Effects of Aggregate Extension on Properties of Rapid-Set Prepackaged Patching Materials

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Rapid-set patching material selection and request

- Selection of materials started with reviewing TDOT approved product list
- Requests were sent out to the major material suppliers
  - Approximately 15 material suppliers/manufacturers were contacted. 8 delivered their products.
  - 23 products were collected with a typical weight of 50 to 60 lbs.
  - 16 were mortars and extended with 3/8" crushed limestone aggregates

Material ID	Material Characteristics	CA Added, % wt.
#1	Rapid-set shrinkage-compensating cement-based mortar	50
#2	Shrinkage-compensating cement-based mortar	50
#3	Magnesium phosphate cement-based mortar	60
#4	Magnesium phosphate cement-based mortar for hot weather	60
#5	High-early-strength cementitious mortar	55
#6	High-early-strength cementitious mortar with extended set time	55
#8	Rapid-set slope-grade cementitious mortar	50
#11	Rapid-set fiber-reinforced cementitious materials-based mortar	60
#12	Rapid-set cementitious materials-based mortar	50
#13	Rapid-set magnesium phosphate cement-based mortar	60
#14	Rapid-set cement-based horizontal-patching mortar	80
#15	Rapid-set low-shrinkage high-early-strength mortar	50
#17	Rapid-set high-strength cementitious materials-based mortar	60
#18	Rapid-set cementitious materials-based mortar	50
#21	Rapid-set high-strength special cement-based grout	50
#23	Rapid set cement-based no-shrink grout	50

Mixing and proportioning

- Proportioned following the instructions in product data sheet.
  - Average water content was added
- All patching materials were mixed in a 2.0 ft^3 rotating drum mixer for quick-set materials (55 -70 lbs), or in a 6.0 ft^3 rotating drum mixer (110 – 140 lbs).
  - Water was first added, then patching materials, and then coarse aggregate.
  - Mixing for 1-2 minutes

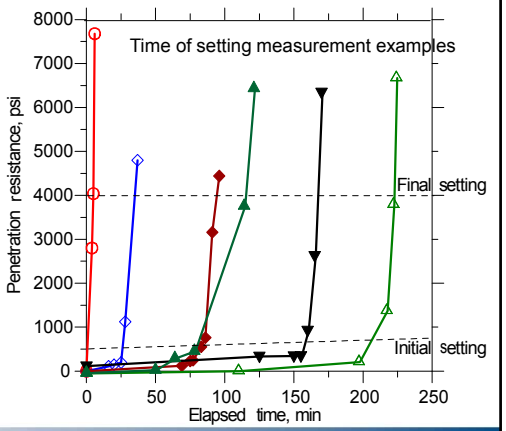
Tests performed

- Setting (ASTM C403)
- Compressive strength development (1hr, 3 hrs, 1 day, 3 days, and 28 days) (ASTM C39)
- Slant shear bond strength (Modified ASTM C882)
- Free dry shrinkage (ASTM C157)
- Restrained shrinkage ring test (ASTM C1581)
- Rapid chloride penetrability (ASTM C1202)
- Rapid freeze and thaw (ASTM C666)

Time of setting

ASTM C403

Courtesy of Gilson Company



Classification of setting

- Initial set - penetration resistance reached 500psi. Mixture was no longer workable.
- Final set - penetration resistance approached 4000psi. Mixture became fully rigid and started to develop strength at a significant rate.
- Normal set - Mixture remained workable for a minimum of 45 minutes and began to solidify within 1 to 4 hours (e.g. #2, #5 and #6).
- Quick set - Considerable loss of workability in 10 to 45 minutes and mixture became hardened in less than 1 hour (e.g. #11).
- Flash set - Instantaneous loss of consistency and mixture started stiffening in less than 10 minutes (e.g. #13).

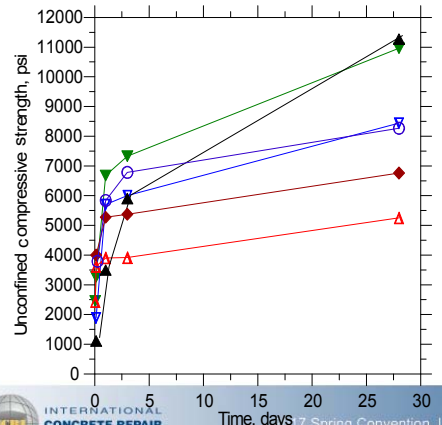
Material ID	Initial Set, min.	Final Set, min.	Type of Setting
#1	26	35	Quick
#2	200	223	Normal
#3	9	10	Flash
#4	10	30	Quick
#5	80	95	Normal
#6	157	168	Normal
#8	25	57	Quick
#11	26	30	Quick
#12	9	14	Flash
#13	6	7	Flash
#14	19	24	Quick
#15	25	36	Quick
#17	48	58	Normal
#18	55	85	Normal
#21	30	38	Quick
#23	31	33	Quick

Result summary for time of setting

Time of setting summary

- 3 materials showed flash set (<10min)
  - Gain strength in about 10 minutes
  - Similar to magnesium phosphate cement-based materials
- 8 materials were quick-set (less than 45 min.)
  - Develop strength in less than an hour.
  - Similar to calcium sulfoaluminate cement-based materials
- 5 materials set at a fairly normal rate with approximately 1-4 hour final setting time
  - Similar to type III cement-based concrete.

Compressive strength development examples



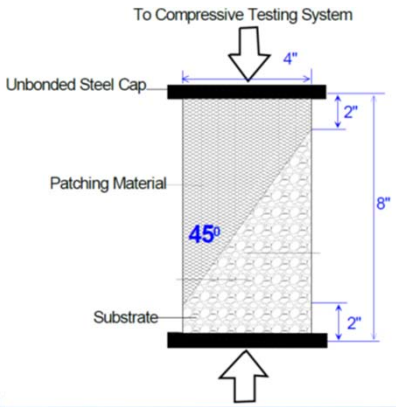
Material ID	Compressive Strength with and without Aggregate Extension, psi							
	3 hours		1 day		3 days		28 days	
	Without	With	Without	With	Without	With	Without	With
#1	3623	3110	3907	4010	3917	4203	5253	5333
#2	3973	*	4750	4153	6087	4623	8057	6080
#3	3133	2687	3407	3000	3757	2903	5053	2897
#4	3353	2663	3353	3020	3703	3080	4193	5273
#5	1900	630	4603	2533	6497	4000	10693	9857
#6	1113	*	3497	1750	5903	3037	11270	6833
#8	517	1687	2463	2750	2883	2560	3210	2905
#11	3225	2077	3590	3013	3975	3563	5690	4710
#12	1520	1037	6553	4797	6710	5663	8050	7320
#13	4693	2857	5277	3393	5223	3770	5830	4870
#14	1777	953	5253	2303	5697	2870	7103	5840
#15	3267	2397	6680	4977	7333	7097	10963	10340
#17	4383	3353	5535	4560	5620	4570	6670	5927
#18	2217	1350	3603	2730	4203	3000	6583	5795
#21	5067	4043	5203	5263	7357	5950	9706	9197
#23	7460	6850	9177	7880	6363	7990	9666	10480

Compressive strength development summary

- Most materials (more than 10 out of 16) showed very high early strength (more than 3000psi in 3 hours), and medium to high 28-days strength (more than 5000 psi)
- Coarse aggregate extension noticeably reduced both early and 28 days compressive strength by several hundreds to several thousands psi.
- In few cases, aggregate extension increased the compressive strength

Slant shear bond test

Modified ASTM C882



Material ID	Without Aggregate Extension		With Aggregate Extension	
	Bond Strength, psi	Failure Plane	Bond Strength, psi	Failure Plane
#1	5460	S+PM	5059	PM
#2	5443	S	5057	PM
#3	0	B	2793	PM
#4	1671	B	2947	B+PM
#5	5790	S	6120	S
#6	5520	S+B	4180	PM
#8	2395	B/PM	2379	B+PM
#11	5101	B/PM/S	4807	PM
#12	5344	S	5606	PM+S
#13	1110	B	1855	B+PM
#14	5162	B/S/PM	4392	PM
#15	5598	S	6723	S
#17	5417	PM	4611	PM
#18	4755	PM	4444	PM
#21	5990	B/PM+S	—	—
#23	5717	B+PM	—	—

Slant shear bond strength result summary

B-Bond
PM-Patching material
S-Substrate

Failure Patterns

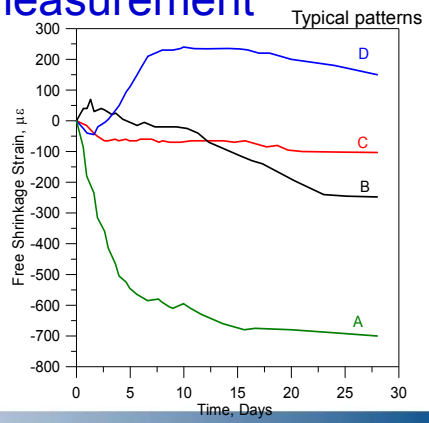
Slant shear bond result summary

- 57% of material showed a reduced slant shear bond strength after aggregate extension, but interestingly nearly 43% exhibited an increased slant shear bond strength after the coarse aggregate was added.
- 12 materials exhibited good or fair bond capacity with the slant shear bond strength greater than 4000psi
- 1 material had poor bond strength due to weak material (#8)
- Magnesium phosphate cement-based materials (#3, #4 and #13) displayed poor bonding to limestone aggregate concrete

Free dry shrinkage measurement

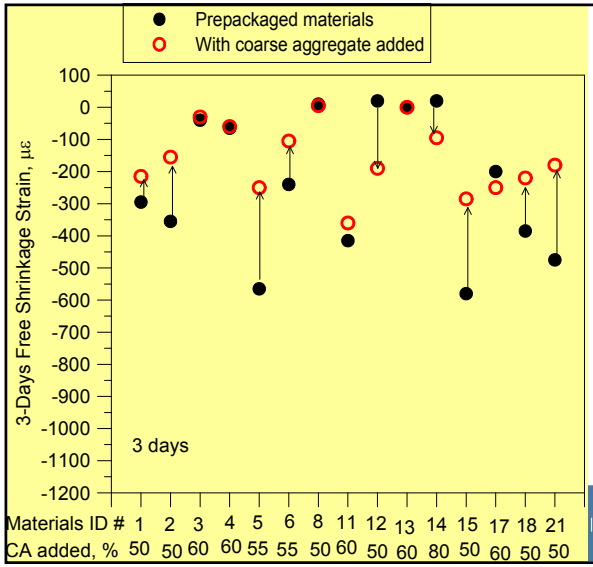
ASTM C157

Comparator for measurement of length change (Courtesy of Humboldt Mfg, Co.)

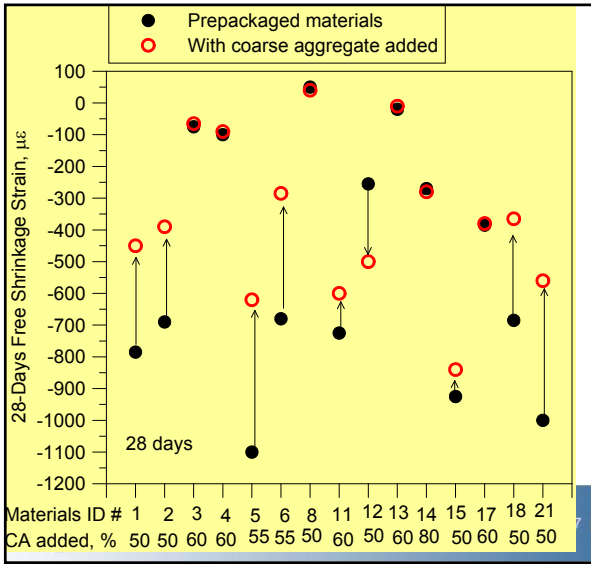


Free dry shrinkage patterns

- Curve “A” – 56%. Rapid increase at the early age (typically a week after the placement), a gradual slow growth over time
  - Similar to type III Portland cement-based concretes
- Curve “B” – 9%. slight expansion at the very early age (normally 1-2 days), slow increase until end of testing.
- Curve “C”- 26%. low or no dry shrinkage materials
  - Similar to magnesium phosphate or calcium sulfoaluminate cement-based mortars.
- Curve “D” – 9%. small free shrinkage at the beginning (approximately 1 day), substantial expansion and then gradual free shrinkage until completion of test

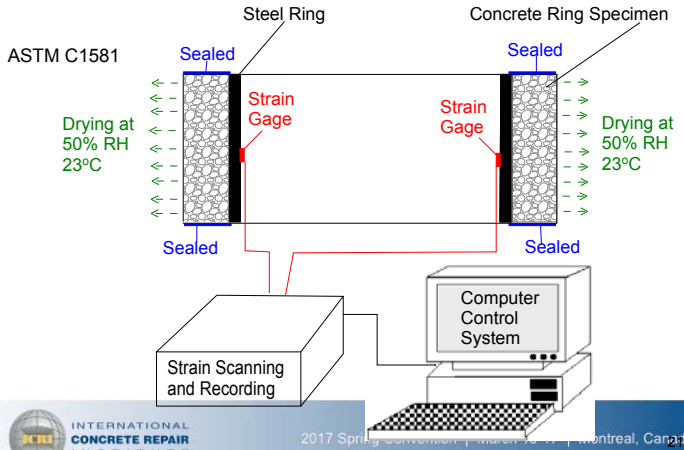


Effects of coarse aggregate extension on early age free dry shrinkage

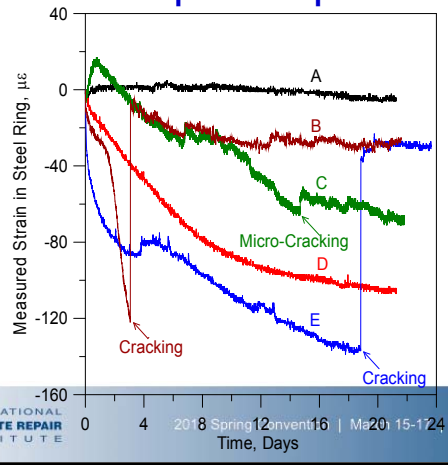


Effects of coarse aggregate extension on 28 days free dry shrinkage

Restrained shrinkage ring test



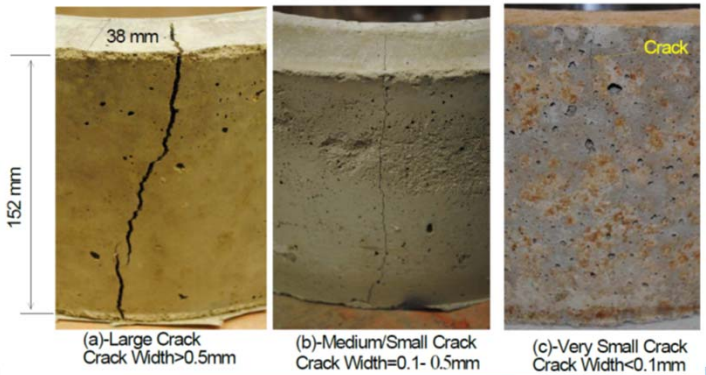
Restrained shrinkage strain development patterns



Restrained shrinkage strain development patterns

- Curve “A” – 22%, nearly zero strain. No cracks.
  - Similar to magnesium-phosphate-cement-based materials
- Curve “B” – 48%, very rapid strain growth at the early age and then a sudden release of strain, high risk of restrained shrinkage cracking at the early age (less than 5 days).
  - Similar to type III Portland cement-based concrete
- Curve “C” – 13%, small positive strain at the beginning followed by a continuous increase of shrinkage strain.
- Curve “D” – 13%, fast at the early age; but steadily slowed down in approximately a week.
  - Similar to calcium sulfoaluminate cement-based materials
- Curve “E” – 4%, rapid growth initially followed by a noticeable release several days after casting. Delayed cracking.
  - Similar to type III cement + an expansive component

Restrained shrinkage cracking classification



Material ID	Free shrinkage at 28 days, %	Restrained ring cracking	Age of cracking, days
#1	-0.079	Cracking	1.5
#2	-0.07	Cracking	2
#3	-0.007	None	N/A
#4	-0.01	None	N/A
#5	-0.1	Cracking	2
#6	-0.068	Cracking	3.5
#8	+0.005*	None	N/A
#11	-0.075	Cracking	0.5
#12	-0.024	Small cracking	7
#13	-0.003	None	N/A
#14	-0.028	Cracking	0.5
#15	-0.093	Cracking	0.5
#17	-0.039	Cracking	3
#18	-0.07	Cracking	3
#21	-0.1	Cracking	3
#23	-0.045	Cracking	3

Without aggregate extension

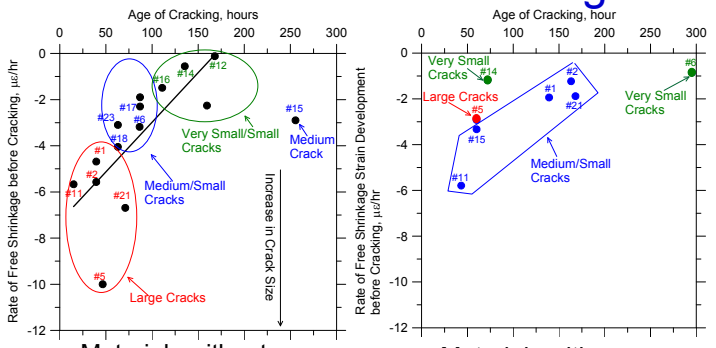
Free dry shrinkage vs. Restrained ring cracking

Material ID	Free shrinkage at 28 days, %	Restrained ring cracking	Age of cracking, days
#1	-0.045	Cracking	6
#2	-0.04	Cracking	7
#3	None	None	N/A
#4	None	None	N/A
#5	-0.06	Cracking	2
#6	-0.03	Cracking	12
#8	None	None	None
#11	-0.055	Cracking	2
#12	-0.05	None	N/A
#13	None	None	N/A
#14	-0.028	Small Cracking	3
#15	-0.085	Small Cracking	3
#17	-0.038	None	N/A
#18	-0.035	None	N/A
#21	-0.052	Cracking	7
#23	—	—	—

With aggregate extension

Free dry shrinkage vs. Restrained ring cracking

Rate of Free Shrinkage vs. Restrained Cracking



Materials without coarse aggregate

Materials with coarse aggregate extension

Aggregate Extension vs Cracking

- Coarse aggregate extension reduced the risk of restrained shrinkage cracking
  - Cracking typically occurred in original prepackaged mortars, but for 50% of these mortars, no cracking took place after coarse aggregates were introduced.
- Coarse aggregate extension reduced the size and delayed the time of cracking
  - For some prepackaged mortars, medium to large cracking was observed at early age, but after aggregate extension, these materials demonstrated small cracks at a later age

Rapid chloride penetrability test

ASTM C1202
Courtesy of Giatech Scientific

Material ID	Total Charge Passed over 6 Hours, Coulombs			
	Prepackaged Materials		Prepackaged Materials w/ Aggregate Extension	
#1	967.5	Very low	653	Very low
#2	1526.7	Low	787.3	Very low
#3	9871.5 (3 hours)	High	2608	Moderate
#4	4838.5	High	3239.7	Moderate
#5	734	Very low	1077.3	Low
#6	275.3	Very low	1988.3	Low
#8	3021	Moderate	1800.7	Low
#11	247	Very low	199.7	Very low
#12	1127	Low	1224.3	Low
#13	7021.3	High	4190.3	High
#14	651.5	Very low	725	Very low
#15	710.5	Very low	1082	Low
#17	404	Very low	298.3	Very low
#18	1477.7	Low	1290.3	Low
#21	1948	Low	1760	Low
#23	632.7	Very low	—	

Rapid chloride penetrability test results

Very low: <1000
Low: 1000 – 2000
Moderate: 2000 – 4000
High: >4000

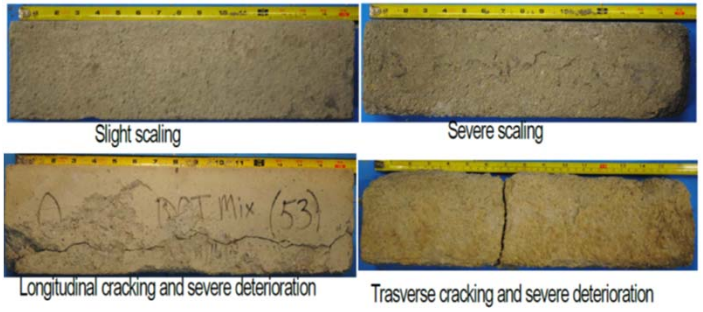
Rapid Chloride Permeability Summary

- Most materials showed very low to low permeability. Only 3 materials showed high permeability
- For most materials (approximately 10 out of 16), aggregate extension slightly reduced or increased the permeability. Only six materials showed significant changes after aggregate extension

Rapid freeze/thaw test

ASTM C666

Typical freeze/thaw damage patterns



Material ID	DF (Durability Factor)	Mass Loss, %	Visual Examination when test stopped
#1	98.7	6.1	Moderate scaling
#2	98	4.6	Slight scaling
#3	44.4	4.1	Severe deterioration
#4	36.1	1.4	Severe deterioration
#5	29.2	3.9	Severe deterioration
#6	28.3	8.7	Severe deterioration
#8	37.8	5.2	Severe deterioration
#11	91.3	0.2	No visible deterioration
#12	86	3.7	Severe scaling
#13	72.6	-1.2*	No visible deterioration
#14	96.8	2.3	Slight scaling
#15	97.5	0	Very slight scaling
#17	90	-0.5*	Moderate scaling
#18	100	2.1	Slight scaling
#21	99	-0.8*	No noticeable deterioration
#23	Not tested	Not tested	Early age cracking before test

Prepackaged materials without aggregate extension

Material ID	DF (Durability Factor)	Mass Loss, %	Visual Examination when test stopped
#1	87.9	1.5	Slight scaling
#2	84.5	1.8	Slight scaling
#3	19.8	4.5	Severe deterioration
#4	24.6	1.4	Deterioration & cracking
#5	14.6	1.2	Severe Cracking
#6	24.9	0.4	Severe deterioration
#8	—	—	—
#11	—	—	—
#12	65.5	2.0	Severe deterioration
#13	23.5	4.2	Severe deterioration
#14	68.5	2.6	Severe scaling
#15	59.3	-0.5	Severe cracking
#17	71.0	9.7	Severe scaling
#18	76.2	6.6	Severe scaling
#21	46.3	0.4	Slight scaling
#23	Not tested	Not tested	Early thermal cracking before test

Prepackaged materials with aggregate extension

Freeze/thaw test summary

- 6 materials showed a durability factor of 95 or above with no significant deterioration through 300 freeze and thaw cycles.
- 4 materials displayed slight to moderate deterioration with a durability factor between 60 and 95.
- 6 materials performed rather poorly with a durability factor of less than 60. Cracking or severe scaling typically occurred.
  - all magnesium phosphate cement-based materials behaved badly due to their high permeability.
- All materials showed reduced freeze and thaw resistance after aggregate extension. Most materials performed very poorly after coarse aggregate was added.

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