Evaluation of Recycled Concrete, Open-Graded Aggregate, and Large Top-Size Aggregate Bases

RICHARD D. BARKSDALE, SAMIR Y. ITANI, AND TERRY E. SWOR

Eight unstabilized aggregate bases were investigated: three recycled concrete materials, an open-graded crushed dolomite drainage material, large top-size crushed dolomite, dense-graded crushed dolomite, sand and crushed gravel blend, and a dense-graded crushed granite. Tests performed included repeated load triaxial tests to evaluate resilient modulus and rutting potential, Los Angeles degradation tests, CBR tests, Hveem stabilometer tests, and gradation tests to define aggregate breakdown due to compaction and repeated loading. The essentially ¾-in. top-size open-graded drainage material, which had about 0.9 percent fines, exhibited the best performance and was not sensitive to moisture effects. The large 1.5-in. maximum size crushed dolomite also exhibited outstanding performance and was only slightly sensitive to moisture. When minus ⅜-in.-size crushed dolomite was added to one recycled concrete, better resilient modulus properties were observed than for the sand and crushed gravel blend; the other recycled concrete material exhibited slightly lower resilient moduli. All of the recycled concrete materials performed better than the sand and crushed gravel blend with respect to rutting potential. The recycled concrete materials, however, exhibited the most degradation with maximum observed levels of degradation being modest. Recycled concrete has been found by others to become significantly stiffer in the field with time, probably because of degradation effects or recementing.

Many concrete structures such as buildings, bridges, and pavements are being demolished as they reach the end of their life cycle or become obsolete. The quantity of this type of construction debris available will become greater in the future. Also, recently passed federal legislation requires that the quantity of material deposited in landfills must be significantly reduced by 1996. These and other environmental factors will encourage more emphasis to be placed on recycling of concrete, rubble, and other construction materials.

One important use of appropriately crushed and screened concrete construction debris is as unstabilized, engineered aggregate base. At the present time, little is known about the engineering characteristics of recycled concrete base, although some important work has been reported (*1*). The purpose of this paper is to compare the behavior of recycled concrete base with two conventional crushed stone bases, an open-graded base, a large top-size base, and a sand and gravel base. Tests performed included repeated load triaxial tests, CBR tests, Hveem stabilometer tests, and gradation tests.

R. D. Barksdale, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga. 30332. S. Y. Itani, Golder and Associates, Inc., Atlanta, Ga. T. E. Swor, American Engineering Testing Corp., 2102 University Avenue West, St. Paul, Minn.

MATERIALS TESTED AND TEST PROCEDURES

Table 1 summarizes selected physical properties of the eight bases studied. The gradation of the bases tested both before and after repeated load testing are included in this table. Materials were tested in accordance with the referenced AASHTO specifications. The gravel tested was crushed and had 48 percent of the particles with two or more fractured faces; sand was added to the gravel to give the desired base course gradation. All of the materials tested except one were from Minnesota and the gradations used conformed to Minnesota DOT (MnDOT) standards. The crushed granite included in the study was from Colorado.

Repeated Load Test Specimen Preparation and Test Procedure

Specimen preparation was in general accordance with the recommendations of AASHTO Specification T-274-82 (which has been withdrawn and is being replaced). Cylindrical specimens of base material 6 in. in diameter by 12 in. high were prepared directly on the base of the triaxial cell. The material was compacted using a vibratory compactor. Complete specimen preparation and testing procedures are described in detail elsewhere (*2*). A second rubber membrane was placed around the specimen after preparation. The use of a second rubber membrane was necessary because the first membrane usually became punctured during the compaction process.

Some samples were tested at a high degree of saturation. To achieve a high degree of saturation, a small vacuum was applied to the top of the specimen through the top porous plate, and a water source was connected to the bottom porous plate. Water was circulated through the specimens until no air bubbles were observed coming out with the circulating water. All the specimens were tested in the fully drained condition by opening the drainage valve on the triaxial cell during the testing phase.

Test Procedure

After sample preparation, specimens were conditioned for 1,200 load repetitions using the stress levels given in Table 2. Then the specimens were tested using the stress states given in Table 3. Both the elastic and permanent axial deformations

TABLE 1 SELECTED PROPERTIES OF AGGREGATE BASES TESTED

Material	Percent Passing(1) 1-1/2"	1	3/4	3/8	No.4	No.10	No.40	No.200	L.A. Abras. (%)(2)	Absorption(3) (%)	γ_{max}(4) (pcf)	Optimum Moisture Content (%)
Sample 1 Dolomite Class 5	-	100	97	70	45	33	19	8.5	41.6	3.19	139	7
	-	100	97.9	71.9	47.3	34.2	21.2	8.7				
Sample 2 Sand & Gravel Class 5	-	100	97	70	45	33	19	8.5	22.9	1.32	145	4.5
	-	100	97.1	71	47	34	21	8.6				
Sample 3 Recycled Concrete I Class 5	-	100	97	70	45	33	19	8.5	37.1	5.56	123	8
	-	100	97	74	49.4	36.8	22.7	9.2				
Sample 4 Recycled Concrete with 3/8 in. Minus Dolomite	-	100	97	70	45	33	19	8.5	37.2	5.9	135	8
	-	100	98.1	72.1	47.9	34.4	21.7	9.3				
Sample 5 2 in. Minus Dolomite	100	89	72	46	29	20	14	7	39.7	2.8	144	6.5
	100	90.6	76	48.9	31.4	21.7	15.3	7.6				
Sample 6 No. 67 Dolomite - Open-Graded Base	-	100	98.3	50.7	27.7	18.5	6.8	0.9	37.2	2.6	131	6
	-	100	98.7	54.6	30.3	19.8	7.16	1.1				
Sample 8 Recycled Concrete II	-	100	97	70	45	33	19	8.5	38.3	4.94	128	8.5
	-	100	97.1	73.6	46.5	34.6	21.2	9.1				

Material	3/4	1/2	3/8	#4	#8	#16	#30	#50	#100	#200				
Sample 7 Crushed Granite	100	94.6	73.8	38	27.3	22.3	18.7	14.6	9.7	6.8	34.6	1.72	140	5.5
	100	95.9	75.7	42.7	30.1	23.2	20.1	16.2	12.3	8.2				

Notes: 1. The first gradation given is before compaction and testing; the second one is after testing.
2. ASTM C-131.
3. AASHTO T-85 Specific Gravity Test.
4. AASHTO T-180 density test method.
5. Gradations were evaluated using dry sieve analysis.

were recorded after 200 load repetitions. After completing the first set of resilient modulus tests (i.e., completing the 20 stress states listed in Table 3), the confining stress was reduced to 6 psi and a deviator stress of 18 psi was then cycled until 8,600 load repetitions were completed. After that, another set of resilient moduli values were evaluated at the same stress levels previously used. Finally, using a confining pressure of 6 psi and the deviator stress of 30 psi, the sample was cycled up to a total of 70,000 load repetitions. At this stage the test was terminated and the total axial permanent deformation was recorded.

TEST RESULTS

Resilient Modulus

Figures 1 and 2 show the variation of the resilient modulus (M_R) as a function of bulk stress θ (i.e., the sum of the principal stress $\sigma_1 + \sigma_2 + \sigma_3$) for the different testing conditions and materials studied. Tables 4 and 5 summarize the variation in resilient moduli due to the effect of material type and test conditions (compaction level, moisture level, and number of repetitions) at a bulk stress (θ) of 50 and 21 psi, respectively. A bulk stress of 21 psi represents approximately the average stress state that exists in the base layer for a moderately thick asphalt concrete surfacing, whereas a bulk stress of 50 psi is representative of thin asphalt concrete surfacing (*3*).

Influence of Material Type

The materials tested are ordered from best to worst on the basis of their resilient moduli performance as follows:

Ranking (θ = 50 psi)	(θ = 21 psi)	*Sample Number*	*Material Type*
1	1	6	No. 67 dolomite—open-graded base (100%, 100%)
2	2	5	2 in. minus dolomite (90%, 99%)
3	4	1	Dolomite—Class 5 (80%, 70%)
4	3	7	Crushed granite (77%, 78%)
5	5	2	Sand and gravel—Class 5 (73%, 69%)
6	6	4	Recycled concrete with ⅜ in. minus dolomite (73%, 65%)
7	7	8	Recycled Concrete II—Class 5 (66%, 59%)
8	8	3	Recycled Concrete I—Class 5 (64%, 51%)

The percentages in parentheses for the ranked materials represent the relative resilient modulus performance of all the samples compared with the open-graded base that had the highest value (values for θ = 50 psi are given first). This relative performance is evaluated at 100 percent AASHTO T-180 density and 1,200 load repetitions. The following discussion is for θ = 50 psi.

TABLE 2 STRESS SEQUENCE USED IN TRIAXIAL TEST—CONDITIONING PHASE

Conditioning Phase	Number of Applications	Confining Stress (psi)	Deviator Stress (psi)
1	200	5	5
2	200	5	10
3	200	10	10
4	200	10	15
5	200	15	15
6	200	15	20

TABLE 3 STRESS SEQUENCE USED IN TRIAXIAL TEST—RESILIENT MODULUS STRESS STATES

Stress State	No. Applications(1)	Confining Stress (psi)	Deviator Stress (psi)	Bulk Stress θ-(psi)
1	200	20	10	70
2			20	80
3			30	90
4			50	110
5		15	10	55
6			20	65
7			30	75
8			50	95
9		10	10	40
10			20	50
11			30	60
12			40	70
13		5	5	20
14			10	25
15			15	30
16			20	35
17		3	3	12
18			6	15
19			9	18
20			12	21

Note: (1) 200 load applications were used for each of the twenty stress states.

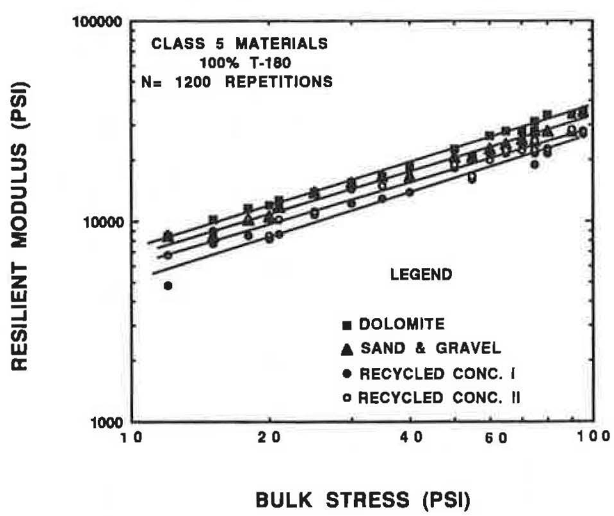

FIGURE 1 Resilient modulus response of Recycled Concrete I and II compared with sand and crushed gravel and dolomite base materials.

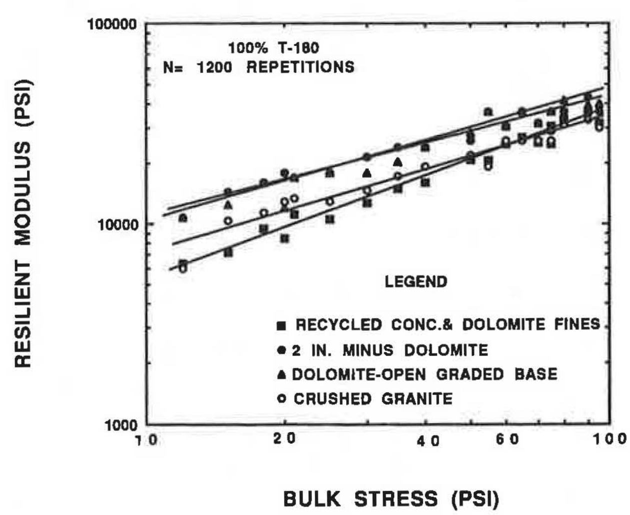

FIGURE 2 Resilient modulus response of recycled concrete with dolomite added compared with large top-size dolomite, open-graded dolomite, and crushed granite base materials.

TABLE 4 SUMMARY OF RESILIENT MODULUS TEST RESULTS AT BULK STRESS OF 50 psi

Material(3)	100% T-180(2) N=1200	100% T-180(2) N=8600	95% T-180(2) N=1200	95% T-180(2) N=8600	Soaked (100% T-180) N=1200	Soaked (100% T-180) N=8600
Dolomite: No.1(1) (Class 5)	23,000	26,000	21,000	24,000	18,000	18,000
Sand & Gravel (Class 5): No.2	21,000	24,000	17,200	18,500	13,500	15,000
Recycled Concrete (Class 5)						
Source I: No.3	18,500	21,600	13,500	15,000	13,000	13,600
Source II: No.8	19,200	22,400	15,500	16,800	13,400	14,400
Recycled Concrete with Dolomite Fines: No.4	21,000	24,000	19,200	19,000	17,240	20,000
2 in. Dolomite (Modified Class 5): No.5	26,000	28,000	20,000	24,000	24,000	28,000
Dolomite - Open-Graded Base: No.6	28,800	28,800	24,000	28,800	24,000	24,000
Granite: No.7 (Colorado Base)	22,000	23,000	17,000	20,800	19,500	21,000

Note: 1. Sample number given in Table 1.
2. Tested at optimum water content.
3. The Class 5 base gradations are from the state of Minnesota specifications.

TABLE 5 SUMMARY OF RESILIENT MODULUS TEST RESULTS AT BULK STRESS OF 21 psi

Material	100% T-180 N=1200	100% T-180 N=8600	95% T-180 N=1200	95% T-180 N=8600	Soaked 100% T-180 N=1200	Soaked 100% T-180 N=8600
Dolomite (Class 5): No.1	12,000	10,500	10,000	10,500	9,100	13,000
Sand & Gravel (Class 5): No.2	11,800	11,200	9,700	11,000	8,000	9,000
Recycled Concrete (Class 5)						
Source I: No.3	8,700	9,800	7,600	8,200	6,800	8,100
Source II: No.8	10,100	10,100	7,500	8,900	7,400	7,400
Recycled Concrete with Dolomite Fines: No.4	11,200	11,200	9,200	9,200	9,300	9,300
2 in. Dolomite (Modified Class 5): No.5	17,000	17,200	10,800	11,400	16,000	16,000
Dolomite - Open-Graded Base: No.6	17,200	19,000	-	-	-	-
Granite: No.7 (Colorado Base)	13,400	13,400	10,400	10,400	10,400	11,400

Note: 1. Sample number given in Table 1.
2. Tested at optimum water content.
3. The Class 5 base gradations are from the state of Minnesota specifications.

The open-graded base (Sample 6), which had only 0.9 percent fines (material passing the No. 200 sieve), has the highest values of resilient moduli. The large, 2-in. top-size dolomite (Sample 5) exhibited the next-to-highest resilient moduli. The three recycled concrete materials exhibited the lowest resilient moduli and hence the poorest resilient moduli behavior. The recycled concrete, which had minus ⅜-in.-size particles of crushed dolomite added, performed the best of the recycled concrete materials with respect to resilient modulus.

The recycled concrete with minus ⅜ in. dolomite particles performed the same as the sand and gravel blend. The sand and gravel blend was crushed, with about 48 percent of the gravel particles having two or more fractured faces. Recycled Concrete II, which performed slightly better than Recycled Concrete I base material, had a resilient modulus about 10 percent less than the sand and crushed gravel blend. The recycled concrete bases, therefore, would be expected to have resilient moduli similar to those of uncrushed sand and gravel blends. In Minnesota an uncrushed sand and gravel blend would serve as the basis of comparison for a conventional base.

The response for $\theta = 21$ psi (Table 5), for practical purposes, is similar to that for $\theta = 50$ psi except that less difference is present in M_R values for the open-graded and large top-size bases. These two bases clearly did quite well. An important difference existed between these two excellent materials and the poorer performing ones.

Influence of Compaction Level

The materials were tested at two levels of density: 95 and 100 percent of AASHTO T-180 (refer to Tables 4 and 5). The effect of density on the resilient modulus can be relatively large, with a decrease in the resilient modulus occurring as the compaction level is reduced from 100 to 95 percent of AASHTO T-180. For the material tested, the results (Table 5) indicate that at a low bulk stress of 21 psi, the decrease in the modulus varied from 13 to 36 percent when the density was decreased from 100 to 95 percent of T-180. At a high bulk stress of 110 psi (*2*), the reduction in the resilient modulus was less pronounced, but still important, varying from 10 to 25 percent for the same decrease in the original density.

Influence of Degree of Saturation

The resilient modulus is known to decrease with increasing degree of saturation (*3,4*). In these tests (*2*) at a low bulk stress of 12 psi, the decrease in the resilient modulus varied from 2 to 50 percent when the water content of the base increased from the optimum value to a high degree of saturation. At high bulk stress, the reduction in the resilient modulus varied from 3 to 35 percent for the same increase in water content. The degree of saturation that was reached, as determined at the end of the test, was material and gradation dependent and varied from 87 to 100 percent. The large top-size and open-graded base materials were least moisture sensitive and hence performed best when wet.

Influence of Number of Load Repetitions

The resilient modulus (M_R) was evaluated for the eight materials tested at both 1,200 and 8,600 load repetitions. The general trend observed for $\theta = 50$ psi was generally a slight increase (0 to 20 percent maximum) in the resilient modulus due to the increase in the number of load repetitions (Table 4). The increase in M_R with load repetitions is hypothesized to be partly due to a slight increase in density or decrease in water content, or both. The M_R for the open-graded dolomite apparently increased with increasing repetitions entirely because of the effects of density. When initially compacted to 95 percent of T-180 density, the M_R of this material increased by about 20 percent with increasing load repetitions. When placed initially at 100 percent of T-180 density, a change in M_R was not observed.

For $\theta = 21$ psi (Table 5), the increase in resilient modulus of the open-graded and large top-size bases was generally less than at $\theta = 50$ psi, and for the poorer-performing materials frequently no increase at all was observed for M_R.

Permanent Deformation Test Results

The approximate ranking of the base materials with respect to permanent deformation behavior and observed rut indices are summarized in Table 6, and the behavior for selected bases is compared graphically in Figure 3. The rut index is used for comparing the permanent strain behavior, with the rut index being approximately proportional to rutting in the material (*3,4*). For this study the rut index was taken as the permanent strain observed in the tests, which were carried out until 70,000 repetitions, multiplied by 10,000.

The open-graded dolomite (which had only 0.9 percent fines) and the oversize minus 2-in. dolomite performed best with respect to permanent strain. The Class 5 sand and gravel performed poorly compared with all the other materials. The Class 5 recycled concrete without dolomite fines, both Sources I and II, performed about the same as the comparable Class 5 dolomite base. In fact, Source II recycled concrete specimens appeared to perform slightly better than the Class 5 dolomite. The Class 5 recycled concrete with minus ⅜-in.-size dolomite appeared to perform slightly poorer with respect to permanent strain than the other Class 5 recycled concrete bases and the Class 5 dolomite base. This difference in performance, however, was small and probably not statistically significant. Average permanent strain is proportional to permanent deformation.

For the materials tested, the increase in the permanent strain varied from 47 to about 75 percent when the compacted density was reduced from 100 to 95 percent of AASHTO T-180 density. The degree of saturation also has a significant effect on the rutting potential, with an increase in the permanent deformation occurring as the water content increases. For the materials tested the increase in the rutting potential, as defined by measured permanent strain and expressed by the rut index, varied from 10 to about 45 percent as the water content was increased from optimum to near saturation.

Sources I and II of the Class 5 recycled concrete both appeared to be very slightly more susceptible to permanent strain

TABLE 6 VARIATION OF RUT INDEX WITH DENSITY AND MOISTURE FOR AGGREGATE BASE MATERIALS TESTED

Rank	Material	Rut Index (1)		
		100% T-180	95% T-180	Soaked 100% T-180
1	Dolomite (open-graded base): No.6 (2)	29	48.6	32
2	2 in. Dolomite (Modified Class 5):No.5	38.5	56	42
3	Granite (Colorado Base) : No.7	41	62	54
4	Recycled Concrete Source II: No.8	51	86	81
5	Recycled Concrete Source I: No.3	55	95	80
6	Dolomite - Class 5:No.1	55	92	76
7	Recycled Concrete with Dolomite Fines: No.4	58.6	100	82
8	Sand and Gravel - Class 5: No.2	62	102	91

Notes: 1. Rut Index is evaluated as the permanent strain observed after 70,000 load repetitions. Rut Index is approximately proportional to the rutting that would be expected in the base course [3,4].

2. These numbers indicate the sample number given in Table 1.

than the comparable Class 5 dolomite, particularly when wet. The sand and crushed gravel blend studied in this investigation was more susceptible to rutting than the other materials when tested at a high degree of saturation. The open-graded material had the least rutting susceptibility among all the materials tested at a high degree of saturation.

CBR and R-Value

Table 7 compares the results of soaked CBR tests, R-values determined from Hveem stabilometer tests, and resilient moduli test results. Sources I and II of the Class 5 recycled concrete performed as well as or better than the comparable Class 5 dolomite base as indicated by the CBR and R-value results, and better than the Class 5 sand and crushed gravel blend.

Degradation

Degradation of base materials due to the combined effects of compaction and repeated loading to 70,000 repetitions was evaluated by comparing the grain size distribution obtained after testing with the original distribution using dry sieve analysis. The results are presented in Table 1 with the gradation before compaction given first and the gradation after compaction and testing given on the line below it. Only modest changes occurred in specimen gradation during specimen preparation and testing. The Class 5 sand and gravel performed best in terms of degradation, and the materials containing dolomite also performed well. The Class 5 recycled concrete (both sources) exhibited the highest degradation of particles compared with the other materials. All specimens were prepared by vibratory compaction, which causes the least particle breakage compared with impact methods of laboratory compaction.

DISCUSSION OF RESULTS

The MnDOT Class 5 recycled concrete base (all three types), open-graded dolomite drainage layer base, and large top-size dolomite base are all materials that are not widely used in pavement construction at this time. Recycled concrete will undoubtedly be used more for base and in other applications in the future as aggregate and disposal costs both rise. Proper drainage of water from beneath a pavement significantly increases the life of a pavement, which accounts for the considerable interest at the present time for using open-graded drainage layers. Rapid removal of water, as shown elsewhere (*5*) and in this study, increases the stiffness of the pavement and decreases susceptibility to rutting. Considerable interest also exists in using large top-size stabilized and unstabilized base mixes to reduce rutting. Therefore, an examination of the engineering characteristics of these unstabilized bases is timely.

Recycled Concrete

The recycled MnDOT Class 5 concrete base, both Sources I and II, performed comparably with the standard MnDOT Class 5 dolomite base with respect to rutting. Although the recycled concrete with dolomite fines exhibited a slightly greater tendency to rut than did the Class 5 recycled concrete and the Class 5 dolomite, the resilient moduli characteristics of the recycled concrete/dolomite blend were superior to the

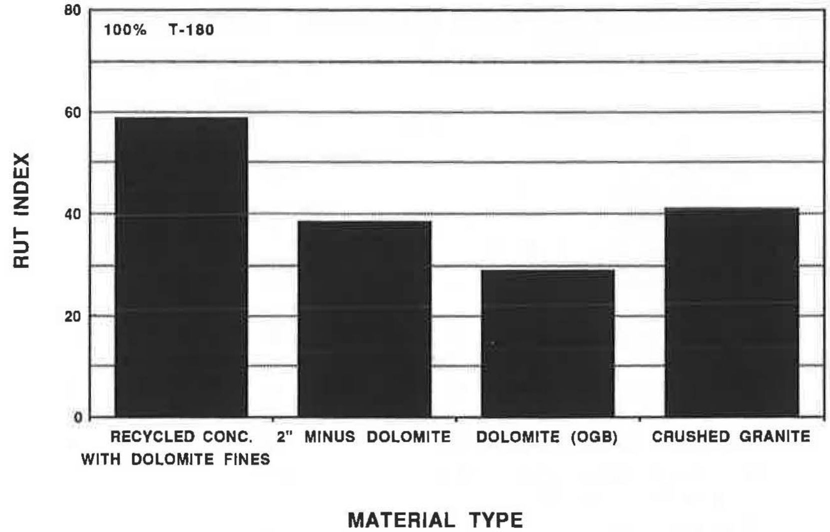

FIGURE 3 Comparison of rut index of recycled concrete (dolomite added) with granite base and large top-size and open-graded dolomite base materials.

TABLE 7 COMPARISON OF RESILIENT MODULUS, SOAKED CBR, AND R-VALUES FOR AGGREGATE BASE MATERIALS TESTED[1]

Material	Soaked CBR	M_R (2) (N = 1200)	R-Value
Dolomite (Class 5) (3)	162	23,000	85
Sand & Gravel (Class 5)	85	21,000	79
Recycled Concrete (Class 5)			
Source I	170	18,500	84
Source II	270	19,200	85
Recycled Concrete with Dolomite Fines	95	21,000	84
2 in. Dolomite (Modified Class 5)	350	26,000	84
Dolomite (Open-Graded Base)	137	28,800	79
Granite (Colorado Base)	126	22,000	71

Note: 1. Specimens prepared at 100% of AASHTO T-180 density.
2. Resilient Modulus determined at a bulk stress of 50 psi.
3. These numbers indicate the sample number given in Table 1.

straight recycled concrete base and only slightly less than for the MnDOT Class 5 dolomite base. Therefore, from the standpoint of overall performance, the use of minus ⅜-in.-size dolomite with the recycled concrete is probably desirable. Replacement of the finer portion of the recycled concrete with dolomite would certainly be desirable if the 1986 AASHTO design guide (*6*) is used as the sole basis for design, since it is based entirely on resilient moduli without any direct consideration being given to rutting. Therefore, an important practical limitation of the 1986 AASHTO design guide is that rutting of not only the base but also other layers is not adequately considered.

The increase in fines (material passing the No. 200 sieve) due to compaction and cyclic loading was between 0.6 and 0.8 percent of the three recycled concrete materials studied; the amount of fines before compaction in the specimen was 8.5 percent. Although the level of degradation observed is not considered serious, it was the highest measured and justifies further investigation, including the effects of degradation on frost action.

Field test results indicate that the stiffness of full-scale pavements constructed with crushed concrete, crushed rubble with slag, and crushed rubble substantially increases with time, whereas crushed masonry has been found to increase only slightly with time (*1*). The increase in stiffness may be due to rehydration or the increase in fines, which occurs as the aggregate degrades with increasing number of wheel loads. The importance of rehydration with time is unclear. However, after about 2 years from the time of pouring, usually less than about 5 percent unhydrated cement particles remains. The general lack of unhydrated cement particles suggests that rehydration may not be the only cause of the observed increase in stiffness with time. Because of the stiffening of this type base with time, short-term laboratory resilient modulus test results, such as those described in this paper, are considered to be on the conservative side.

Reflective properties and color uniformity of recycled concrete are poor. Non-air-entrained concrete may have reduced freeze/thaw durability compared with air-entrained concrete or natural aggregate. Fines generated from the recycled concrete have been found in some instances to clog up filter-fabric wrapped subsurface drains. Recycled concrete has a limited history of use, and observed field performance has been variable. This material can contain extraneous debris such as metal, wood, brick, and organics.

Because the leachate from recycled concrete is highly alkaline (concrete has a pH of 11.5 to 12.5), caution should be exercised to satisfy applicable state and federal regulations concerning pollution.

If aluminum contaminants, such as conduit pipe, are present within the recycled concrete, the high pH of the concrete can cause accelerated corrosion and formation of expansive products and hydrogen gas. At a pH between 4.66 and 6.32, aluminum forms an oxide film of aluminum, which protects the aluminum from further oxidation. Corrosion of aluminum occurs outside of these pH limits.

Open-Graded Drainage Material

The open-graded dolomite drainage layer material exhibited the best resistance to rutting of all the materials investigated (Table 6) and the highest (best) resilient moduli values (refer, for example, to Tables 4 and 5). When properly placed and subjected to confinement, this drainage layer material should exhibit excellent structural performance and good drainage characteristics. The open-graded drainage material used in this study had a 1-in. top size, about 28 percent passing the No. 4 sieve, and about 1 percent fines (unwashed). This gradation has a smaller top size and is finer than the extremely open-graded materials that have sometimes been used for drainage layers. The finer gradation and smaller top size appear to account for the very good structural performance of this material. Even though a reasonably fine gradation was used, the permeability should be about 200 to 400 ft/day, which is approximately 400 times greater than the conventional Class 5 base as determined by MnDOT permeability tests.

Large Top-Size Base

The large top-size dolomite base material, with the top size increased from 1 in. to 1.5 in., reduced the rutting potential (Table 6) when compared with the conventional Class 5 gradation, which for practical purposes has a 0.75-in. top size. When well-compacted to 100 percent AASHTO T-180 density, the larger top-size dolomite base also exhibited higher resilient moduli than the conventional Class 5 base (Tables 4 and 5). Therefore, use of the larger top-size gradation should give improved pavement performance, which has also been found true for other aggregates and gradations (*7*).

Granular Equivalency

The granular equivalency is defined for this discussion as the ratio of the AASHTO layer coefficient (a_2) of a selected base aggregate to the layer coefficient (a_2) of the sand and crushed gravel blend used in this study. For example, a base with a granular equivalency of 1.25 means that 1.25 in. of sand and gravel base can be replaced by 1 in. of the selected base. The granular equivalency can be estimated by comparing the base layer coefficient (a_2) of a selected base material with the base layer coefficient of the MnDOT Class 5 standard sand and gravel. For this comparison the a_2 layer coefficients were determined using the AASHTO pavement design guide (*6*) relationship between the laboratory-determined resilient modulus and a_2. An alternative granular equivalency factor was also evaluated on the basis of the rutting potential of a selected material compared with the MnDOT Class 5 sand and gravel. Table 8 gives the granular equivalencies based on both the resilient modulus (θ = 50 psi) and rutting potential. On the basis of resilient moduli, the Class 5 recycled concrete (Source I) has the lowest granular equivalency of 0.92. The open-graded base has the best (highest) granular equivalency on the basis of both the resilient modulus (1.39) and the rutting potential (2.13).

Sensitivity of M_R on Base Thickness

To illustrate the potential influence of variations in the resilient modulus (M_R) between the different base materials tested, a 1986 AASHTO pavement design (*6*) was developed for each different base studied (Table 8). For this illustrative example the structural base coefficient (a_2) of the Class 5 sand-gravel base used in this study was assumed to be 0.14, and the relative structural base coefficient was determined for the other materials. A fair subgrade was assumed having a resilient modulus of 5,000 psi. Other factors used in the analysis are summarized in Footnote 1 at the bottom of Table 8. An asphalt concrete surface layer thickness of 3 in. was used for each design. The base thickness, which reflects the influence of the variation in resilient modulus of the base with material type, was determined. Required base thicknesses varied from 14 to 24 in. for a reliability of 80 percent and from 12 to 20 in. for a reliability of 50 percent. These designs do not consider the influence of difference in rutting potential, which should also be taken into account. Of significance is the fact that the gravel tested was crushed and had 48 percent of the particles with two or more fractured faces. Hence, the sand-gravel tested was better than the uncrushed gravel usually used in Minnesota.

TABLE 8 GRANULAR EQUIVALENCIES AND REQUIRED LAYER THICKNESS BASED ON RESILIENT MODULUS AND RUTTING DETERMINED FROM REPEATED LOAD TESTING

Material Type	Granular Equivalency Based on M_R	Granular Equivalency Based on Rutting	Base Layer Thickness (in.)[1] 80% Reliability	Base Layer Thickness (in.)[1] 50% Reliability
Dolomite (Class 5): No.1[2]	1.11	1.14	20	16
Sand & Gravel (Class 5 - Crushed): No.2	1.00	1.00	22	19
Recycled Concrete (Class 5)				
Source I: No.3	0.92	1.14	24	20
Source II: No.8	0.98	1.21	22	19
Recycled Concrete with Dolomite Fines: No.4	1.00	1.09	22	19
2 in. Dolomite (Modified) (Class 5): No.5	1.27	1.61	17	15
Dolomite - Open Graded Base: No.6	1.39	2.13	14	12
Granite (Colorado Base): No.7	1.06	1.52	21	17

Note: 1. Assumptions made for illustrative example: 3 in. AC Surfacing; Terminal Serviceability of 2.5; $w_{18} = 2.5 \times 10^6$; reliability = 50 and 80%; Overall standard deviation = 0.45; initial serviceability = 4.5; final serviceability index = 2.5; serviceability loss due to frost heave and swelling = 0.64.

2. These numbers indicate the sample number given in Table 1.

SUMMARY

The following conclusions can be drawn from the findings of this study:

1. A wide range in performance was observed between the eight different aggregate base materials tested. Hence, care must be exercised in selecting an aggregate base that will be suitable for an intended application. Whether the materials are compacted to 95 or 100 percent of AASHTO T-180 density is also important for most materials studied as well as the level of moisture present.

2. The stiffness characteristics of an aggregate base, as determined by the resilient modulus, are not necessarily related to rutting behavior as defined by permanent strain measured in the repeated load triaxial test. For example, the recycled concrete exhibited lower resilient moduli compared with the other type bases after 8,600 load repetitions. The recycled concrete, however, performed better in permanent strain (rutting) than the sand and gravel (crushed) and about the same as dolomite aggregate base.

3. Both the laboratory test results and previous field measurements indicate that a base constructed with recycled concrete should become significantly stiffer with time, perhaps because of rehydration or a small increase of fines. The recycled concrete (Sources I and II) should perform on the average as well as an uncrushed sand and gravel base, and probably about as well as a sand and gravel base that has been crushed. Experience indicates that recycled concrete has a more varied performance record than for other base materials.

4. The essentially 0.75-in. top-size open-graded dolomite having 0.9 percent fines performed, overall, the best with respect to both resilient modulus and permanent strain characteristics of the eight bases studied. The resilient modulus of the open-graded drainage material was not sensitive to the effects of water; rutting showed only a slight moisture sensitivity. The other materials were sensitive to water but to varying degrees. The large 1.5-in. top-size crushed dolomite performed next to best, showing only a slight sensitivity to water.

ACKNOWLEDGMENT

The authors are grateful to the J. L. Shiely Company for sponsoring this study and granting permission to publish the results. Special appreciation is given to Patrick Gannaway of the J. L. Shiely Co. for encouraging this study.

REFERENCES

1. G. T. H. Sweere. *Unbound Granular Bases for Roads*. Ph.D. thesis. Delft Technical University, Delft, Netherlands, 1990.
2. S. Y. Itani, R. D. Barksdale, and T. E. Swor. *Evaluation of Resilient and Rutting Characteristics of Selected Materials*. Final report, Research Project E20-635. Georgia Institute of Technology, Atlanta, 1990.
3. R. D. Barksdale and S. Y. Itani. Influence of Aggregate Shape on Base Behavior. In *Transportation Research Record 1227*, TRB, National Research Council, Washington, D.C., 1989, pp. 173–182.
4. R. D. Barksdale. Laboratory Evaluation of Rutting in Base Course Materials. *Proc., Third International Conference on the Structural Design of Asphalt Pavements*, London, 1972, pp. 161–174.
5. H. R. Cedergren and K. A. Godfrey Jr. Water: Key Cause of Pavement Failure? *Civil Engineering*, Vol. 44, No. 9, ASCE, Sept. 1974, pp. 78–82.
6. *AASHTO Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, D.C., 1986.
7. S. Y. Itani. *Behavior of Base Materials Containing Large Sized Particles*. Ph.D. thesis. Georgia Institute of Technology, Atlanta, 1990.

Publication of this paper sponsored by Committee on Mineral Aggregates.