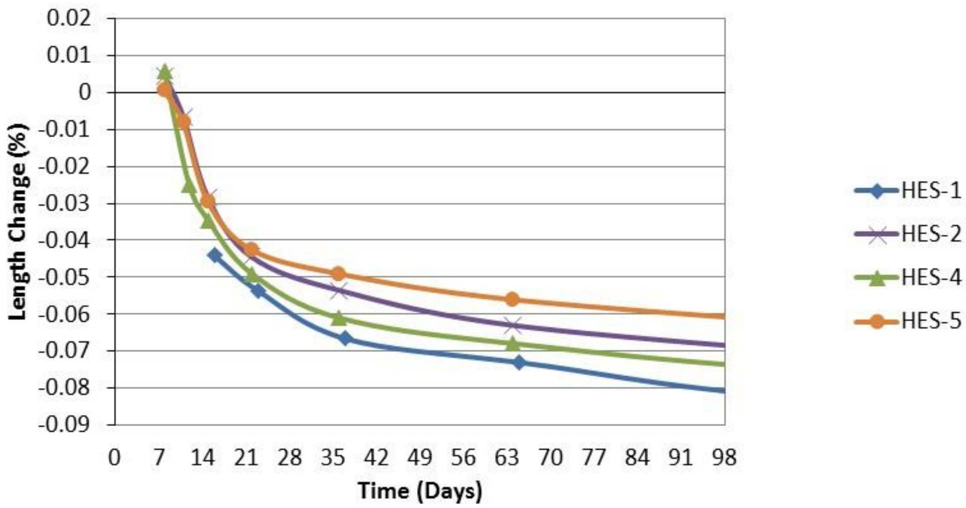

Figure 2. Length Change Data for High Early Strength (HES) Mixtures

ES Mixtures

Fresh concrete properties for the ES mixtures are given in Table 8. The concretes were workable, and the workability could be increased by additional HRWR admixture.

Table 8. Fresh Concrete Properties for Early Strength (ES) Mixtures

Batch No.	Density (lb/ft^3)	Slump (in)	Air (%)
ES-1	148.4	7.5	6.8
ES-2	147.2	4.5	7.3
ES-3	149.6	3.25	6.0
ES-4	148.8	5.0	6.0
ES-5	148.8	5.75	5.9

The compressive strengths at 1, 3, 7, and 28 days for ES mixtures are given in Table 9. The ES mixtures were able to attain 3,000 psi in 1 day. The specimens cured in the insulated curing box had higher 1-day strengths then the specimens cured in the laboratory. The high temperature accelerated the strength development, as expected.

Length change results for ES mixtures after 28 days of drying are displayed in Figure 3. The shrinkage values ranged from 0.049% to 0.055% at 35 days of age. The paste content of ES mixtures was less than that of the HES mixtures, and their maximum shrinkage was less compared to that of the HES mixtures. However, the shrinkage values of the ES mixtures were also more than the 0.035% required by VDOT specifications for low cracking bridge deck concretes (VDOT, 2016).

Table 9. Compressive Strength and Permeability Data for Different Early Strengh (ES) Batches

Batch No.	Curing Type	1-Day Compressive Strength (psi)	3-Day Compressive Strength (psi)	7-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)	Permeability (C)
ES-1	Curing box	4,590	---	---	---	779
	Lab	3,870	5,480	6,340	7,700	
ES-3	Curing box	4,300	---	---	---	711
	Lab	3,630	5,350	6,260	7,560	
ES-4	Curing box	4,020	---	---	---	603
	Lab	3,620	5,350	6,180	7,750	
ES-5	Curing box	3,850	---	---	---	---
	Lab	3,170	4,590	---	7,510	

--- = no data.

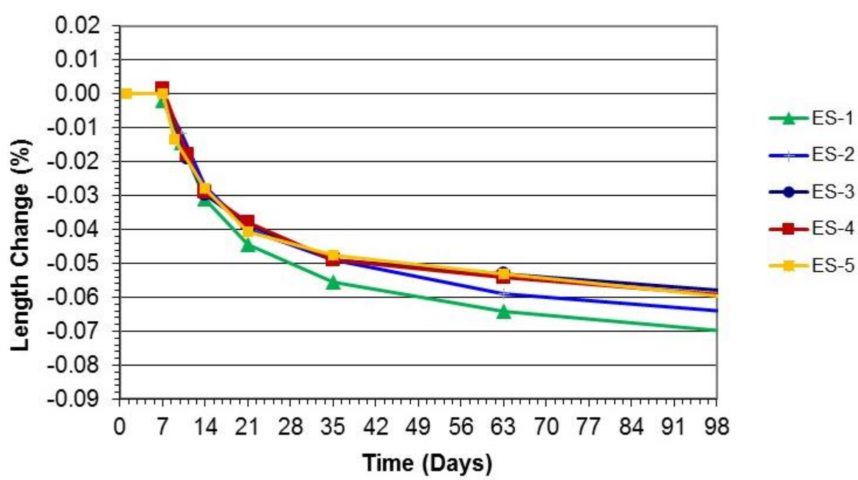

Figure 3. Length Change Data for Early Strength (ES) Mixtures

RSM Mixtures

Fresh concrete properties for the RSMs are given in Table 10. The compressive strengths at 7 and 28 days for RSMs are given in Table 11.

Table 10. Fresh Concrete Results for Regular Strength Mixtures (RSMs)

Batch No.	Fresh Density (lb/ft^3)	Slump (in)	Air (%)
RSM-1	148.4	2.5	5.3
RSM-2	147.2	6.5	6.7

Table 11. Compressive Test Results for Regular Strength Mixtures (RSMs)

Batch No.	Curing Type	1-Day Compressive Strength (psi)	7-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)
RSM-1	Curing box	2,800	4,510	5,500
	Lab	---	4,860	5,840
RSM-2	Curing box	3,420	4,760	6,100
	Lab	---	4,890	6,140

--- = no data.

The RSMs had the low cementitious materials content, which were within the maximum requirements in VDOT specifications for low cracking bridge deck concrete. These should be the mixtures of choice if 7 days of curing is possible. The RSMs achieved a compressive strength of more than 4,500 psi at 7 days. They could also achieve the desired strength of 3,000 psi within fewer days, possibly even at 1 day, with insulation. The length change of the RSM mixtures was not measured, but these mixtures can have shrinkage values exceeding that required by VDOT specifications for low cracking bridge decks (Nair et al., 2017). In such cases, SRA could be added to reduce the shrinkage to the allowed limit (Nair et al., 2016).

CONCLUSIONS

- *HES concretes with portland cement and an SCM achieved a compressive strength of 3,000 psi within 10 hours.* The specimens were kept in the insulated box to retain heat. The cementitious material range in the mixtures with portland cement was 825 to 1,000 lb/yd^3, and the w/cm was 0.27 to 0.29.

- *HES concretes with RSC or a combination of portland cement and RSC achieved a compressive strength of 3,000 psi earlier than mixtures without RSC.* In the combinations, the increase in RSC percentage enabled an increase in strength development. When only RSC was used, the cementitious material content was low, 658 lb/yd^3.

- *Mixtures with portland cement had longer initial setting times compared to mixtures with RSC.* Longer setting times delay strength development.

- *ES concretes with portland cement and fly ash as an SCM can achieve a compressive strength of 3,000 psi within 1 day.* The cementitious material range in ES concretes was 600 to 658 lb/yd^3, and the w/cm was 0.38 to 0.41.

- *The RSMs had the lowest cementitious materials content of the three groups (HES, ES, and RSM), satisfying VDOT's maximum cementitious material content requirement of 600 lb/yd^3 for low cracking bridge deck concrete.*

- *Portland cement mixtures had higher shrinkage values than required by VDOT specifications for low cracking bridge deck concretes.*

- *Concretes with fibers had differing levels of residual strength, depending on the type and amount of fibers.* Concretes with high amounts of steel fibers exhibited deflection hardening. Fibers were distributed well without any clumping with the use of the efficient laboratory pan type mixer.

- *Curing temperatures affect the development of strength; higher temperatures or temperature retention by insulating the concrete enables the attainment of strength at earlier ages.*

RECOMMENDATIONS

1. *VDOT's Materials Division and Structure and Bridge Division should use mixtures with SCM and enough portland cement to achieve early strength or mixtures with RSC for more rapid bridge repairs*. RSC mixtures have short setting times requiring on-site mixing. When longer times in days are possible for strength development, mixtures with a minimal amount of portland cement and SCM should be used. If cracking is an issue, SRA and fibers should be considered.

2. *VTRC should study the field delivery systems for these materials for uniformity of the mixture and proper fiber distribution.*

IMPLEMENTATION AND BENEFITS

Implementation

For Recommendation 1, VDOT's Materials Division and Structure and Bridge Division will indicate in their manuals of instruction that concrete mixtures should be selected to meet the needs of the project within 36 months of the publication of this report. If high early strengths are needed because of scheduling or traffic demands, mixtures with SCM and enough portland cement to meet early strengths should be specified. These mixtures have long setting times, enabling mixing in ready mixed concrete trucks. These concretes may need to be insulated at the jobsite to retain heat to ensure early strengths are achieved unless a large volume of concrete is placed. RSC mixtures that are commonly used in Virginia with a latex modifier to improve durability should be used for very early strengths. Concretes with RSC have short setting times and need mobile mixers. If more time, in days, is available to perform the concrete work, mixtures with minimal amounts of portland cements and SCM should be used for cost-effectiveness, ease of placement, and less cracking potential. Whenever cracking is anticipated, SRA and fibers can be added. Fibers must be the right type and in the right amount in the mixture.

For Recommendation 2, the delivery system will be investigated as part of a new study underway by VTRC on partial-depth link slabs.

Benefits

For Recommendation 1, to maintain traffic volumes and the safety of travelers, traffic interruptions must be minimized during concrete placement. In addition, the concretes should be workable and durable. This study addressed strength and durability issues and drew attention to concerns with a range of early strength concretes. It was shown that high early strengths can be achieved in mixtures with SCM and increased amounts of portland cement, which are essential for durability. HES concretes with high cementitious material contents and high paste contents are prone to cracking. RSC mixtures that attain high early strengths faster than the portland cement mixtures but cost more than mixtures with portland cements and require mobile mixers can be used when very early strengths are required. If more time is available, more user-friendly portland cement concrete mixtures containing SCM with lower cementitious materials and paste contents can be used that are more cost-effective, less prone to shrinkage cracking, and easier to make than the HES mixtures.

For Recommendation 2, this study was conducted in the laboratory using the efficient pan type mixer. However, in the field, a large amount of material would be mixed and delivered in a ready mixed concrete truck or a mobile mixer, which are not as efficient as the laboratory mixers and should be investigated for uniformity of the mixture and fiber distribution.

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