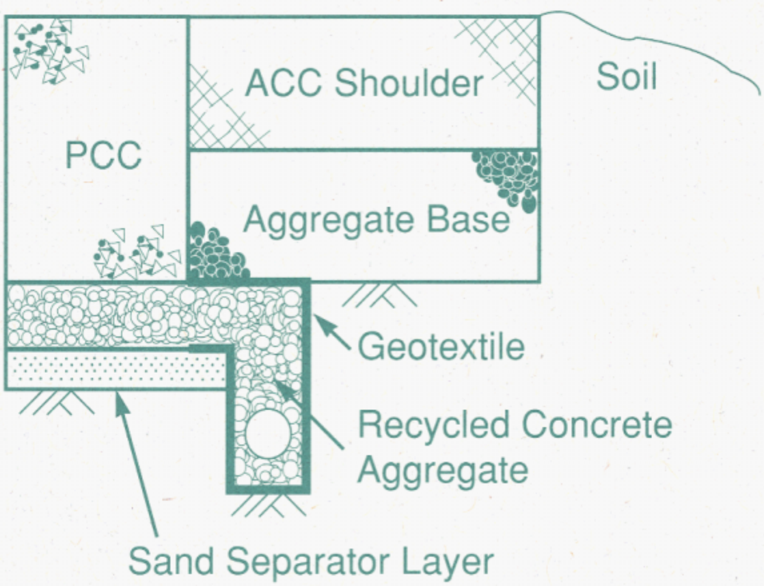
Report Number 96-12

Research



Use of Crushed Concrete Products in Minnesota Pavement Foundations

Technical Report Documentation Page

1. Report No.	2.	3. Recipient's Accession No.
MN/RC - 96/12		

4. Title and Subtitle	5. Report Date
USE OF CRUSHED CONCRETE PRODUCTS IN MINNESOTA PAVEMENT FOUNDATIONS	March 1995
	6.
7. Author(s) Mark B. Snyder, Ph.D., P.E.	8. Performing Organization Report No.
9. Performing Organization Name and Address Mark B. Snyder, Consulting Engineering 1216 Driving Park Road Stillwater, MN 55082-3718	10. Project/Task/Work Unit No.
	11. Contract (C) or Grant (G) No. (C) 72603
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St.Paul Minnesota, 55155	13. Type of Report and Period Covered Final Report 1987-1994
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report reviews eleven field and laboratory studies that have been performed to address concerns about the use of recycled concrete aggregate in pavement foundations. Performance concerns have centered on the possible impairment of drainage systems by deposits of calcium carbonate precipitate and other fines derived from the recycled concrete base materials. Environmental concerns have focused on the relatively high pH of the effluent produced by drainage systems that remove water from untreated recycled concrete aggregate foundation layers.

The studies considered in this report demonstrate that all recycled concrete aggregates are capable of producing various amounts of precipitate, with the precipitate potential being directly related to the amount of freshly exposed cement mortar surface. It appears that selective grading and blending with virgin aggregates are techniques that should significantly reduce precipitate potential. One study suggests that washing recycled concrete products will reduce accumulations of crusher dust and other fines in and around the pavement drains. Others indicate that the use of filter fabrics with sufficiently high initial permittivity will allow the accumulation of precipitate and other fines without significantly impairing drainage function.

This report discusses study results related to environmental concerns and provides recommendations for revisions to current specifications.

17. Document Analysis/Descriptors		18. Availability Statement
Recycled concrete Base materials	Pavement drainage Precipitate	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	52	

USE OF CRUSHED CONCRETE PRODUCTS IN MINNESOTA PAVEMENT FOUNDATIONS

Final Report

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March 1995

Published by

Minnesota Department of Transportation
Office of Research Administration
200 Ford Building Mail Stop 330
117 University Avenue
St Paul Minnesota 55155

Acknowledgments

This work was sponsored by the Minnesota Department of Transportation (Mn/DOT). The author gratefully acknowledges the support of the agency and the cooperation and assistance of its personnel, especially: Mr. Wayne Murphy, Mr. Ron Canner, Mr. Glenn Engstrom, Mr. Doug Schwartz, Mr. Mark Hagen, Mr. Joe Meade, Mr. Rudy Ford, Mr. Tim Anderson, Mr. Willis Enloe and Mr. Chuck Howe.

The author would also like to thank the following persons and agencies for their assistance in compiling and analyzing the information summarized in this report: Mr. Bob Muethel of the Michigan Department of Transportation; Mr. Rick Meininger of the National Aggregates Association; Mr. Dan Frentress of the Concrete Paving Association of Minnesota; Mr. Jerry McCarthy of the Michigan Concrete Paving Association; and Mr. James Bruinsma and Ms. Julie Vandenbossche of the University of Minnesota.

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Executive Summary

The Minnesota Department of Transportation (Mn/DOT) has been using recycled concrete aggregate (RCA) products as replacements for virgin aggregate products in pavement foundation and other applications since the early 1980s. However, concerns have developed in recent years about some aspects of the performance and environmental impact of these materials when used in pavement foundations. Performance concerns have centered on the production of deposits of calcium carbonate precipitate and other fines, which are believed to reduce the permeability or drainage capacity of the recycled concrete foundation layer and any associated drainage structures and filter fabrics. Environmental concerns have focused on the relatively high pH of the effluent produced by pavement drainage systems that remove water from untreated recycled concrete aggregate foundation layers.

The author has reviewed the results of 11 field and laboratory studies that have been performed since the middle 1980s to examine these concerns and others. The report details the results of that review, and the following summarizes some key points.

Mitigation of Precipitate/Drainage Problems

The tests and field studies demonstrate that calcium-based compounds are present in recycled concrete aggregates in quantities that are sufficient to be leached and precipitated in the presence of atmospheric carbon dioxide. It has further been demonstrated that all recycled concrete aggregates, regardless of gradation, are capable of producing various amounts of precipitate, with the precipitate potential being directly related to the amount of freshly exposed cement paste surface especially with increased quantities of cement paste fines. In addition, it does not appear that selective grading to eliminate fines or blending with virgin aggregates will eliminate precipitate potential. However, these steps may significantly reduce precipitate potential.

The University of Toledo researchers found that about one-third of recovered "tufaceous" material was insoluble residue that had washed out of the base. Mn/DOT permittivity testing of field samples of drainage fabric also indicate the presence of significant quantities of insoluble or noncarbonate-based compounds. Therefore, it seems likely that washing or otherwise cleaning the recycled concrete products before using them in pavement foundation layers should reduce the

accumulation of crusher dust and other fines in and around pavement drains. However, it seems unlikely that precipitate potential will be significantly reduced or eliminated by washing or cleaning the crushed concrete before using it.

Mn/DOT field studies have shown that precipitate and insoluble residue accumulations can produce significant reductions in the permittivity of typical drainage filter fabrics. However these studies also show that filter fabrics are available with initial permittivities that are great enough to withstand significant amounts of material deposits without reducing permittivities to unacceptably low levels; pipe drains that are unwrapped and placed in trenches back-filled with permeable granular materials may exhibit better long-term flow characteristics than those that are wrapped and placed in similar trenches; and accumulations of precipitate and insoluble residue have not, thus far, been found to occur in quantities large enough to significantly reduce the flow capacity of most pipe drains.

The report details specific recommendations for RCA base composition and gradation; drain system design and maintenance; and use of RCA fines, including the following:

- Eliminate the intentional inclusion of RCA fines (#4-minus) in drained, unstabilized pavement foundation layers.
- Design the drainage systems to accommodate the limited quantity of crusher fines and insoluble residue that are produced by pavement bases, both natural and recycled.
- Blend open-graded RCA products with virgin aggregates to produce gradations required to improved stability and density and to further reduce precipitate potential in drained pavement foundation layers.
- Use drain pipes that are either unwrapped or wrapped in filter fabrics with high initial permittivities. The report also offers a more detailed analysis of drain pipe and pavement drain specifications.
- The use of unstabilized RCA fines (#4-minus materials) should be restricted to areas that are below any drainage layers or structures.

Testing for Precipitate Potential

The Michigan Department of Transportation recommends the use of calcium ion concentration to determine the precipitate potential of recycled concrete products. Research currently under way at the University of Minnesota is also comparing the abilities of pH and calcium ion concentration measures to predict the formation of calcium carbonate precipitate. If it proves an improved measure, the test should be developed further to include appropriate acceptance/rejection criteria.

Recementing of RCA Containing Fines

Eliminating the use of fines from drained foundation layers should all but eliminate this concern as well. While the recementing phenomena does appear to take place when significant quantities of fines are present, Mn/DOT stockpile experience suggests that course, open-graded materials do not become recemented in the short term (one year of exposure). The report also discusses the design of concrete pavements that are constructed directly on RCA foundation layers containing significant quantities of fines.

Corrosion of Rodent Guard Screens

Concerns about the corrosion of rodent guards would be eliminated if Mn/DOT were to require the use of rodent guards fabricated from plastic or other corrosion-resistant materials. In addition, the recommendations made concerning the reduction of precipitate/drainage problems would also probably reduce corrosion problems.

Environmental Concerns

While the effluent from RCA foundation layers is initially extremely alkaline, it has rarely been documented as being sufficiently alkaline to be considered an environmental hazard. With the effluent usually effectively diluted at a short distance from the drain outlet, it seems likely that environmental concerns are probably restricted to a very small region in the vicinity of the drain outlets. Furthermore, the recommendations provided above, which are intended to reduce the formation of precipitate and the deposit of other insoluble residue, also should reduce initial pH levels and the time required to stabilize the pH of the runoff to "tap water" levels. Evidence to support or disprove this theory will be available when the Michigan Concrete Paving Association study is completed later this year.

The report also talks about environmental concerns other than pH.

Interpretation of Applicable Specifications by Contractors

The report reviews current applicable Mn/DOT specifications that relate to the use of crushed concrete materials in granular base and backfill applications. While the current specifications already address many of the concerns addressed in the report, they also appear to be very conservative and could be clarified and modified to allow increased use of crushed concrete products without risking significant drainage problems. Appendix A contains a copy of the current, relevant Mn/DOT specifications with modifications that reflect these recommendations.

INTRODUCTION

The Minnesota Department of Transportation has been using recycled concrete aggregate (RCA) products as replacements for virgin aggregate products in pavement foundation and other applications since the early 1980's. However, concerns have developed in recent years about some aspects of the performance and environmental impact of these materials when used in pavement foundations. Performance concerns have centered on the production of deposits of calcium carbonate precipitate and other fines, which are believed to reduce the permeability or drainage capacity of the recycled concrete foundation layer and any associated drainage structures and filter fabrics. Environmental concerns have focused on the relatively high pH of the effluent produced by pavement drainage systems that remove water from untreated recycled concrete aggregate foundation layers.

The Minnesota Department of Transportation and other agencies have conducted a number of studies since the middle 1980's to examine these concerns and others. This report summarizes the activities and findings of some of the more relevant studies, and provides recommendations concerning the continued use of crushed concrete products in Minnesota pavement foundations.

FIELD STUDIES

I-90 near Austin, Minnesota

A section of I-90 near Austin, Minnesota was reconstructed in 1985 using recycled concrete base materials. Site visits conducted as early as 1987 revealed that while some of the drain pipes had remained clean, others were approximately 1/4 filled with material deposits (Figures 1 and 2). More recent site visits by this author (summer of 1994) found minor material deposits in some drain pipes, with more significant deposits in and around the concrete drain pipe head walls (see Figures 3 and 4). Interviews with Mn/DOT personnel indicate that the drains have been maintained (cleaned) periodically since construction. All of the drains observed now appear to be carrying water and are not significantly obstructed at the outlets. Areas of vegetation kill were observed near some drain outlets and some metal rodent guards were corroded (see Figures 5 and 6). However, frogs and water insects were observed living in the water that was pooled in and around the drain outlet headwalls, suggesting that current effluent is not toxic.

Filter fabric samples were obtained from several project locations for permittivity testing by Mn/DOT in 1989 and 1993. The intent of these tests was to determine whether the accumulation of deposits on the filter fabrics surrounding the drain pipes was significantly impeding drainage. The results of these tests, summarized in Table 1, indicate that all of the samples have experienced significant permittivity losses during their field service (average of 50% after 4 years of service and 53% after 8 years). Many of these samples now exhibit permittivities that might be considered marginal or unacceptable for continued pavement drainage (less than 0.7/sec, which is the Mn/DOT Specification 3733 Type 1 fabric limit). Samples obtained from the side of each pipe generally exhibited lower permittivities than those taken from the top or bottom; samples taken from the top generally exhibited lower permittivities than those taken from the bottom of each pipe. This phenomena is consistent with the theory that the fabric on the bottom of the pipe would accumulate lesser amounts of precipitate because it is submerged for longer periods of time (and is, therefore, exposed to atmospheric carbon dioxide for less time) than the side or top of the pipe.

Figure 1. Photo of typical I-90 (Austin, MN) drain outlet, 1987.

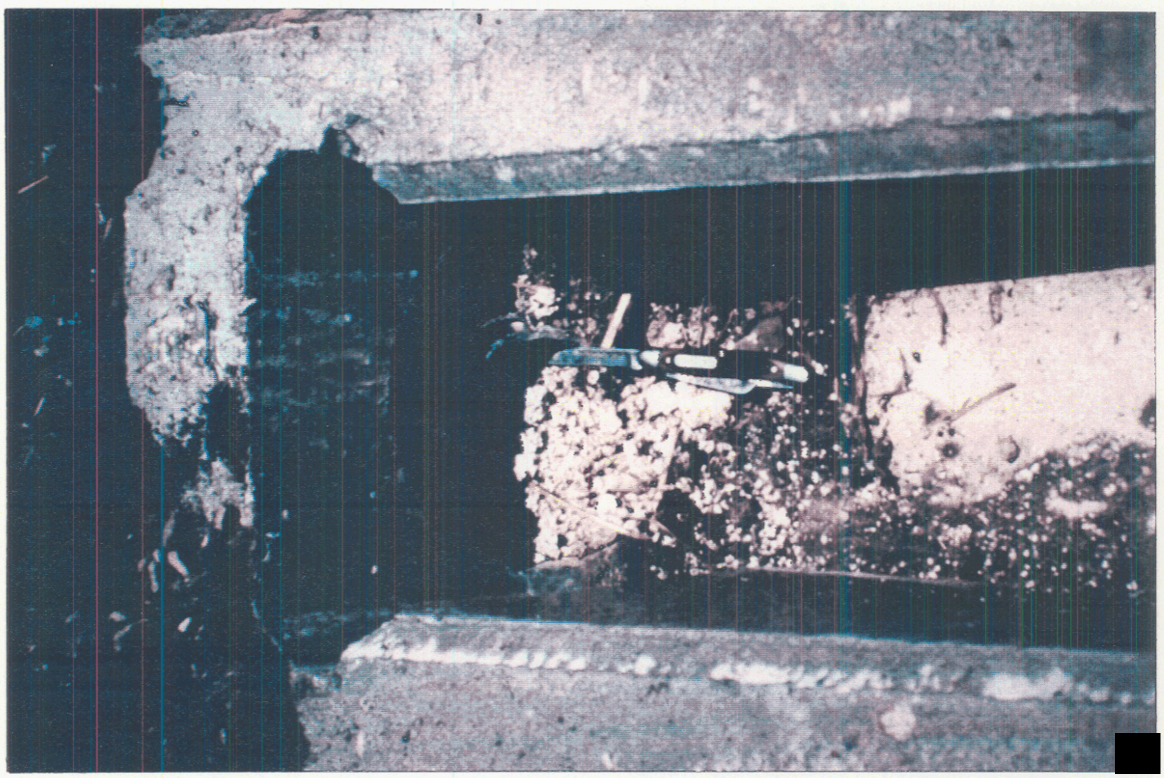

Figure 2. Photo of typical I-90 (Austin, MN) drain outlet, 1987.

Figure 3. Photo of typical I-90 (Austin, MN) drain outlet, 1994.

Figure 4. Precipitate around I-90 (Austin, MN) drain headwall.

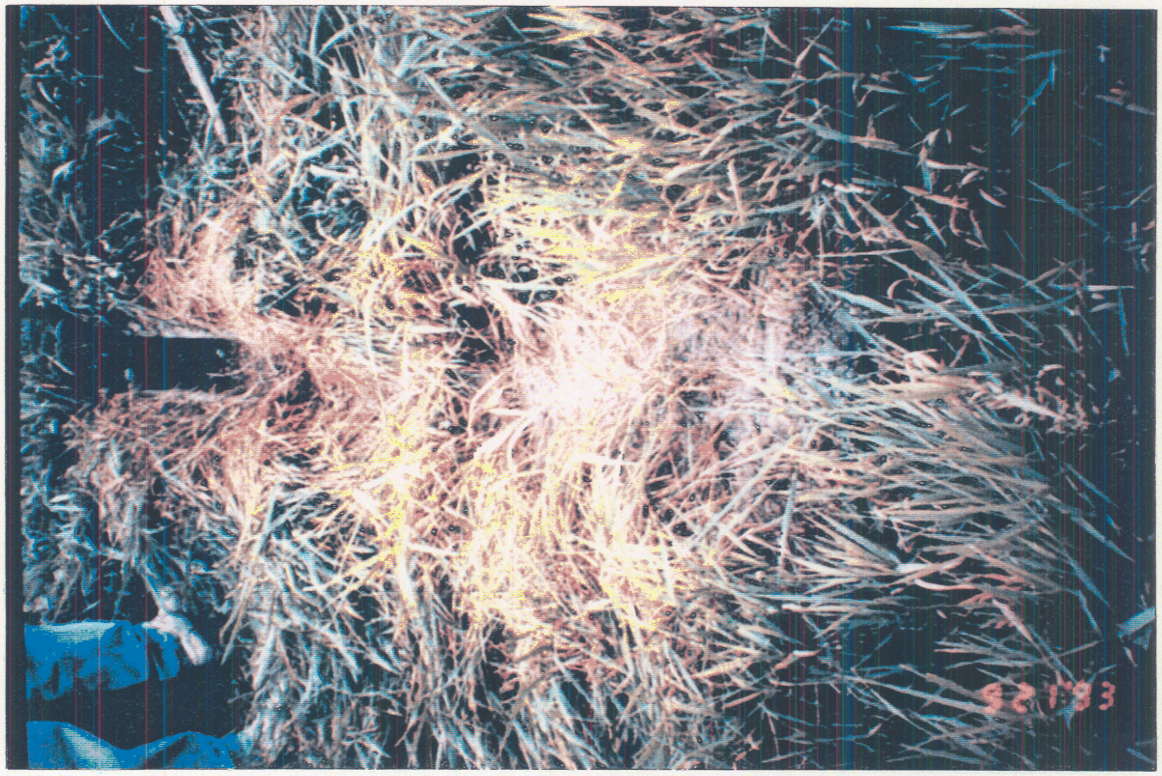

Figure 5. Photo of vegetation kill on I-90 (Austin, MN), 1994.

Figure 6. Rodent guard corrosion on I-90 (Austin, MN), 1994.

Table 1. Average permittivity measurements for I-90 (Austin, MN) drainage filter fabric samples, 1989 and 1993.

	Permittivity Data (1/sec) - 1989 Measurements							
	Bottom of Pipe				Top of Pipe			
	Average (6 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %	Average (6 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %
As Sampled	0.6	0.4 - 1.0	-45		0.50	0.3 - 0.9	-55	
After Acid Soak	0.7	0.4 - 1.0	-36	17	0.8	0.3 - 1.3	27	60
After 1% Alconox Wash	1.2	1.0 - 1.5	9	100	1.2	1.28 - 1.6	35	196

	Permittivity Data (1/sec) - 1993 Measurements							
	Bottom of Pipe				Top of Pipe			
	Average (9 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %	Average (6 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %
As Sampled	0.55	0.23 - .83	-50		0.50	0.37 - 0.6	-55	
After Acid Soak	0.90	0.35 - 1.6	-18	64	1.32	1.16 - 1.4	20	164
After 1% Alconox Wash	1.37	0.69 - 1.8	25	149	1.48	1.28 - 1.6	35	196

Fabric = Typar 3341 (nominal permittivity = 1.1/sec)

1993 Measurements (Continued)	Side of Pipe			
	Average (7 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %
As Sampled	0.36	0.16 - 0.5	-67	
After Acid Soak	0.90	0.51 - 1.6	-18	150
After 1% Alconox Wash	1.20	0.79 - 1.8	9	233

These tests also indicate that, while much of the observed permittivity losses were due to buildups of carbonate-based materials (17 - 84%, as indicated by the increases in permittivity after soaking in acid), significant permittivity losses (83 - 16%) were caused by buildups of non-carbonate materials that were not soluble in acid, but were removed upon washing with 1% Alconox solution (see Table 1).

It should also be noted here that the nominal initial permittivity of the Typar 3341 filter fabric used on this job is only 1.1/sec, which is not much higher than the Mn/DOT Specification 3733 limit of 0.7/sec. Many fabrics are available with initial permittivities that are much higher than this and would, presumably, still provide acceptable drainage in the presence of comparable deposits (see reference 9).

In summary, the results of this study suggest the following conclusions:

1. Large quantities of fine materials were discharged into and through the pavement drainage system within the first two years of service (see figures 1 and 2). Periodic maintenance has successfully kept the drain pipes free of significant buildups.
2. These fines have also accumulated on the fabric that wraps the drain pipes, resulting in an average permittivity loss of 50% after 4 years (or less) of service. Only minor additional losses (an average of 3%) were observed after a total of 8 years of service.
3. The materials that accumulate within and around the pavement drainage system are composed of varying proportions of both carbonate-based and noncarbonate-based materials.
4. After nine years of service, there are still areas of dead vegetation near some of the drainage outlets. It is not known for certain whether this is a result of initial discharges of undesirable materials (e.g., soon after construction) or of continuing discharges. The current presence of small animals and insects in the discharge pools suggests that current discharges are not toxic.

Trunk Highway 212 near Glencoe, Minnesota

Edge drains were retrofit along highway 212 near Glencoe, Minnesota in 1985. The pre-existing base consisted of *natural* aggregates graded to Mn/DOT Class 5. Samples of the longitudinal edge drain wrap were removed in 1989 (after 4 years of service) for permittivity testing of the type described previously. Permittivity losses at the top of the pipe averaged 1.0/sec, dropping the fabric permittivity below the Mn/DOT Specification 3733 limit of 0.7/sec; losses at the bottom averaged 0.5/sec. The permittivity losses were determined to be almost entirely due to buildups of noncarbonate material.

Although little additional documentation of this study was available to this author, the data provided illustrate that significant reductions in filter fabric permittivity can take place even in the absence of recycled concrete base materials. Thus, evaluations of the permittivity loss associated with recycled concrete aggregates should include a determination of the amount of loss that is due to noncarbonate materials that might be produced by other types of base materials.

Lakeville, Minnesota Test Beds

Seven test beds were constructed in the fall of 1989 using recycled PCC, recycled AC and virgin limestone base materials to measure variations in the quality and quantity of water flowing through these beds over time. Each test bed was constructed 75 ft long, 10 ft wide, 6 in deep and with a constant cross slope of 0.015. The base materials were not compacted. Edge drains were placed at the low side of the cross-section and one headwall was provided at the end of each section. Polyethylene sheets were placed under each bed and berms were constructed around each bed to prevent the entry of runoff or groundwater. Three of the test beds were constructed using recycled concrete materials:

- #1 was a blend of crushed concrete and gravel graded to meet Mn/DOT Class 5 (with most of the material passing the #4 sieve being composed of crushed concrete particles), and a 4-in unwrapped perforated drain pipe in an edge drain trench that had been backfilled with fine filter aggregate;
- #2 was identical to #1 except that the drain pipe was wrapped with filter fabric;
- #7 was an open-graded blend of #4-plus crushed rock and #4-minus RCA, with an unwrapped perforated pipe placed in an edge drain trench backfilled with permeable aggregate.

- #3 was composed of Class 5 gravel and sand, #4 was composed of 1-in minus milled bituminous, #5 was composed of crushed bituminous between #4 and 3/4-in, and #6 was an open-graded crushed rock.

The testing was terminated in 1992 when Mn/DOT researchers removed the drainage pipes to test the permittivity of the drainage fabrics and determine the amount of precipitate that was accumulated in the drain systems.

The results of permittivity testing on samples obtained from the top and bottom of the RCA drainage pipes are summarized in Table 2. These data indicate that all sections experienced permittivity losses during their field service; however all of the samples retrieved exhibited permittivities that would be considered acceptable for continued pavement drainage (all were greater than 1.6/sec, and the average was 2.44/sec; Mn/DOT's specification 3733 provides a lower limit of 0.7/sec on this value). The nominal original permittivity of Exxon GTF 130-EX fabric used on this job is approximately 3.6.

These tests also indicate that, while much of the observed permittivity losses were due to buildups of carbonate-based materials (64 - 71%, as indicated by the increases in permittivity after soaking in acid), significant permittivity losses (29 - 36%) were caused by buildups of non-carbonate materials that were not soluble in acid, but were removed upon washing with 1% Alconox solution (see Table 2).

Samples obtained from the top of each pipe often (but not consistently) exhibited greater losses of permittivity (averaging 34% less than nominal) than those taken from the bottom of each pipe (which averaged 31% less than nominal). These differences were not generally statistically significant. It is likely that the isolation and efficiency of the drainage systems associated with these test sections prevented the accumulation of standing water in the pipes. A more typical drainage system (e.g., the one at I-90, Austin, MN) would be more likely to accumulate standing water and, therefore, exhibit differences in permittivity loss between the top and bottom of the pipe, as described previously.

Boroscope inspections performed in late August of 1992 found small amounts of calcium deposits in the drain pipes associated with the recycled concrete sections. The sediment in section 2 was only deep enough to fill the pipe corrugations in low areas of the pipe; section 1 had somewhat more sediment in several areas. It was noted that these deposits did not appear to be clogging the pipes or interfering with drainage [1, 2].

Table 2. Average permittivity measurements for Lakeville test bed filter fabric samples, 1992.

	Permittivity Data (1/sec) - 1992 Measurements							
	Bottom of Pipe				Top of Pipe			
	Average (9 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %	Average (9 Samples)	Range	Change from Nominal %	Change from "As-Sampled" %
As Sampled	2.499	1.81 - 3.7	-31		2.394	1.64 - 3.7	-34	
After Acid Soak	2.717	1.89 - 3.5	-25	9	3.087	2.42 - 4.7	-14	29
After 1% Alconox Wash	2.847	1.99 - 3.8	-21	14	3.382	2.85 - 4.9	-6	41

Fabric = Exxon GTF 130-EX (nominal permittivity = 3.6/sec)

Table 3 summarizes pH data obtained from the Lakeville test pads. These data indicate that the average pH of the effluent from the bases containing recycled concrete aggregate (pads # 1, 2, and 7) was slightly more alkaline, on the average, than those of the other bases. These averages are driven up in part by the fact that the pH of the recycled concrete beds showed an initial high peak within the first year (10, 12 and 9.2 for pads 1, 2 and 7, respectively); effluent from the other beds started (and generally remained) between 7.7 and 8. The pads containing recycled concrete bases typically dropped off quickly from the initial peak values and produced effluent with an average pH of around 8. It is also worth noting that bed #7, an open-graded blend with relatively few recycled PCC fines, exhibited lower pH values and less variability in results than either beds #1 or 2. This supports the theory that the recycled concrete fines are the principal source of increased pH and precipitate.

Table 4 summarizes rainfall and tipping bucket flow data for the Lakeville test beds. These data show that test bed 2 generally produced less outflow for any given rainfall than any other test bed; test bed 1 produced 10 - 160 percent more outflow than bed 2 (probably because bed 1 included an unwrapped pipe), but still less than the other test beds. Test bed 7 produced 2 to 35 times as much outflow as test bed 1, and often produced more outflow than any other test bed.

These data are probably best explained in terms of the effects of aggregate grading and drain configuration. The dense-graded Class 5 materials found in test beds 1, 2 (recycled fines) and 3 (natural materials) are not intended to be fast draining materials, and they aren't. However, the presence of recycled fines probably further impedes drainage in these materials by further reducing flow channels (through self-cementing action, as evidenced by comparing the results of bed 3 with bed 1) and by depositing precipitate or other fines on filter fabrics (as evidenced by comparing the results of bed 2 with bed 1). The superior performances of test bed 7 and 6 (which was made using an open-graded natural material) provide testimony to the overwhelming influence of aggregate grading on base drainage.

Thus, the data presented in table 4 suggest that crushed concrete should provide acceptable drainage performance in open-graded bases that are drained by properly-designed longitudinal drain systems that do not include geotextile fabric-wrapped longitudinal pipes. In addition, it is also reasonable to assume that, from a drainage standpoint, recycled concrete products could be dense-graded bases and other layers that are not intended to be drainable.

Table 3. Summary of pH data for test pads near Lakeville, MN.

Test Pad	1	2	3	4	5	6	7
Mean	8.07	7.33	7.23	6.98	7.08	7.23	7.53
Std. Dev.	1.14	1.04	0.32	0.36	0.32	0.24	0.71
C.O.V.	14.09	14.23	4.45	5.16	4.48	3.34	9.39
Minimum	6.60	6.40	6.50	6.00	6.40	6.40	6.10
Maximum	10.80	11.30	7.80	7.60	7.70	7.80	11.20
Median	7.95	6.90	7.30	6.90	7.10	7.20	7.40

Table 4. Summary of rainfall and tipping bucket flow data for test pads near Lakeville, MN.

Flow in Test Bed, gallons								
Date	Rainfall (in)	1	2	3	4	5	6	7
5/19/90	1.19	81.12	72.05	196.04	141.12	101.52	370.04	210.97
6/12/90	1.05	10.40	7.15	40.60	14.88	41.76	280.72	350.40
6/16/90	1.24	13.52	57.20	73.08	385.92	341.28	535.92	455.52
7/27/90	1.32	16.12	N/A	N/A	300.96	252.72	537.66	307.33
3/22/91	1.14	79.04	12.10	284.20	386.40	82.80	247.08	154.03
5/25/91	1.65	75.40	55.55	341.04	1617.60	181.44	631.62	800.81
9/12/91	1.14	110.76	100.65	293.48	1522.08	193.32	493.00	1005.21
4/18/92	1.52	53.04	27.50	241.28	136.80	23.04	N/A	N/A
7/11/92	0.46	N/A	N/A	N/A	N/A	N/A	141.52	23.36
8/7/92	1.63	147.16	56.10	219.24	134.88	61.92	1026.02	N/A

Normalized Flow in Test Bed, gallons/in								
Date	Rainfall (in)	1	2	3	4	5	6	7
5/19/90	1.19	68.17	60.55	164.74	118.59	85.31	310.96	177.29
6/12/90	1.05	9.90	6.81	38.67	14.17	39.77	267.35	333.71
6/16/90	1.24	10.90	46.13	58.94	311.23	275.23	432.19	367.35
7/27/90	1.32	12.21	N/A	N/A	228.00	191.45	407.32	232.83
3/22/91	1.14	69.33	10.61	249.30	338.95	72.63	216.74	135.11
5/25/91	1.65	45.70	33.67	206.69	980.36	109.96	382.80	485.34
9/12/91	1.14	97.16	88.29	257.44	1335.16	169.58	432.46	881.76
4/18/92	1.52	34.89	18.09	158.74	90.00	15.16	N/A	N/A
7/11/92	0.46	N/A	N/A	N/A	N/A	N/A	307.65	50.78
8/7/92	1.63	90.28	34.42	134.50	82.75	37.99	629.46	N/A

Mn/DOT's Environmental Engineering section monitored various measures of the outflow water quality for the seven test beds, including: pH (already discussed), alkali concentration, hardness, bicarbonate alkali concentration, aluminum concentration, chromium concentration and conductance. While summaries of these data have been compiled, this author was not provided with any reports or conclusions that have been drawn from this raw data; it would be inappropriate for this author to comment further on these data.

From this study of drainage test beds constructed near Lakeville, Minnesota, Mn/DOT's researchers concluded that:

1. The drainage characteristics of the sections constructed using crushed concrete did not deteriorate significantly over the 2.5-year study;
2. The quantity of flow and percentage of rainfall retrieved was slightly higher for the section constructed using unwrapped drain pipe;
3. The pH of the effluent generally decreased over time, with slight peaks early in the year;
4. Some calcium deposits were observed in the drain pipes associated with the RCA base materials, but these deposits did not appear to be clogging the pipes or interfering with drainage;
5. There was some "cementing" of the top few inches of the trench filter aggregate on test beds 1 and 2.

This author agrees with the conclusions given above that are based on the reported data and offers the following additional observations and conclusions:

1. The minor peaks in pH that occurred every spring (and most falls, as well) are probably due to more frequent wetting of aggregate without complete drying during these wetter seasons, which may allow the leaching of greater quantities of calcium-based compounds.
2. The pH of the effluent from test beds 2 and 7, which varied between 8.5 and 9.0, rarely exceeded that of "hard" tap water and averaged only slightly more than 7 (neutral); the pH of bed 1 was greater than 8.5 to 9 about 50% of time, but never higher than 10 (since 3/90) and averaged only 8. While pad 3 (control) consistently averaged about 7.3 (range of 6.5 to 7.7), all of the test data indicate pH values that should pose no long-term environmental concern. Even the effects of initially high pH values would be limited because: a) they are of short duration; and b) the high-pH outflow would be quickly diluted and/or neutralized by the larger influx of surface runoff.

3. Much more water generally flowed from bed 7 than almost any other bed; much less flowed from beds 1 and 2, with bed 2 generally producing the least outflow of all. These results may be explained by the differences in aggregate grading and the use of fabric wrap around the drain pipes. Beds 1 and 2 were constructed of a relatively densely-graded Class 5 material, which should have a lower water loss potential and slower drainage rate than the more open-graded materials used in bed 7. In addition, the probable accumulation of materials on the filter fabric used in bed 2 would account for the decreased outflow when compared to bed 1, which did not incorporate the fabric wrap.

In summary, the results of this study suggest that recycled concrete materials can be used in drainable base layers provided that: a) large quantities of recycled fines are not included; b) the drainage system is properly designed; and c) filter fabrics are not used to wrap the longitudinal drain pipes. In addition, the use of recycled materials in undrained layers should present no drainage-related problems.

TH 15 near Hutchinson, Minnesota

Eight test sections were constructed on TH 15 in 1991 to mirror the Lakeville project, each being 400 feet long and 27 feet wide with edge drains on both sides of the road. Three of the eight sections were constructed using recycled concrete products in the pavement foundation:

- Section 1 is similar to Lakeville beds 1 and 2. It consists of 5 inches of the same type of Class 5 blended RCA-gravel material, with the #4-minus material being primarily RCA. The northbound perforated pipe is unwrapped and placed in a drain trench that was backfilled with a modified fine aggregate filter; the southbound perforated pipe is wrapped with fabric and placed in a drain trench that was backfilled with fine filter aggregate.
- Section 2 is identical to section 1 except that the Class 5 material is 100% crushed concrete.
- Section 7 is constructed on a 4-in open-graded layer of crushed rock (#4-plus) and crushed concrete (#4-minus).
- Section 8 is constructed on a 4-in layer of crushed concrete that was supposed to be graded to 100% passing 1 inch and retained on #4, although lab tests found about 10% passing the #4 sieve. The edge drain trench was backfilled with permeable aggregate and the perforated pipe was unwrapped.

- The remaining sections contained no recycled concrete: section 3 includes a natural base of virgin sand and gravel graded to meet Mn/DOT Class 5; section 4 includes milled bituminous materials graded to meet Mn/DOT Class 5; section 5 includes crushed bituminous materials graded between the #4 and 1 inch sieves; and section 6 contains open-graded crushed rock.

The layout of the test section is illustrated in Figure 7.

Precipitate accumulation in the Hutchinson recycled concrete sections was observed to be much greater than that found in comparable test beds at Lakeville. These differences in precipitate production were attributed to differences in water flow patterns and wetting and drying characteristics at the two sites (i.e., the Lakeville site dries out more quickly because it is constructed to accept no moisture from surrounding ground or underneath while draining all of its moisture to the tipping buckets; the Hutchinson test is a typical pavement section that probably stays wet for longer periods of time, allowing more leaching of calcium-based compounds from the base). In addition, the volume of base being drained at each Hutchinson section is approximately 6 times that of each Lakeville test bed, which would lead one to expect a greater quantity of precipitate from a single drain. In spite of the observed precipitate, Mn/DOT researchers found that comparisons of similar rain events two years apart (one and three years after construction) showed no apparent difference in flow characteristics over time.

A summary of selected flow data from these sections is presented in Table 5. Given the variability of the data and the limited number of data points available for comparison, it is difficult to state conclusively that there is a significant difference in outflows between the wrapped and unwrapped pipes. However, trends suggest the following:

- Comparisons of the flow characteristics of comparably graded and drained natural and recycled base materials (i.e., buckets 3 and 4 or 11 and 12) *generally* show significantly increased flow (-24% less to +221% more) for the natural base materials.
- Blending crushed rock with the recycled concrete improved base flow characteristics by up to 175% for any given blend or drain wrap condition (i.e., compare data from buckets 2 and 3, 9 and 10, or 12 and 13).
- The use of open-graded materials generally increased base flow as well (i.e., compare data from buckets 3 and 10 or 2 and 9).

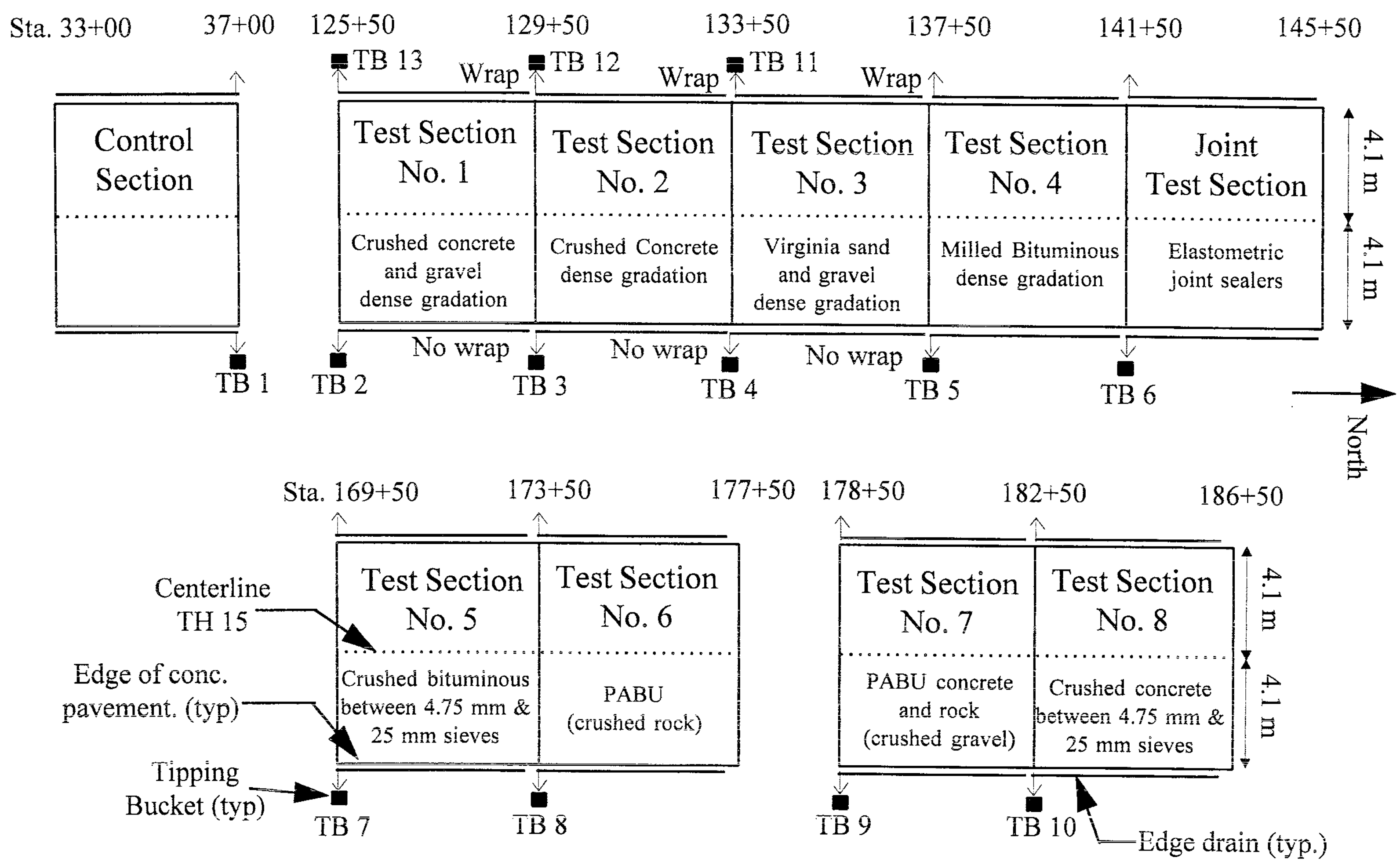

Figure 7. Layout of recycled base test site on Minnesota Trunk Highway 15 near Hutchinson, MN.

Table 5. Tipping bucket flow data from recycled base test site on Minnesota Trunk Highway 15 near Hutchinson, MN.

Tipping Bucket	Test Section	Section Description	Rainfall = 1.35" April 1993		Rainfall = 2.20" April 1994		Rainfall = 0.55" May 1994		Rainfall = 0.46" June 1994	
			gals	gals/in	gals	gals/in	gals	gals/in	gals	gals/in
1	Control		852	631	1427	649	429	780	89	193
2	#1, NB	RCA blend, unwrapped	N/A	N/A	N/A	N/A	N/A	N/A	122	265
3	#2, NB	100% RCA, unwrapped	1889	1399	N/A	N/A	N/A	N/A	108	235
4	#3, NB	Sand and gravel, unwrapped	N/A	N/A	2734	1243	962	1749	347	754
5	#4, NB	Milled bituminous,	1580	1170	1483	674	625	1136	207	450
6	Elastomeric Joint Seal Test, NB		1263	936	N/A	N/A	N/A	N/A	N/A	N/A
7	#5, NB	Bituminous OGAB,	2250	1667	N/A	N/A	N/A	N/A	499	1085
8	#6, NB	Crushed rock OGAB,	2260	1674	3776	1716	1231	2238	412	896
9	#7, NB	RCA blend OGAB,	2213	1639	3061	1391	893	1624	349	759
10	#8, NB	100% RCA OGAB,	1576	1167	1105	502	502	913	162	352
11	#3, SB	Sand and gravel, wrapped	1229	910	1514	688	330	600	45	98
12	#2, SB	100% RCA, wrapped	1617	1198	704	320	147	267	N/A	N/A
13	#1, SB	RCA blend, wrapped	1679	1244	1150	523	404	735	46	100

- Wrapped pipes produce less outflow during and after any given rainfall event than do unwrapped pipes, regardless of whether the base is composed of natural materials (i.e., consider the results of buckets 4 and 11 in April - June 1994) or recycled materials (i.e., consider the results of buckets 2 and 13 in June 1994, or buckets 3 and 12 in April 1993).
- Of the four open-graded base materials tested, the bituminous and crushed rock consistently provided the largest outflows, followed closely by the open-graded RCA blend and then the 100% RCA material. All four generally provided drainage that was comparable to or better than that of either the control (bucket 1) or the sand and gravel base with wrapped pipe (bucket 11).

In summary, the results of this study suggest that the use of recycled concrete products (in lieu of natural materials) in untreated pavement bases may contribute to a decrease in drainage outflow during any given rainfall event. However, this decrease can be reduced or eliminated through the use of open-graded materials, blending with natural crushed rock and/or by eliminating the fabric wrap around the drain pipes. Recycled materials in open-graded bases with unwrapped pipes exhibited greater outflows than the natural base/wrapped pipe section.

More data points should be examined to verify the trends described above. However, if these trends are correct, they suggest that the use of open-graded recycled materials with unwrapped pipes in permeable aggregate-filled trenches should produce acceptable performance.

Shakopee, Minnesota Test Stockpiles

The Minnesota Department of Transportation constructed three aggregate stockpiles at their truck station near Shakopee in the summer of 1993 -- one of open-graded, coarse RCA, one of RCA fines (100% passing #4 sieve) and one of dense-graded, recycled asphalt concrete. These stockpiles were constructed on sheets of polyethylene and surrounded with lined and bermed trenches that allowed the collection and analysis of all runoff. Chemical analysis of the runoff data for the August-November 1993 period were provided to this author for consideration and a summary of some of this data is presented in Table 6.

It appears that the pH of the runoff from the coarse RCA gradually decreased from an average of about 10.5 to 9.7 over the three-month period, with slight increases observed during periods of longer wetness and runoff. The fine RCA pH values decreased from slightly higher values (in the 11 to 12 range) to about 9.5 as well. The recycled asphalt concrete stockpile produced relatively stable pH values of 6.8 to 8.4. Total alkali contents were highest for the coarse RCA and were much less for the fine RCA; there was no clear trend of alkali content over time for these materials. The alkali content of the recycled bituminous runoff was negligible. Total solids produced were also consistently higher for the RCA stockpiles than for the recycled bituminous aggregate pile; there was no clear trend of total solids content over time. There was no significant difference in total solids between the fine and coarse RCA piles.

Table 6. Summary of selected chemical analysis data from Shakopee, MN. test piles.

		Coarse RCA	Fine RCA	Bituminous
pH	Average	10	10.6	7.6
	Std. Dev.	0.4	1.1	0.4
	n	21	16	20
Total Alkalis (mg/L)	Average	1770	460	38
	Std. Dev.	1270	370	13
	n	9	7	9
Total Solids (mg/L)	Average	2190	1820	390
	Std. Dev.	1850	1650	390
	n	27	22	27
Total Chlorides (mg/L)	Average	290	600	75
	Std. Dev.	380	580	100
	n	20	15	19

The author visited the test stockpile site in late September 1994. The stockpile of RCA fines was strongly recemented while the stockpile of coarse RCA was not recemented to any detectable extent. The recycled asphalt concrete stockpile was also "recemented," presumably under the compactive force of its own weight and the asphalt-softening effects of the warm summer weather.

The Minnesota Department of Transportation is in the process of producing a report that will address the results of this study in more detail. It is this author's understanding that some of the project researchers are concerned that the runoff was found to contain some elements and compounds in concentrations that are well above currently-accepted standards for safe drinking water. This report was not made available to this author (even in draft form), so it would be improper to comment on these concerns at this time. However, any analyses of the concentrations of such concerns should be performed in the context of the amounts of these contaminants that would be transported from a pavement foundation that drains only a small amount of any given rainfall event (assuming that most water runs off the pavement surface), and that any drainage effluent is quickly diluted by that same surface runoff (as well as the runoff from adjacent lands). Thus, the limits of hazardous concentrations, if any, may be limited to the immediate vicinity of the drain outlet pipes (as indicated by vegetation kills that have been observed at some outlets along I-90 near Austin, MN).

Additional Performance Observations in Other States and Countries

Recycled concrete products have been and continue to be used successfully in numerous other states and countries. There have been observations of precipitate production in some of these installations, as noted below.

The Michigan Department of Transportation (MDOT) has observed up to 1/4-in of precipitate in drainage pipes associated with pavements placed over RCA bases after 2-3 years of service. Although they have noted no problems with the performance of these pavements that can be attributed to losses of drainage quality, MDOT has taken what they consider to be a proactive position by requiring that all open-graded RCA materials being placed in drainage base layers must be stabilized with either asphalt cement (3% by weight of aggregate) or cement paste. In addition, the diameter of the longitudinal drains was increased to 6 inches for cement-stabilized RCA bases. Dense-graded RCA materials being used in undrained foundation layers are considered acceptable; stabilization of these materials is not required.

The Illinois Department of Transportation (IDOT) has also noted some precipitate in pavement drains and is beginning to research the phenomena. Christine Reed of IDOT is leading studies in this area and is looking into the potential of using acidic fly ash to stabilize the RCA.

In June of 1993, Long-Term Pavement Performance (LTPP) project surveyors noted substantial precipitate in the vicinity of drains on a section of I-35 in Harrison County, Missouri that includes rubblized concrete pavement as a foundation. This pavement section is included as an SPS-6 study section in the LTPP program.

LABORATORY STUDIES

Minnesota Department of Transportation (1987)

G. R. Ford of the Minnesota Department of Transportation conducted a series of studies to examine the plugging of geotextile and perforated pipe subdrainage systems by the formation of calcium carbonate precipitate deposits. The earliest experiments consisted of soaking samples of RCA in a 5-gallon bucket with a sand filter and fabric layer placed over a drain in the bottom of the bucket [3]. The fabric layer often plugged within hours and pH values as high as 11.5 were observed. In a revised experiment, recycled concrete aggregate was soaked in a bucket of tap water to produce high-pH water, which was then poured into a reservoir. Water from the reservoir was circulated by pump through an inclined 6-in PVC pipe with a geotextile fabric covering the lower end. Plugging of the geotextile was measured by measuring the depth of water retained behind the geotextile, indicating the permittivity of the fabric. Depth of water increased with increases in precipitate and water pH. Tests conducted using aggregate blends including as little as 25% RCA still produced high soak water pH values (12.2 - 12.5) and sufficient precipitate to plug the geotextile. The researchers provided a context for the production of this precipitate, however, noting that the volumes of water circulated through the recycled concrete samples in these tests probably represented "tens of years in field conditions."

It was verified that the precipitate was calcium carbonate when the precipitate effervesced strongly and dissolved in the presence of a weak acid. In addition, the permittivity of the fabric increased after the addition of the acid.

Some water chemistry work was accomplished under this study, and the researchers concluded that the calcium ion concentration might be a better indicator of the potential for precipitate formation than pH level.

Construction Technology Laboratories, Inc. (1989)

P. J. Nussbaum of Construction Technology Laboratories, Inc. (CTL) performed tests to determine the calcium ion concentration in water being circulated at a rate of 14.5 gal/hr in a closed loop through a 19-in thick, 10-in diameter sample of RCA graded to meet Michigan DOT Series 8 requirements (open-graded base material). Water samples were drawn prior to initiating flow, and after 1, 7 and 28 days. The calcium ion concentration increased from an initial level of 34 ppm (prior to water circulation) to 718, 714 and 698 ppm after 1, 7 and 28 days, respectively [4].

Since no additional increase in calcium ion concentration was observed after the first day, the researchers concluded that the initial increase was due to "water pickup of crushing dust and that no significant calcium leaching occurred."

It is this author's opinion that little can be concluded from this study because of serious flaws in both its approach and conclusions. While it is possible that the initial increase in calcium ion concentration was due to "water pickup of crusher dust ...," it is also possible that a state of chemical equilibrium had been established, thereby preventing further dissolution or leaching of calcium compounds from the crushed concrete. In addition, the use of a closed loop test system prevented the introduction of atmospheric carbon dioxide, making it difficult for calcium carbonate to form and precipitate out of solution.

Michigan Department of Transportation (1989)

R. W. Muethel of the Michigan Department of Transportation performed a study to determine the potential for leaching calcium-based compounds from samples of RCA (3 sources), gravel, crushed limestone and blast furnace slag. Several 500-g samples of various gradings (e.g., 1" - 1.5", 3/4" - 1", etc.) were prepared for each aggregate source. Each sample was soaked in distilled water for one week, then allowed to dry before being soaked and dried for two more one-week cycles. Measurements of weight loss, soak water pH and precipitate production were made after each soak-dry cycle [5].

The recycled concrete aggregates produced precipitate in amounts that varied inversely with the aggregate particle surface area (e.g., gradings that featured more fine particles produced more precipitate). The slag aggregates also produced some precipitate, while the gravel and limestone produced none. Precipitate was also observed as encrustations on partially-immersed aggregate particles, but not on fully-immersed particles, indicating the need for atmospheric carbon dioxide for precipitation to occur. Soak water pH was found to vary with RCA particle size and number of soak cycles, with the finest grading (#4 - #200) yielding the highest initial values (in excess of 11), while the coarser particles ranged from 10 - 11 initially and decreased to 9 - 10 over the three soak periods

It can be concluded from these tests that: 1) RCA aggregates are susceptible to precipitate formation, and that the potential for formation increases with increasing amounts of RCA fines; 2) carbon dioxide is necessary for precipitate production; and 3) a correlation between soak water pH and precipitate production was observed, indicating that measurement of soak water pH may be a quick test for precipitate formation potential.

Mr. Muethel also provided the following recommendations:

- Crushed concrete fines passing the No. 4 sieve should not be used in conjunction with drainage systems containing geotextile fabrics due to the high potential for heavy calcium carbonate precipitation.
- The use of crushed concrete for open-graded drainage courses should be limited to installations where the drainage gradients are adequate to prevent stagnant water conditions which would promote long-term calcium carbonate build-up on perforated conduits, resulting in progressive impairment of drainage.
- The process of calcium hydroxide depletion due to long-term acid leaching should be investigated as a contributor to the deterioration of pavements at joints and cracks where continued chemical activity is likely to occur.

Ohio Department of Transportation/University of Toledo (1993)

"Tufaceous" or paste-like precipitate materials have been observed in deposits around and near the drains of pavements constructed using unbound slag and RCA subbases in northeastern Ohio. Research performed at the University of Toledo by Gupta, Kneller and Tamarisa included both a field study (to identify the chemical composition of the deposits) and a lab study (to determine the precipitate potential of RCA and various types of slag aggregates) [6, 7]. The chemical analyses revealed that the primary component of the precipitate associated with the RCA subbases was calcium carbonate (52 - 61%), although significant quantities of insoluble residue (26 - 34%) and other oxides and organic matter (13 - 14%) were also found. The calcium carbonate was associated with the presence of calcium hydroxide (a normal product of the reaction of cement and water) and residual free lime. The insoluble residue was primarily silica-based, presumably from the aggregate portion of the RCA base because silica becomes more soluble in alkaline solutions ($pH > 9$).

Laboratory studies were performed on samples from the two RCA bases (and on samples from the slag bases as well). Samples were prepared for each source with both a coarse grading and a grading meeting applicable ODOT specifications. Hot ethylene glycol, X-ray diffraction and scanning electron microscopy (SEM) analyses indicated that both specimens contained calcium carbonate and calcium hydroxide (as expected), but that one specimen contained no free lime. Neither source of RCA produced precipitate when simply soaked in distilled water, although the pH of the soak water generally increased to more than 11 within 24 hours. Both sources of RCA produced precipitate in the laboratory when soaked in deionized water that was saturated with carbon dioxide. The amount of precipitate produced was generally proportional to the amount of fines in the sample. The pH levels returned to near 7.0 as the precipitate was formed. Repeated cycles of soaking in carbon dioxide-saturated water yielded little additional precipitate.

From these results it can be concluded that: 1) the presence of either free lime or calcium hydroxide in cement paste can result in the precipitation of calcium carbonate; 2) carbon dioxide is necessary for the precipitation of this calcium carbonate; and 3) the precipitate potential of a susceptible RCA source is proportional to the amount of cement paste fines that are present.

The authors provided the following conclusions concerning the use of recycled concrete aggregate in pavement foundation layers:

- "Various economic reasons and the easy availability of slag and [recycled PCC] aggregates warrant the use of these materials as subbase aggregates. For continued use of these materials it is imperative to chemically fix or physically coat the free lime (CaO) or the calcium hydroxide that forms by hydration of the free lime."
- "Before using [recycled PCC] as a subbase aggregate, the construction records of the demolished rubble should be evaluated for mix design and degree of hydration. A study of the cement paste matrix and the unbonded cement present in the rubble should help to predict the tufa precipitate potential of the rubble."
- "Improvements in the drainage system such as slope on drains, larger pipe size, etc. may help reduce the problem."

Michigan Concrete Paving Association (1995)

The Michigan Concrete Paving Association is sponsoring work to verify the work described above (Ohio Department of Transportation/University of Toledo) and further investigate the effects of aggregate grading, original concrete aggregate source (limestone, gravel, slag, etc.) and aggregate treatment (crusher run, washed, etc.) on precipitate potential. This work is being performed by Mark Snyder of the University of Minnesota, and is following techniques similar to some of those used in the University of Toledo study. In addition, this study also includes permittivity testing of geotextile filter fabrics that have been allowed to accumulate laboratory-produced precipitate and insoluble residue. This work is now being completed; the final report will be submitted in June 1995.

Preliminary unpublished results suggest that: 1) precipitate production increases with decreases in particle size, with open-graded recycled materials producing relatively little precipitate; 2) aggregate washing practically eliminates the accumulation of insoluble residue (i.e., "crusher dust") but does little to reduce the formation of calcareous precipitate; 3) washing with a soapy solution produces results that are not appreciably different from those obtained by washing with distilled water.

CONCLUSIONS AND RECOMMENDATIONS

Mitigation of Precipitate/Drainage Problems

Summary of Findings

The tests and field studies described above demonstrate that calcium-based compounds are present in recycled concrete aggregates in quantities that are sufficient to be leached and precipitated in the presence of atmospheric carbon dioxide. It has further been demonstrated that all recycled aggregates, regardless of gradation, are capable of producing various amounts of precipitate, with the precipitate potential being directly related to the amount of freshly exposed cement paste surface (i.e., increased quantities of cement paste fines). In addition, it does not appear that selective grading (to eliminate fines) or blending with virgin aggregates will *eliminate* precipitate potential. However, these steps may significantly reduce precipitate potential.

The University of Toledo researchers found that about one-third of recovered "tufaceous" material was insoluble residue that had washed out of the base. Mn/DOT permittivity testing of field samples of drainage fabric also indicate the presence of significant quantities of insoluble or noncarbonate-based compounds. Therefore, it seems likely that washing or otherwise cleaning the recycled concrete products prior to using them in pavement foundation layers should reduce the accumulation of crusher dust and other fines in and around pavement drains. However, it seems unlikely that *precipitate* potential will be significantly reduced or eliminated by washing or cleaning the crushed concrete before using it. This supposition is backed up by the preliminary, unpublished results of testing currently underway at the University of Minnesota (sponsored by the Michigan Concrete Paving Association).

Mn/DOT field studies have shown that precipitate and insoluble residue accumulations can produce significant reductions in the permittivity of typical drainage filter fabrics. However, these studies also show that: 1) filter fabrics are available with initial permittivities that are great enough to withstand significant amounts of material deposits without reducing permittivities to unacceptably low levels; 2) pipe drains that are unwrapped and placed in trenches back-filled with permeable granular materials may exhibit better long-term flow characteristics than those that are wrapped and placed in similar trenches; and 3) accumulations of precipitate and insoluble residue have not (thus far) been found to occur in quantities large enough to significantly reduce the flow capacity of most pipe drains.

Recommendations

1. RCA base composition and gradation:

   a. Eliminate the intentional inclusion of RCA fines (#4-minus) in drained, unstabilized pavement foundation layers (i.e., use open-graded RCA bases). Furthermore, use the largest top size material that is practical.

   b. The removal of fines and other insoluble residue that weakly cling to coarse RCA particles would further reduce the potential for degradation of pavement drain efficacy where unstabilized granular bases are used. This could be accomplished through either a wet process (e.g., aggregate washing, which would incur the costs associated with the washing equipment, and storage and/or recycling of the wash water) or a dry process (e.g., air blasting the aggregate as it passes over various screens and collecting the dust and fines). The benefits of removing fines through washing are being seen directly in ongoing laboratory studies at the University of Minnesota.

   However, Minnesota field studies (e.g., TH 212) have shown that significant reductions in fabric permittivity can be caused by the insoluble residue derived from *natural* base materials. In addition, the removal of this type of material can be expensive (particularly if a wet process requiring settlement ponds is adopted in an urban area), and the aggregate industry is already faced with the problem of finding a market for 100 million tons of fines annually. Therefore, unless Mn/DOT intends to remove these materials from both natural *and* recycled materials, it seems that a better approach may be to design the drainage systems to accommodate the limited quantity of crusher fines and insoluble residue that are produced by pavement bases, both natural and recycled.

   Another option is to require stabilization of the materials. The Michigan DOT currently requires asphalt stabilization (minimum 3% asphalt cement) or cement stabilization of recycled concrete in drained base layers. This would be one way to allow the inclusion of significant quantities of fines in drained base layers, provided that adequate permeability (> 500 ft/day) is maintained and would help to provide good base stability under construction traffic. However, this author believes that the stabilization of RCA with few fines would provide little benefit and would drive up costs unnecessarily. Suggested gradations for various permeable base materials (both stabilized and unstabilized) are presented in reference 8.

c. Blending open-graded RCA products with virgin aggregates could be accomplished to produce gradations required for improved stability and density and to further reduce precipitate potential in drained pavement foundation layers. Any grading modifications should be selected as a compromise between ideal drainage and stability performance characteristics. Some minimum base permeability characteristics must be maintained (e.g., > 500 ft/day).

2. Drain system design and maintenance

a. Use drain pipes that are either unwrapped or wrapped in filter fabrics with high initial permittivities (e.g., 3.0/sec or greater). Increasing the diameter of the drain pipes would increase both the pipe capacity and the surface area of the fabric wrap, which should greatly reduce losses in both permittivity and rate of outflow. For example, going from a 4-in diameter pipe to a 6-in diameter pipe would result in a 125% increase in pipe cross-sectional area and a 50% increase in pipe circumference and fabric area. Drain pipe openings should be designed to be resistant to accumulation of precipitate and other fines. Drain pipes should be placed in trenches that are backfilled with permeable granular materials.

It is this author's opinion that one potentially effective drainage system design would include the use of a fabric-wrapped trench (to prevent migration of subgrade fines into the trench) and a 6-in diameter unwrapped pipe. The pipe would be constructed of slotted PVC and would have a minimum slope of 1% or more to ensure that no water would accumulate in pipe. This slope requirement might dictate a closer spacing of drain outlets than is typically used now. The trenches would be backfilled with permeable, open-graded granular material (RCA would be acceptable). Outlet pipes would also be constructed of PVC (without slots) and headwalls and markers would be required at all outlets to facilitate maintenance and prevent damage to the pipe ends.

With regular maintenance, this type of drainage system should provide positive drainage indefinitely.

b. Pavement drains should be designed to allow periodic flushing. This would include the use of radius transitions from outlet pipes to longitudinal collector pipes (rather than "T" connections) and outlets at both ends of each collector pipe to allow flushing from either end. The systems should be flushed and maintained annually for the first 2 years and every 2-4 years thereafter. The costs of periodic maintenance performed by maintenance crews are generally significantly less than costs of replacing the drains (typically $1.00 - $2.25 per lineal foot, plus "inconvenience costs" to the highway users during rehabilitation).

The use of mild acidic backwash has been suggested as a means of dissolving or loosening calcium carbonate precipitate buildups in pavement drain systems. The cost-effectiveness and potential environmental impact of this approach should be studied before adoption. This author believes that the use of open-graded recycled concrete drainage layers along with unwrapped pipes placed with adequate slope should eliminate the formation of most precipitate in drainage pipes and would, therefore, also eliminate the need for an acidic backwash.

3. Use of RCA fines

The use of unstabilized RCA fines (#4-minus materials) should be restricted to areas that are below any drainage layers or structures. These fines are probably acceptable in undrained foundation layers, as stabilizing agents for soft subgrades, or as components of other stabilized foundation layers. Care should to be taken in design and construction to ensure that water that comes into contact with layers of RCA fines is not removed to pavement drainage layers, trenches or pipes.

Federally-sponsored research work is also underway at the University of Minnesota to increase the utilization of RCA fines in concrete mixtures. It is hoped that this will provide another major application for the use of these materials.

Testing for Precipitate Potential

The Michigan DOT recommends the use of calcium ion concentration tests to determine the precipitate potential of recycled concrete products. Research currently underway at the University of Minnesota is also comparing the abilities of pH and calcium ion concentration measures to predict the formation of calcium carbonate precipitate. Assuming that the calcium ion concentration test provides a better measure of precipitate formation potential (because it better represents the actual mechanism of precipitate formation and is not as likely to be biased by ambient environmental factors as a pH-based test), that test should be developed further to include appropriate acceptance/rejection criteria.

Recementing of RCA Containing Fines

Eliminating the use of fines from drained foundation layers should all but eliminate this concern as well. While the recementing phenomena does appear to take place when significant quantities of fines are present (i.e., Shakopee stockpiles and Mn/DOT field experience), Mn/DOT stockpile experience suggests that coarse, open-graded materials do not become recemented in the short term (1 year of exposure). Furthermore, it is this author's opinion that significant recementing of the coarse aggregates will not take place in the long term because there is insufficient contact between particles and insufficient unhydrated cement on the particle surfaces to bind the coarse (#4-plus) particles.

Concrete pavements that are constructed directly on RCA foundation layers containing significant quantities of fines (presumably in undrained systems) should be designed with short joint spacings (i.e., JPCP) or no joints at all (i.e., CRCP) to avoid the development of large curling and warping stresses. In the event that it should become necessary to excavate through this recemented layer after several years of service, the weakly-bound material should provide resistance no greater than that of a weakly-stabilized cement-treated base. Mn/DOT field experience suggests that this layer can be trenched without significant difficulty.

Corrosion of Rodent Guard Screens

Concerns about the corrosion of rodent guards would be eliminated if Mn/DOT were to require the use of rodent guards fabricated from plastic or other corrosion-resistant materials. In addition, the recommendations made concerning the reduction of precipitate/drainage problems would also probably reduce corrosion problems.

Environmental Concerns

While the effluent from RCA foundation layers is initially extremely alkaline, it has rarely been documented as being high enough to be considered an environmental hazard. Furthermore, when one considers that the effluent is usually effectively diluted at short distance from the drain outlet with much greater quantities of surface runoff (from the pavement, ditches and surrounding land), it seems likely that environmental concerns are probably restricted to a very small region in the vicinity of the drain outlets (where vegetation kills have been observed).

Furthermore, the recommendations provided above which are intended to reduce the formation of precipitate and the deposit of other insoluble residue (crusher dust, etc.) should also reduce initial pH levels and reduce the time required to stabilize the pH of the runoff at "tap water" levels. Evidence to support or disprove this theory will be available when the Michigan Concrete Paving Association study is completed later this year.

It is worth noting that there may be environmental concerns other than pH. The Shakopee stockpile study is identifying some constituents in the effluent that are considered hazardous and are present in quantities that exceed currently-accepted standards for drinking water. These include arsenic, chromium, aluminum and vanadium. It is not clear to this author whether it is appropriate to apply drinking water standards when evaluating the quality of water being discharged from a pavement base, especially when the discharge itself is diluted many times over within a short distance from the point of discharge. This is an issue which should be considered when the Mn/DOT Shakopee stockpile report is completed.

Interpretation of Applicable Specifications by Contractors

Current applicable Mn/DOT specifications that relate to the use of crushed concrete materials in granular base and backfill applications (3138 and 3149) have been reviewed. It is this author's opinion that these specifications already address many of the concerns that have been discussed above. The current specifications do appear to be very conservative, however; it is this author's opinion that these specifications could be clarified and modified to allow increased use of crushed concrete products without risking significant drainage problems.

Appendix A contains a copy of current Mn/DOT specifications concerning the use of recycled concrete aggregate base materials. This copy has been modified to reflect this author's recommendations and suggestions and should be considered as a "first draft attempt" to propose specifications that will be easily understood, interpreted and placed into practice successfully by qualified contractors. These modifications do not reflect recommendations concerning drainage system design (i.e., location and permittivity of fabric wrap, drain system sizing and geometry, pipe materials and slopes, etc.) or the use of stabilized recycled concrete products. It is also expected that these proposed modifications will stimulate discussion that will result in further modifications of the specifications. They are not intended to be final, ready-to-implement specifications.

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5. Muethel, R. W. "Calcium Carbonate Precipitate from Crushed Concrete." Research Report No. R-1297. Michigan Department of Transportation, Materials and Technology Division. Lansing, MI. March 1989.

6. Gupta, J.D. and W. A. Kneller. "Precipitate Potential of Highway Subbase Aggregates." Final Report. University of Toledo Department of Civil Engineering. Toledo, OH. November 1993.

7. Tamirisa, R. "Study of Highway Base/Subbase Aggregates That Cause Depositions of Calcareous "Tufa" in Drains." Master's Thesis. University of Toledo Department of Civil Engineering. Toledo, OH. April 1993.

8. "Drainable Pavement Systems." Participant Notebook - Demonstration Project 87. Publication No. FHWA-SA-92-008. Federal Highway Administration. Washington, D.C. March 1992.

9. "Geotechnical Fabric Report Specifier's Guide." Industrial Fabrics Association. St. Paul, MN. 1995.

APPENDIX A

SUGGESTED MODIFICATIONS TO Mn/DOT SPECIFICATIONS

The following specifications (3138 and 3149) are taken from the Minnesota Department of Transportation's "Supplemental Specifications To the 1988 Standard Specifications for Construction" dated May 2, 1994. The current approved specification is presented in this same character size and font (Times Roman 12 point). Suggested deletions are lined out. Suggested additions are underlined.

3138
Aggregates for Surface and Base Courses

3138.1 SCOPE

This Specification covers aggregates for surfacing and base courses.

3138.2 REQUIREMENTS

Class 1A, 2A, 3A, 4A, 5A, and 6A aggregate designations are provided for application under the Random Sampling Gradation Acceptance Method as described in 2211.3.

A Composition of Aggregates

The source of supply and quality of the material is subject to approval by the Engineer in accordance with 1601.

All pits from which base aggregates are produced shall be stripped to uncover the granular material to be used.

The material shall consist of sound durable particles of gravel and sand, crushed quarry or mine rock, crushed gravel or stone, crushed concrete, salvaged bituminous mixture, or any combination thereof, except that Class 2 and 2A aggregates shall be crushed quarry or mine rock. The Engineer may allow aggregate containing a limited quantity of binder soil but not sod, roots, plants, other organic matter, reinforcing steel or other objectionable material.

A1 Salvaged Bituminous Mixture

For a base course, the bitumen content in the composite aggregate shall not exceed 3 percent by weight.

For a surface course, a composite aggregate mixture of up to 100 percent salvaged bituminous may be used.

A2 Crushed Concrete

Crushed concrete may be used in base courses where drainage layers or perforated drainage pipes will not be installed, provided that the crushed concrete material meets all other requirements of this specification.

The Contractor must receive the Engineer's approval before using crushed concrete in proximity to perforated drains for all uses not specifically addressed in the Contract. The Engineer *may* approve the following uses of

The Contractor shall not use crushed concrete in surface and base courses where perforated drainage pipe is either installed, or to be installed, or where water moving through crushed concrete may enter the perforated pipe, except:

(a) As a blend with permitted aggregate materials placed on any subgrade material provided that all of the crushed concrete aggregate is retained on the No. 4 sieve. and the percent of crushed concrete does not exceed 15 percent by weight of the total blend.

(b) As an aggregate or a blend with permitted aggregate when placed on material meeting the requirements of 3149.2B, Select Granular, provided that no more than 3 percent of the crushed concrete aggregate passes the No. 4 sieve.

(c) As an aggregate or a blend with permitted aggregate when placed on material meeting the requirements of 3149.2B, Select Granular, when more than 3 percent of the crushed concrete aggregate passes the No. 4 sieve provided that the amount of aggregate blend does not exceed the equivalent of 3 inches of 100 percent crushed concrete, such as, 6 inches of a 50-50 blend of crushed concrete and permitted aggregate. If crushed concrete aggregate/blends are used for both base and stabilizing aggregate at the same location, the total equivalent application rate shall not exceed 3 inches (approximately 300 pounds per square yard of surface area as described above).

(c) As a surface or base aggregate in shoulder areas including locations where perforated pipe is in place. The Contractor may use up to 100 percent crushed concrete at these locations.

(d) As a base aggregate under the pavement where the only subsurface drains are behind retaining walls or other structures. The Contractor shall not use crushed concrete as base

~~aggregate within 100 feet of subsurface drains associated with bridge approach treatments.~~

A3 Crushed Carbonates

The following provisions shall apply in these listed counties:

Anoka - 02	Ramsey - 62
Carver - 10	Scott - 70
Dakota - 19	Washington - 82
Hennepin - 27	

(a) If crushed carbonate (limestone or dolostone) quarry/bedrock is used in total or in part for base applications, unless exempted below, the total portion passing the No. 200 sieve of the carbonate aggregate insoluble residue shall not exceed 10 percent.

(b) An exemption to this 10 percent insoluble residue Specification will be made for carbonate rock to be used as temporary by-passes and parking lots. Use on other specific non-exempted applications must be approved by the Engineer. For these exempted applications, the portion passing the No. 200 sieve of the carbonate aggregate insoluble residue shall not exceed 16 percent.

B Gradation .... Table 3138-1

In the event that it is necessary to add a portion of the overburden or binder soil from an outside source, the materials shall be introduced into the aggregate producing plant at a uniform rate by a separate conveyor simultaneously with the base aggregate. Binder soils or overburden shall meet 3146 except that when the aggregate is crushed to a maximum size of 1 inch or less, the pulverization Specification shall not apply.

When salvaged bituminous mixtures are used in the production of Class 5, 6, 5A, or 6A base aggregates, the composite mixture shall meet the gradation requirements shown in Table 3138-1, except that up to 5 percent by weight of the total composite mixture may exceed 1 inch, but not larger that 1-1/2 inches, provided these larger particles are bituminous mixture and not natural aggregate. (All gradations will be run on the composite mixture before extraction of the bituminous material.)

C Crushing

Crushing will be required for Class 5, 6, 5A, and 6A aggregates. For these classes of aggregate, crushing will be required of all stones larger than the maximum size permitted by the gradation requirements and that will pass a grizzly or bar grate having parallel bars spaced 8 inches apart. However, the Engineer may allow rejection of oversize material when excessive crushing results in an unsatisfactory gradation.

Class 6 and 6A aggregates shall contain at least 15 percent crushed material. Class 5 and 5A aggregates shall contain at least 1- percent crushed material. The percentage of crushing shall be determined by the weight of the material retained on a 3/4-inch sieve. A tolerance of 2 percent will be allowed on each individual test made to determine the percent of crushing, but the average of all material tested for the Project shall meet the Specification requirements. To meet the crushing requirement, it may be necessary to add stones or crushed rock from another source.

D Los Angeles Rattler Loss

The Los Angeles Rattler Loss requirements shall apply only to the crushed quarry or mine rock portion of the aggregate.

Class of Aggregates	Los Angeles Rattler Loss
1, 2, 3, 4, 5, 1A, 2A, 3A, 4A, & 5A	40% maximum
6 & 6A	35% maximum

E Shale

Class 3, 4, 5, 3A, 4A, and 5A aggregate shall contain not more than 10 percent shall in the total sample except that when the part passing a No. 200 sieve exceeds 7 percent, the percentage of shale in the total sample shall not exceed 7 percent.

Class 6 and 6A aggregate shall contain not more than 7 percent shale in the total sample.

3138.3 SAMPLING AND TESTING

Samples for testing to determine compliance with the aggregate gradation Specifications for base and shoulder surfacing will be obtained from the road at a time when the material is ready for compaction. If additives such as calcium chloride or bituminous material are incorporated in a central mixing plant, the aggregate will be sampled before such materials are added.

3149
Granular Material

3149.1 SCOPE

This Specification covers granular material for use in bedding or backfilling structures and miscellaneous service facilities; for use in grading construction to correct or improve subgrade and foundation weaknesses; or for other specified purposes.

3149.2 REQUIREMENTS

The source of supply and quality of the material is subject to approval by the Engineer in accordance with 1601.

The material shall consist of sound durable particles of gravel and sand, crushed quarry or mine rock, crushed gravel or stone, crushed concrete, salvaged bituminous mixture, or any combination thereof, subject to the requirements hereof. The material shall not contain sod, roots, plants, other organic matter, reinforcing steel or other objectionable materials.

Unless otherwise permitted, specific gravity of the material shall not be less than 2.3 nor more than 2.9.

In the production of stabilizing aggregate (3149.2C) and aggregate bedding (3149.2G), crushing will be required of all stones larger than the maximum size permitted by the gradation requirements and which will pass a grizzly or bar grate having parallel bars spaced 8 inches apart. However, the Engineer may allow rejection of oversize material when excessive crushing results in an unsatisfactory gradation. The crushed particles in stabilizing aggregate and aggregate bedding shall be not less than 10 percent of the material. The percentage of crushing shall be determined by weight of the material retained on a 3/4-inch sieve.

A tolerance of 2 percent will be allowed on each individual test made to determine the percent of crushing, but the average of all material tested for the Project shall meet the Specification requirements. To meet the crushing requirements, it may be necessary to add stones or crushed rock from another source.

A Salvaged Bituminous Mixture, Crushed Concrete, and Crushed Carbonates

The Contractor may use salvaged bituminous, crushed concrete and crushed carbonates as a granular material except as limited below.

A1 Salvaged Bituminous Mixture

The Contractor shall not use salvaged bituminous mixture as a filter aggregate (3149.2H and 3149.2J).

The bitumen content in the composite aggregate shall not exceed 3 percent by weight.

A2 Crushed Concrete

Crushed concrete may be used without restriction where drainage layers or perforated drainage pipes will not be installed, provided that the crushed concrete material meets all other requirements of this specification.

The Contractor must receive the Engineer's approval before using crushed concrete in proximity to perforated drains for all uses not specifically addressed in the Contract. The Engineer *may* approve the following uses of crushed concrete ~~Contractor shall not use crushed concrete~~ as a granular material in embankment or backfill where perforated pipe is installed, or is to be installed, or where water moving through these materials may enter the perforated pipe~~,~~ ~~except as~~:

(a) Granular material (3149) below the invert elevation of any perforated subsurface drainage pipe.

(b) Granular material (3149) provided that:

(1) All recycled concrete products are ~~material is~~ larger than the No. 4 sieve.

~~(2) Concrete material between the No. 4 sieve and the 2 inch sieve does not exceed 15 percent by weight, based on the composite of all material smaller than 2 inches.~~

(2~~3~~) ~~When the concrete material is larger than 2 inches the limitations described in the above provisions of (2) shall not apply. However, t~~The Contractor shall not place material larger than 2 inches within 2 feet of the location of any perforated pipe drain that will subsequently be placed by machine trencher. Such material must be blended/mixed as appropriate with other non-concrete materials to meet all gradation and construction requirements.

(3~~4~~) For perforated drains associated with retaining walls/structures, the above provisions (1) and (2) ~~through (3)~~ shall apply only to the portion of select granular modified (0 to 10 percent passing the No. 200 sieve) above the invert of the perforated pipe and within the zone 18 inches from the pipe centerline and up and away from the structure at a 1/2:1 slope.

A drawing of the included (or excluded) zone would help contractors visualize the intent of the spec here ....

(c) As stabilizing aggregate (3149.2C). However, if crushed concrete material with more than 3 percent passing the #4 sieve is to be used, the application rate shall not exceed the equivalent of 300 pounds per square yard of surface area (approximately 3 inches thick), such as, 300 pounds of 100 percent crushed concrete, 600 pounds of 50/50 blend of crushed concrete and permitted aggregate, etc. If the crushed concrete aggregate/blends with more than 3 percent passing the #4 sieve are used as both stabilizing aggregate and aggregate base at the same location, the total equivalent application rate shall not exceed 300 lbs per square yard of surface area (approximately 3 inches thick) as described above.

A3 Crushed Carbonates 3138.2A

B Granular Borrow and Select Granular Borrow

B1 Granular Borrow

Granular borrow, for general use in embankment or backfill construction, may be any pit-run or crusher-run material that is so graded from coarse to fine that, of the portion passing a one inch sieve, not more than 20 per cent, by weight, will pass a No. 200 sieve. The material shall not contain oversize salvaged bituminous particles or stone, rock or concrete fragments in excess of the quantity or size permissible for placement as specified.

B2 Select Granular Borrow

Select granular borrow, for special use in embankment or backfill construction or other specified purposes, may be any pit-run or crusher-run material that is so graded from coarse to fine that, of the portion passing a one inch sieve, not more than 12 per cent, by weight, will pass a No. 200 sieve. The material shall not contain oversize salvaged bituminous particles or stone, rock or concrete fragments in excess of the quantity or size permissible for placement as specified.

C Stabilizing Aggregate

Stabilizing aggregate used in improving subgrade stability shall meet the following gradation requirements:

Sieve Size	Per Cent Passing
1"	100
3/4"	90 - 100
3/8"	50 - 95
No. 4	35 - 85
No. 10	20 - 70
No. 40	10 - 45

No. 200	7 - 15

When the aggregate consists totally of crushed concrete the part passing the No. 200 sieve shall be not less than 3 percent nor more than 15 percent. (Also see 3149.2A)

D Granular Backfill

Granular backfill material may be any pit-run or crusher-run mineral product that will all pass a 3 inch sieve and that is so graded from coarse to fine that, of the portion passing a one inch sieve, not more than 20 per cent, by weight, will pass a No. 200 sieve.

E Aggregate Backfill

Aggregate backfill material shall be a graded mineral product meeting the following gradation requirements:

Sieve Size	Per Cent Passing
2"	100
No. 4	35 - 100
No. 10	20 - 70
No. 40	10 - 35
No. 200	3 - 10

F Granular Bedding

Granular bedding material shall be a graded aggregate product which all passes a 1-inch sieve with not more than 10 percent passing a No. 200 sieve.

G Aggregate Bedding

Aggregate bedding material shall be a graded mineral product meeting the following gradation requirements:

Sieve Size	Per Cent Passing
1"	100
3/4"	90 - 100
3/8"	50 - 90
No. 4	35 - 80
No. 10	20 - 65
No. 40	10 - 35
No. 200	3 - 10

H **Coarse Filter Aggregate**

Coarse filter aggregate shall be a free-draining mineral product, excluding crushed carbonate quarry rock , crushed concrete, and salvaged bituminous mixture, and meeting the following gradation requirements:

Sieve Size	Per Cent Passing
1"	100
3/4"	85 - 100
3/8"	30 - 60
No. 4	0 - 10

I **Blank**

J **Fine Filter Aggregate**

Fine filter aggregate shall be a free draining mineral product, excluding crushed carbonate quarry rock, crushed concrete, and salvaged bituminous mixture, and meeting the following gradation requirements:

Sieve Size	Per Cent Passing
3/8"	100
No. 4	90 - 100
No. 10	45 - 90
No. 40	5 - 35
No. 200	0 - 3

K **Sand Cover**

Sand cover material shall consist of sound durable particles of sand or gravel meeting the following gradation requirements:

Sieve Size	Per Cent Passing
No. 4	100
No. 10	95 - 100
No. 40	0 - 50
No. 200	0 - 8

3149.3 **SAMPLING AND TESTING**

A **Sampling and Testing .... Mn/DOT Grading and Base Manual**

B	**Bitumen Content by the Colorado Vacuum Extraction**	**AASHTO T 164 Method E**
C	**Insoluble Residue**	**Mn/DOT Laboratory Manual**

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