Performance Evaluation of Ultra-Rapid-Hardening Roller-Compacted Concrete with Styrene Butadiene Latex

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ABSTRACT: This study was conducted to evaluate the performance of rapid-hardening roller-compacted concrete containing styrene butadiene latex. This material has no slump and is compacted with a roller after being poured. Volume reduction is not a concern and the material has a high initial strength due to the high pressure applied. Latex improves the durability of ultra-rapid-hardening cement composites. This study evaluated the performance of an optimum mixture (L) and a mixture with no styrene butadiene latex (NL), which had almost the same workability as the optimum mixture. The L mixture exhibited better performance than the NL mixture in terms of bond strength and chloride ion permeability, as well as resistance to abrasion, repeated freezing and thawing, and scaling. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 196–201, 2011

Key words: composites; latex-modified; styrene butadiene latex; ultra rapid hardening roller compacted

INTRODUCTION

The repair period of pavement decreases as the quantity of traffic and number of heavy vehicles increases. Because the early strength of repair materials is an important consideration due to the necessity of opening repaired roads to traffic quickly after repair, regulated-set cement is often used. However, even though regulated-set cement has a higher early strength than normal concrete, its high cost is a major drawback. Therefore, the development of mixtures and construction methods that use more cost-effective materials or smaller amounts of expensive materials is essential. However, the early strength characteristic, which is so important, cannot be sacrificed.

Regulated-set cement, which is frequently used as repair material in emergency construction, can quickly support traffic after being poured, but it develops microcracks because the movement of heat and moisture is increased due to the high heat of hydration.[1] Under actual field conditions, this movement of heat and moisture is bound internally and externally, and generates tensile stress in the concrete structure.[2] These microcracks contribute to various forms of damage by increasing the permeability of the pavement, leading to the requirement for reconstruction in a relatively short period. The addition of styrene butadiene latex is one solution because it can increase the workability of unsolidified concrete and decrease the water-cement ratio.

The viscosity and water impermeability of latex prevent the separation of materials, which is closely related to the durability of concrete. These characteristics in turn improve the adhesion of cement paste and aggregate in the concrete after solidification and simultaneously form an impermeable layer in the form of a film membrane.[3] Therefore, to solve the problems of regulated-set cement, a construction method using roller-compacted latex-modified concrete was developed. The addition of the styrene butadiene latex was used to improve the quality of the concrete and the bond strength with existing layers. This method can be used to maintain high commonality even with thin layers and achieve early strength through roller compacting. It can also retain its high commonality because of the denser structure.[4]

The optimum mixture of roller-compacted latex-modified concrete was determined, and the impact of the latex on the early strength of the concrete was investigated to see if the mixture would be suitable for quick repairs on busy roads that cannot be closed for long periods of time.

EXPERIMENTAL

Cement

The cement used in this study was a special mixture of high early-strength cement and calcium sulfoaluminate (CSA) admixture so that the 4-h target

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TABLE I
Properties of Cement for Ultra-Rapid-Hardening Roller-Compacted Concrete

(wt %)						
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition
13.9	10.4	2.07	55.1	2.90	11.3	4.43

strength[5] could be tested using a roller-compacted latex-modified concrete construction method. The working time was reduced by decreasing the quantity of Al_2O_3, to induce rapid hardening compared to normal regulated-set cement. Table I shows the chemical characteristics of the mixture. The coarse crushed aggregate had a maximum dimension of 13 mm. The fine aggregate was river sand with a specific gravity of 2.59.

Styrene butadiene latex

Styrene butadiene latex was used as an admixture to ensure a sufficient amount of air in the concrete and to improve the bond strength between the cement paste and the aggregate. The styrene butadiene latex was in the form of small spherical polymer particles 0.5 to 5.0 μm in diameter and coated with surfactant. All particles remained suspended because of the surfactant; this provided space for the possible generation of a single polymer through the formation of chains between monomers. The unit quantity required to obtain the desired water-cement ratio by improving the workability of the unhardened concrete was reduced, and this increased the strength. During the hydration reaction, latex particles formed a film membrane and reduced the permeability by filling pores and attaching the generating materials of the hydration reaction and the aggregate surface. This increased the tensile strength. Table II shows the physical characteristics of the styrene butadiene latex used in this study.

Specimen preparation

Specimens for the roller-compacted latex-modified concrete were cylinders, 100 mm in diameter and 200 mm high. They were compacted using a 9.7-kg vibrating hammer with a striking frequency of 2000 times/min at a single impact energy of 17 J.[6] Each specimen was made up of four 50-mm compacted layers. The specimens were cured in a controlled atmosphere at a temperature of 23 ± 2°C and a relative humidity of 50 ± 5%.

Mix proportions

Table III shows the composition of the nonlatex (NL) mixture with the same workability as the experimentally determined optimum latex (L) mixture.

Test method

The roller-compacted latex-modified concrete was exposed to a normal atmosphere throughout its life starting at the time of pouring. It was also exposed to various physical and chemical environments to cause degradation. In general, harmful materials outside the concrete progress inside the concrete via various mechanisms such as one or a combination of partial permeation or spreading, absorption, and capillary action.[7] The penetration characteristics are important in determining the durability of concrete against the permeation of various harmful substances.[8] The performance was tested after simulating physical and chemical deterioration of the samples.

Bond strength

The bond strength was tested using direct tensile test methods to evaluate the degree of detachment from the existing substrate concrete. For this test, 100 mm of roller-compacted latex-modified concrete was placed in two 50-mm layers on top of a 100-mm concrete substrate layer in a cylindrical mold, 100 mm in diameter and 200 mm high. The surface of the substrate concrete had been chipped, sandblasted, and wire-brushed. To simulate actual field conditions, water was sprayed on the surface of the substrate concrete until surface dry saturation status was achieved. The substrate concrete was aged for 28 days. The bond strength was measured for three pieces after 4 h, and again 28 days after overlaying. To measure the bond strength, epoxy was painted on both ends of a specimen to attach jigs, and the specimen was tested using a universal tester at a speed of 1.0 mm/min. Figure 1 shows how each specimen was prepared for the bond strength tests. The specimens were cured in a controlled atmosphere at a temperature of 23 ± 2°C and a relative humidity of 50 ± 5%. The bond strength evaluation was based on the standard of bond strength quality

TABLE II
Properties of Styrene Butadiene Latex

Solids content (wt %)	Styrene content (wt %)	Butadiene content (wt %)	pH	Specific gravity	Surface tension (dyne/cm)	Particle size (nm)	Viscosity (cps)
46.5	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	170	42

TABLE III
Mixture Proportions

Type of mix.	G_{max} (mm)	W/C (wt %)	S/a[a] (wt %)	Unit weight (kg/m^3)					
				Water	Cement	Sand	Gravel	Latex	CSA admixture
L	13	27	53	62.89	235	994.12	902.00	85.11	165
NL	13	35	53	140	235	950.19	862.14	–	165

[a] Sand-aggregate ratio.

suggested by the Virginia Department of Transportation, as shown in Table IV.

Chloride permeability test

To evaluate the influence of $CaCl_2$, which is used as a road de-icing agent during winter, chloride ion penetration testing was carried out according to the ASTM C 1202 and AASHTO T 259 tests.[9] Cylindrical specimens, 100 mm in diameter and 200 mm high, were manufactured and cured for 3 h, 24 h, and 28 days (two specimens for each) and the center 50-mm section was cut out and used for further testing. The air trapped inside the concrete was removed with a vacuum pump operated for 1 h before the chloride ion penetration test. Then the specimen was placed in a dessiccator and water was added while maintaining a vacuum for 3 h. Each specimen was kept completely saturated in water for 18 ± 1 h in the dessiccator.

After completing the above treatment, the specimen was attached to a voltage cell, and the quantity of electric charge that passed during a 6-h period in response to an applied 60-VDC voltage with a 0.3*M* NaOH solution at the plus electrode and a 3% NaCl solution at the minus electrode was measured. Table V shows the standard relationship between the level of chloride ion penetration and the quantity of electric charge for a 60-VDC voltage; this is an indirect indication of the permeability.

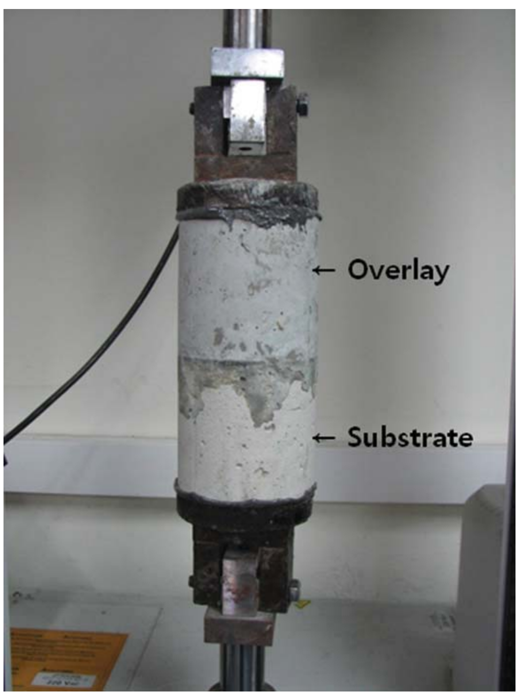

Figure 1 Direct tensile bond test setup. [Color figure can be viewed in the online issue, which is available at www.wileyonlinelibrary.com].

Abrasion test

The ASTM C 944[10] test was used to measure abrasion resistance. Two cylindrical specimens, 100 mm in diameter and 60 mm high, were manufactured for each combination type of material, and the abrasion test was conducted after atmosphere curing for 4 h, 24 h, and 28 days at a temperature of 23 ± 2°C. Rotating cutters operating at 200 RPM delivered a continuous 20-kg load to the specimens by applying a 20-kg weight to the center axle. The weight loss per unit area was measured three times, every 2 min for 6 min, with a precision of 0.01 g.

Scaling

$CaCl_2$, which is used as a de-icing agent during winter, permeates the cracks generated by the seasonal change of concrete volume, and exfoliates from the surface. This phenomenon is called surface scaling. The ASTM C 672[11] test was used to measure the resistance to scaling in the face of repeated freezing and thawing. Cylindrical specimens, 100 mm in diameter and 200 mm high, were manufactured and cured for 28 days in a controlled environment at a temperature of 23 ± 2°C and a relative humidity 50 ± 5%. A 6-mm high wall was erected at the edge of the specimen surface, and the surface of the

TABLE IV
Quality Based on Bond Strength[5]

Bond strength (MPa)	Quality
2.1	Excellent
1.7–2.1	Very good
1.4–1.7	Good
0.7–1.4	Fair
0–0.7	Poor

TABLE V
Chloride Permeability Based on Charge Passed[6]

Charge passed (Coulombs)	Chloride permeability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
<100	Negligible

TABLE VI
Visual Rating of the Concrete Surface[8]

Rating	Condition of surface
0	No scaling
1	Very slight scaling (3.2 mm depth, maximum, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

specimen was exposed to a 4% $CaCl_2$ solution. Repeated freezing and thawing then took place for a total of 50 cycles, where each cycle was composed of freezing for 16 to 18 h at -17 ± 1.7°C and thawing for 6 to 8 h at 23 $\pm$ 2°C at a relative humidity of 50 $\pm$ 5%. The degree of scaling was observed visually every five cycles according to standards of the ASTM test given in Table VI. Two specimens per mixture were tested this way.

TEST RESULTS AND DISCUSSION

Bond strength

Table VII shows the results of the bond strength measured through direct tensile testing. The L mixture with styrene butadiene latex had a bond strength 1.4 times that of the NL mixture without styrene butadiene. The NL mixture exhibited a bond strength

TABLE VII
Bond Strength Test Results

Type of mixture	Curing time (d)	Bond strength (MPa)			Evaluation
		1	2	Mean	
NL	28	1.24	1.36	1.30	Fair
L	28	1.87	1.64	1.76	Very good

performance of *fair*, which does not meet the minimum bond strength of 1.4 MPa after 28 days suggested by the Virginia Department of Transportation. The L mixture, on the other hand, had a bond strength of *very good*; this exceeds the minimum bond strength and is much better than that of the NL mixture without latex. The impermeability was greater, and thus the bond performance was better, since a latex film membrane was formed by filling the micropores with solid styrene butadiene latex.

One of the important indices of whether poured overlay concrete with an existing substrate concrete is the damage pattern. The damage pattern can be classified as damage to the overlay layer, damage at the boundary surface, or damage to the substrate concrete. The tests showed that for the NL mixture without styrene butadiene latex, damage occurred mainly at the boundary surface, while in the L mixture, damage occurred mainly in the substrate concrete, indicating excellent relative bond performance. Figures 2 and 3 show the surfaces of damaged specimens after the bond strength experiments for the NL and the L specimens, respectively.

Chloride permeability

Table VIII shows the results of the chloride ion penetration tests of the roller-compacted latex-modified concrete. The quantity of electric charge was reduced in all mixtures as aging increased. Based on the evaluation standard suggested by the ASTM,

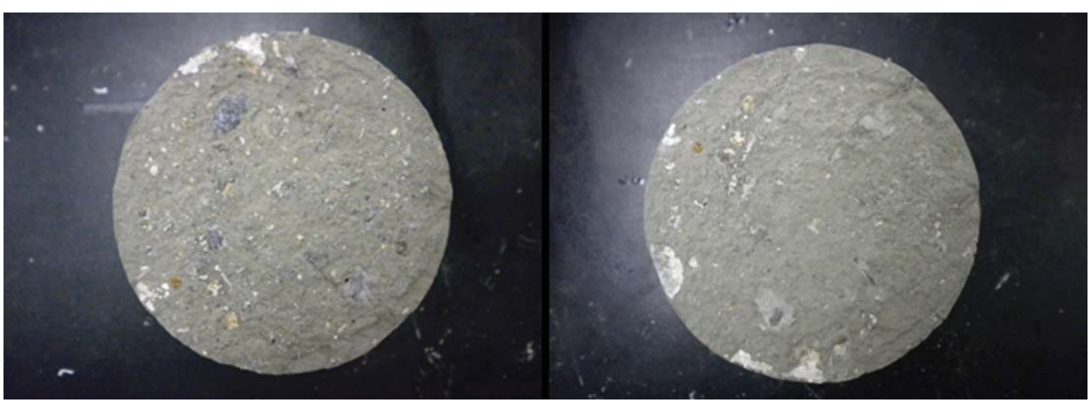

Figure 2 Interface morphology of NL mixture after bond strength test. [Color figure can be viewed in the online issue, which is available at www.wileyonlinelibrary.com].

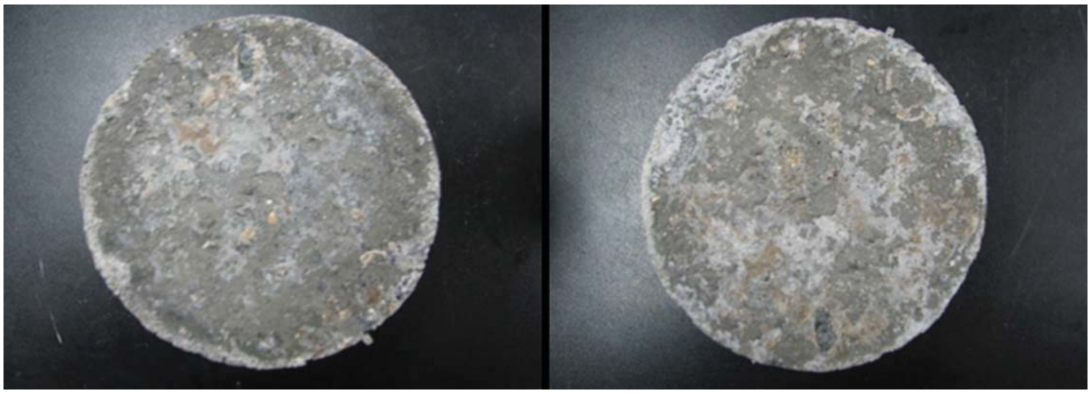

Figure 3 Interface morphology of L mixture after bond strength test. [Color figure can be viewed in the online issue, which is available at www.wileyonlinelibrary.com].

the NL mixture exhibited *moderate* permeability after 4 h, and *very low* permeability after 7 days and 28 days, while the L mixture exhibited *low* permeability after 4 h, *very low* permeability after 7 days, and *negligible* permeability after 28 days. The results of both mixtures after 28 days showed excellent resistance to chlorine ion penetration, probably because of the reduction of micropores due to the compression effect of roller compacting. The difference in penetration resistance of the NL and L mixtures measured by the reduction of permeability was likely due to the improvement in bond strength between the cement paste and aggregate caused by the formation of a styrene butadiene latex resin film membrane in the L mixture, and the minimization of crack formation and micropores by the charging effect of polymer particles.

Abrasion test

The abrasion resistance of concrete is an indication of the density, and is also related to the impermeability to water. That is, denser concrete will have increased abrasion resistance. Figure 4 shows the abrasion resistance of roller-compacted latex-modified concrete. The weight loss after 4 h (i.e., early aging) was less for the NL mixture than the L mixture. In the case of the L mixture with styrene butadiene latex, latex particles distributed inside the unhardened concrete adhered to the cement gel formed at the start of solidification and were distributed uniformly throughout the cement paste. At that point, the generation of ettringite became more unstable than in standard regulated-set cement since the early cement hydration reaction was hindered by the forming latex film membrane. However, as aging increased, the NL mixture exhibited a greater weight loss than the L mixture. In that case, the abrasion resistance increased because many pores were intercepted by the micropore charging effect of the styrene butadiene latex solid and by the formation of the latex film membrane.

TABLE VIII
Chloride Ion Permeability Results

Type of mixture	Curing time	Specimen (Coulombs) 1	2	Mean	Evaluation
NL	4 h	3768	3607	3687.5	Moderate
	7 d	503	575	539	Very low
	28 d	228	195	211.5	Very low
L	4 h	1812	1599	1705.5	Low
	7 d	125	127	126	Very low
	28 d	65	68	66.5	Negligible

Scaling

Table IX shows the results of the visual evaluation of scaling for the NL and L mixtures. In the case of the NL mixture, scaling started gradually after 10 cycles and reached a maximum (level 5) after 35 cycles. The L mixture exhibited no scaling even after 50 cycles. This was due to the excellent permeability resistance caused by the formation of a dense structure as the latex film membrane formed inside of the concrete between the cement paste and the aggregate. This was also likely due to the fact that

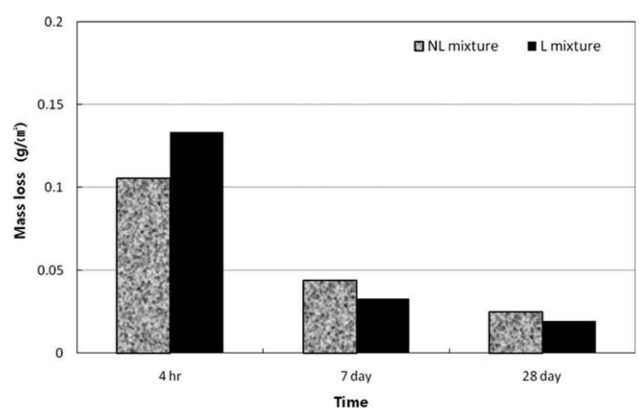

Figure 4 Mass loss after abrasion test. [Color figure can be viewed in the online issue, which is available at www.wileyonlinelibrary.com].

TABLE IX
Concrete Surface Scaling Results

Cycle	Type of mixture	5	10	15	20	25	30	35	40	45	50	Sum of rating
NL	Batch 1	0	1	2	3	4	4	5	5	5	5	34
	Batch 2	0	1	2	2	3	3	4	5	5	5	30
L	Batch 1	0	0	0	0	0	0	0	0	0	0	0
	Batch 2	0	0	0	0	0	0	0	0	0	0	0

Visual rating: 0 = best, 5 = worst.

the $CaCl_2$ did not significantly permeate the material and thus did not generate cracks under repeated freezing and thawing cycles, aided by the elasticity of the latex. In addition, the latex helped trap an adequate quantity of air that could tolerate the contraction and expansion due to the freezing-thawing cycle.

CONCLUSIONS

In this study, comparative experiments were conducted on a concrete mixture with (L) and without (NL) styrene butadiene latex to test their suitability for use in the rapid repair of roads. The results are as follows.

a. A bond strength test showed that the L mixture had a bond strength 1.4 times that of the NL mixture. The bonding performance was better than that of standard regulated-set cement with the substrate concrete was made by improving the bond strength through formation of a latex film membrane between the cement paste and the aggregate.
b. A chlorine ion penetration test, used as an indirect indication of concrete permeability, showed a trend to reduced permeability as aging increased. For a curing time of 28 days, the two mixtures both showed excellent chlorine ion penetration resistance. The permeability was reduced because of the high density inside the concrete due to the compression effect of roller compaction. The L mixture had better penetration resistance than the NL mixture because a nonpermeable layer was formed inside the concrete in the form of a film membrane. The formation of cracks was minimized, and the permeability was reduced due to the charging effect of micropores by polymer particles.
c. After conducting an abrasion resistance test for 4 h, the L mixture showed a larger weight loss. However, as aging increased, the abrasion resistance performance improved. The hydration reaction was delayed in early aging as latex particles were absorbed and adhered to the cement gel. This occurred simultaneously with the start of solidification but after hardening. The weight loss decreased when a dense structure was formed due to the charging effect of micropores by solid latex. The formation of a latex film membrane intercepted many pores.
d. According to a visual evaluation of scaling resistance, scaling started gradually after 10 cycles in the case of the NL mixture and reached a maximum after 35 cycles. For the L mixture, on the other hand, no scaling occurred at all up to 50 cycles. This was because of the excellent permeability resistance due to the formation of the latex film membrane between the cement paste and aggregate, creating a dense structure. This excellent scaling resistance was also due to the fact that $CaCl_2$ could not enter the material because no cracks were generated by repeated freezing and thawing due to the elasticity of latex and the sufficient amount of air inside, which could tolerate the temperature cycles.

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