ACKNOWLEDGMENT

This work was sponsored by the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB) of the National Academies.

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APPENDIX A

RESULTS OF

LITERATURE SEARCH AND CONTACT WITH STATE DOTS

LITERATURE SEARCH AND REVIEW

The major application categories where recycled materials can be used as aggregate in highway construction include [1,2,3]:

- Asphalt concrete layers
- Portland cement concrete slabs
- Unbound (granular) pavement layers (base/subbase)
- Embankments or fills
- Stabilized pavement layers (base/subbase)
- Landscaping applications

The United States Geological Survey (USGS) estimates that about 330 million tons (300 metric tons) of crushed stones were used in road base construction in 1996 [4]. The USGS further stated that developing aggregate resources is "being constrained by urbanization, zoning regulations, increased costs, and environmental concerns." A small increase in the amount of RAP and RCP to replace the virgin aggregate in highway construction will have large economic and environmental benefits while extending the supply of traditional construction materials [4,5]. The benefit of recycling road construction materials can exceed $41 per ton; this estimate does not include processing and transportation costs, but includes the avoided cost of virgin aggregate [6].

Most of the recycling research has been conducted by the Federal Highway Administration (FHWA), the Recycled Materials Research Centers, the Transportation Research Board (TRB), the National Cooperative Highway Research Program (NCHRP), State Departments of Transportation (DOTs), Army Corps of Engineers, and industry associations. The primary support for recycling has been from the FHWA, which began its recycling program in the 1970s. Since then, the FHWA has conducted numerous feasibility studies and demonstration projects. In 1997, FHWA published *User Guidelines for Waste and Byproduct Materials* (7). More recently, two NCHRP projects were completed: NCHRP Project 4-21 (8) developed appropriate uses for waste materials in transportation, and NCHRP Project 25-9 (9,10) evaluated the environmental impact of (highway) construction and repair materials on surface and groundwater.

Many DOTs have actively promoted the use of recycled materials. For example, Saeed et al. (11) report that Texas DOT started its recycling program in 1994 to promote the use of recycling in Texas DOT construction projects. Saeed investigated the use of RAP and RCP in granular bases for Texas DOT Research Project 1348 in 1996 and developed specifications for their use based on laboratory tests (12,13). While discussing research on waste materials that have shown promise as a substitute for conventional materials, Schroeder (14) reported that the use of RAP and RCP as aggregate in unbound base/subbase layer is gaining acceptance. Most agencies require that recycled materials used in unbound pavement layers must meet the virgin aggregate specifications for unbound pavement layers.

ORIGIN AND GENERAL PROPERTIES OF RAP

PRODUCTION OF RAP

RAP is produced when an existing HMA layer is removed for reconstruction or resurfacing. The two methods generally used for RAP production include (1) cold milling, and (2) ripping and crushing. Proper crushing and screening of RAP can produce well-graded aggregate particles that are partially or wholly coated with asphalt binder (7,15).

The cold milling method of removing an existing HMA pavement is most widely used these days. Cold milling generally removes up to 2 inches (50 mm) of HMA thickness in a single pass while restoring the surface to a specified grade and slope. A number of passes may be required, depending on the distress severity, to free the surface of any ruts, bumps, or other imperfections. The Asphalt Recycling and Reclaiming Association (ARRA) categorizes cold milling into five classes [15]:

- Class I – Milling existing HMA to the necessary depth to remove surface irregularities
- Class II – Milling existing surface to a uniform depth (as shown on plans)
- Class III – Milling existing surface to a uniform depth and cross slope
- Class IV – Milling the entire thickness of the HMA layer
- Class V – Milling the existing surface to a variable depth

Ripping of an existing HMA layer using earthmoving equipment, scarifiers, or rippers and crushing the pieces is an alternative method to produce RAP. Cold milling is more efficient than ripping and crushing, because cold milling reduces RAP to small pieces eliminating the need to haul RAP to a crusher. However, cold milling produces more fines than ripping and crushing [7,15]. Most RAP produced using ripping and crushing is hauled to a central processing plant for crushing, screening, conveying, and stockpiling for later use. Asphalt pavements may also be pulverized in place and used as granular base courses.

Of the estimated 45 million tons (41 million metric tons) of RAP produced each year, about 80 to 85 percent is recycled into pavement construction as part of HMA, cold mix, or as aggregate in base/subbase layer. The remainder is stockpiled for use during the next construction season [7].

RAP PHYSICAL AND MECHANICAL PROPERTIES

RAP can be used as an aggregate in a number of ways in highway construction, such as in hot-mix or cold-mix paving, as base and subbase layers, or as embankment fill. The processing requirements depend on the needs of the final product. For use as aggregate in unbound pavement layers, RAP must first be crushed and screened if it was not cold milled. It may then be used singularly or in combination with other materials.

RAP properties are governed by the milling and crushing operation, as well as by the characteristics of the binder and aggregate in the existing asphalt pavement from which the RAP is obtained and age. RAP produced from surface courses (compared to binder courses) is usually of a higher quality because of higher quality aggregates used in the original construction. Aggregate degradation occurs during milling and crushing operations, which causes the RAP gradation to be finer than the gradation of the original virgin aggregate. However, RAP produced using ripping and crushing is generally less fine than the RAP produced using crushing and milling, but it is still finer than the original virgin aggregate. The equipment used during milling and crushing operations also affects the gradation of RAP. RAP gradation is further influenced by the gradation of the underlying base/subbase layer if the depth of reclamation included parts of these layers.

Aggregate degradation during milling is a function of the aggregate top size and gradation of the aggregate in the asphalt pavement [(15)]. During milling, aggregate fraction passing the No. 8 (2.36-mm) sieve increases from a premilled range of 41 to 69 percent to a postmilled range of 52 to 72 percent. Similarly, the fraction passing the No. 200 (0.075-mm) sieve increases from 6 to 10 percent to about 8 to 12 percent. However, in most cases RAP is well graded and slightly finer than crushed natural aggregate [(7)].

Crushing of HMA pavements at a central plant is accomplished using compression and impact crushers. RAP breakers are used if crushed RAP starts to form a flat, dense mass, especially on warm and humid days. Impact crushers are generally used for RAP production, as there is less chance of getting plugged with RAP material, which sometimes happens when using jaw crushers. Impact crushers can be used as both primary and secondary crushers. An impact crusher can also be used as a secondary crusher when a jaw crusher is used as a primary crusher. In a combination crusher, the jaw crusher reduces the HMA slabs to more manageable size, which are then further reduced to a useable size using the secondary roll crusher. Typical RAP gradations after milling or processing are shown in Table 1.

The mechanical properties of RAP are a function of the mix type of the original HMA pavement, the method of milling and crushing, and the method of processing for a particular application. Typical physical and mechanical properties of RAP are shown in Table 2.

Table 1. Range of RAP particle size distribution after milling or processing.

Sieve Size	Range of Particle Size Distribution (Percent Finer)			
	FHWA (7)	New Jersey DOT (16)	Florida DOT (22)	Texas DOT (17)
1.5 in (37.5 mm)	100	100	100	100
1.0 in (25 mm)	95 – 100	98	-- [a]	97
3/4 in (19 mm)	84 – 100	90	88	86
1/2 in (12.5 mm)	70 – 100	76	-- [a]	72
3/8 in (9.5 mm)	58 – 95	68	76	58
No. 4 (7.5 mm)	38 – 75	52	52	35
No. 8 (2.36 mm)	25 – 60	20	34	27
No. 10 (2.00 mm)	-- [a]	18	-- [a]	-- [a]
No.16 (1.18 mm)	17 – 40	11	25	10
No. 30 (0.60 mm)	10 - 35 [b]	8	17	5
No. 50 (0.30 mm)	5 – 25 [c]	4	-- [a]	2
No. 60 (0.25 mm)	-- [a]	-- [a]	8	-- [a]
No. 100 (0.15 mm)	3 – 20 [d]	2	4	1
No. 200 (0.075 mm)	2 – 15 [e]	0.5	0.5	0

[a] Data not provided
[b] Usually less than 30 percent
[c] Usually less than 20 percent
[d] Usually less than 15 percent
[e] Usually less than 10 percent

Table 2. Typical physical and mechanical properties of RAP [7].

Property Type	Property	Typical Value
Physical	Unit weight of original HMA	120 - 140 lbs/ft^3 (1940 - 2300 kg/m^3)
	Moisture content	Normal: up to 5 percent Maximum: 7 – 8 percent
	Asphalt content	Normal: 4.5 – 6 percent Maximum Range: 3 – 7 percent
	Asphalt penetration	10 – 80 at 77 ^{o}F (25 ^{o}C)
	Absolute viscosity of recovered asphalt binder	4,000 – 25,000 poises at 140 ^{o}F (60 ^{o}C)
Mechanical	Unit weight of RAP	100 - 125 lbs/ft^3 (1600 - 2000 kg/m^3)
	California bearing ratio	100 % RAP: 20 – 25 % 40 % RAP and 60 % aggregate: ≥ 150 %

ORIGIN AND GENERAL PROPERTIES OF RCP

PRODUCTION OF RCP

RCP is produced from the demolition of existing PCC highway slabs during highway reconstruction. The demolished concrete is usually hauled to a central processing facility where metal (reinforcing steel and dowel bars) is removed, and crushing and screening processes take place. Processed RCP typically consists of 60 to 75 percent high-quality, well-graded aggregates that are held together by the hardened cement paste [7,18,19]. The amount of cement paste that remains attached to aggregate particles in RCP after processing depends on the process used to manufacture RCP and properties of the original concrete. Cement paste attached to aggregate particles in RCP makes RCP less heavy than conventional aggregate; it also has a higher water absorption and lower abrasion resistance [18].

The production process of RCP affects its particle size and shape properties. A combination of jaw crusher as the primary crusher and a rotating crusher as the secondary crusher yields the best particle gradation and shape [18].

The predominant use of RCP in highway construction is as aggregate replacement in granular and stabilized base layers, HMA, and PCC. RCP base was determined to have a higher stiffness in terms of resilient modulus compared to dense graded aggregate base currently being used in New Jersey (16). However, its use as granular base layer has not been well documented.

RCP PHYSICAL AND MECHANICAL PROPERTIES

Compared to typical virgin aggregate, processed RCP particles are highly angular in shape and have a rougher surface texture, lower specific gravity, and higher water absorption. In addition, processed RCP is more permeable than most natural sands, crushed limestone and gravel (7). Typical RCP gradations after processing are shown in Table 3.

Table 3. Range of RCP particle size distribution after processing.

Sieve Size	Range of Particle Size Distribution (Percent Finer)		
	New Jersey DOT (16)	Florida DOT (18)	Texas DOT (17)
1.5 in (37.5 mm)	92	100	100
1.0 in (25 mm)	86	97.6	98
3/4 in (19 mm)	80	-- [a]	77
1/2 in (12.5 mm)	64	46.4	70
3/8 in (9.5 mm)	56	-- [a]	58
1/4 in (6.3 mm)	-- [a]	4.8	-- [a]
No. 4 (4.75 mm)	42	-- [a]	45
No. 8 (2.36 mm)	34	4.2	35
No. 10 (2.00 mm)	32	-- [a]	-- [a]
No.16 (1.18 mm)	28	-- [a]	25
No. 30 (0.60 mm)	22	-- [a]	17
No. 50 (0.30 mm)	14	-- [a]	5
No. 100 (0.15 mm)	10	-- [a]	1
No. 200 (0.075 mm)	8	-- [a]	0

[a] Data not provided

Laboratory tests performed on different sources of PCC show consistent results [20]. When RCP is used as aggregate in unbound base/subbase, there is little or no RCP particle breakdown during material handling and construction. Typically, RCP has a higher Los Angeles (LA) abrasion loss, a lower dry density, and a higher optimum moisture content than virgin aggregate materials. However, these values still are within the acceptable range for use as unbound base/subbase aggregate. Typical physical properties of processed RCP are given in Table 4 [7,18].

Table 4. Typical physical and mechanical properties of RCP.

Property Type	Property	Typical Value
Physical	Specific Gravity	Coarse (plus No. 4 sieve): 2.2 to 2.5 Fine (minus No. 4 sieve): 2.0 to 2.3
	Absorption (%)	Coarse (plus No. 4 sieve): 2 to 6 Fine (minus No. 4 sieve): 4 to 8
Mechanical	LA Abrasion Loss (%)	Coarse ((plus No. 4 sieve): 20 - 45
	Magnesium Sulfate Soundness loss (%)	Coarse (plus No. 4 sieve): 4 or less Fine (minus No. 4 sieve): less than 9
	California Bearing Ratio (%)	94 to 184

EFFECT OF PROCESSING EQUIPMENT

Powell [21] studied the effect of crushing equipment and its operation on the crushed aggregate particle shape. Although, Powell’s research did not include recycled materials, these results were used to estimate their behavior because studies have not been conducted on RAP or RCP.

Powell processed three products (coarse, screenings, and sand) from two source materials (granite and limestone) at eight different rotor speeds starting with 35 meters per second (mps) and increased in 5 mps increments. Results indicted that increasing the rotor speed decreased the amount of uncompacted voids indicating that more equidimensional particles were being produced at higher speeds. The test for uncompacted voids quantifies the effect of particle shape and texture. The mineralogy of the source material also plays a part because the increase in fines content with an increase in processing speed for limestone was determined to be more consistent than for granite. This is shown in Figure 1 [21].

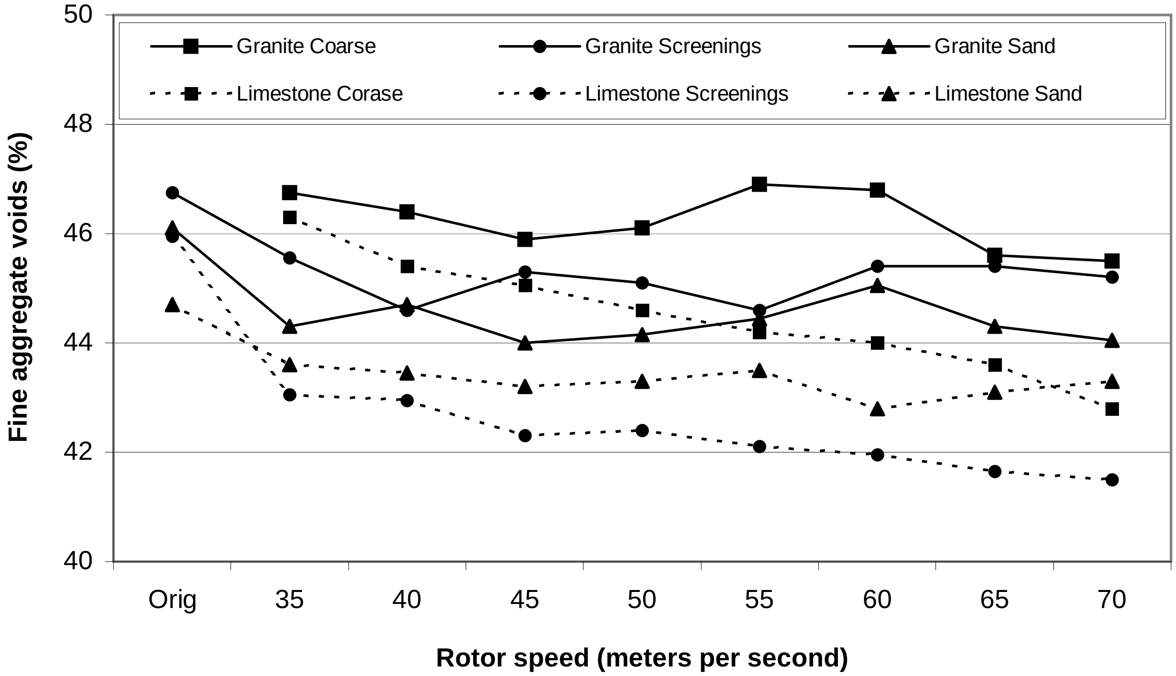

Figure 1. Effect of processing speed on fine aggregate shape and texture.

Similarly, gradation of the final product was also affected by a change in processing speed and source material. Increasing the rotor speed results in an increase in the production of minus No. 200 (0.075 mm) material as shown in Figure 2; source material, as expected, also has an influence on the production of fines.

Cosentino and Kalajian [22] tested RAP from two sources in Florida, including RAP after milling and after post-milling processing with either a hammermill crusher or a tubgrinder. They determined that post-milling of RAP with the tubgrinder or hammermill process causes the material to fall outside the range of AASHTO M 147, [23] "Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses," or its counterpart ASTM D 2950, [24] "Standard Specification for Graded Aggregate Materials for a Base or Subbase." The hammermill RAP is classified as a well-graded sand (SW), and the tubgrinder RAP is classified as a poorly graded sand (SP) using the Unified Soil Classification System [25]. The results are shown in Figure 3 and Table 5. A comparison of tubgrinder and hammermill processed with Talbot ranges [25] is shown in Figure 4 [22].

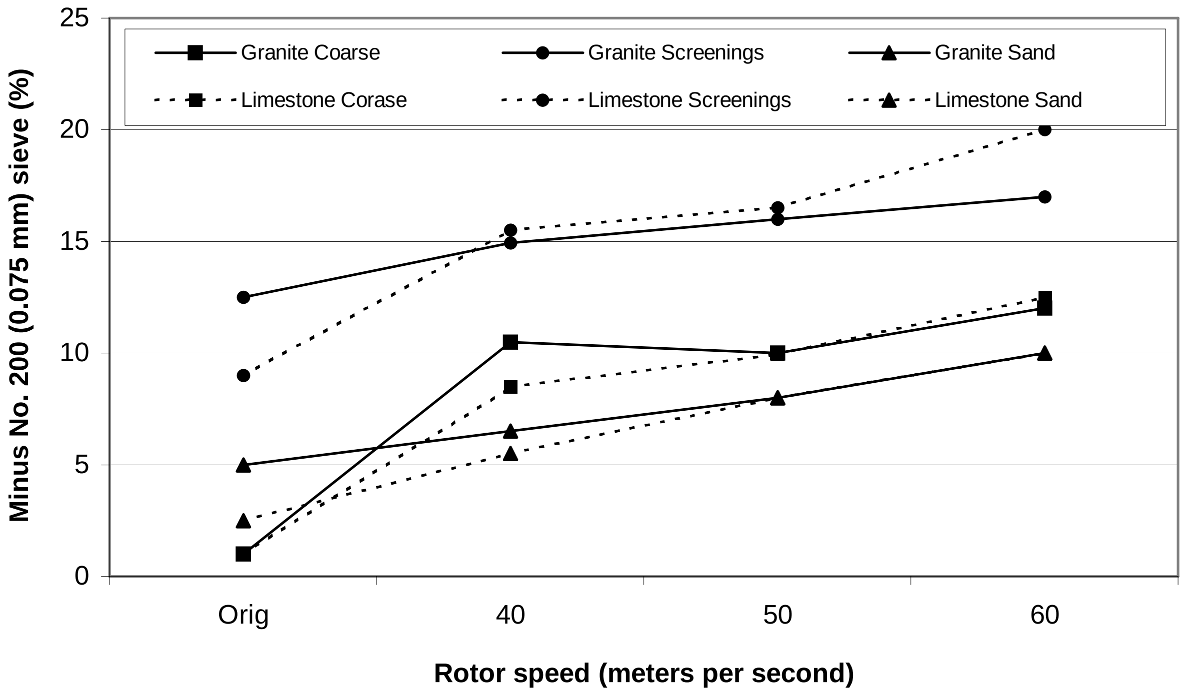

Figure 2. Effect of processing speed on amount of fine aggregate produced.

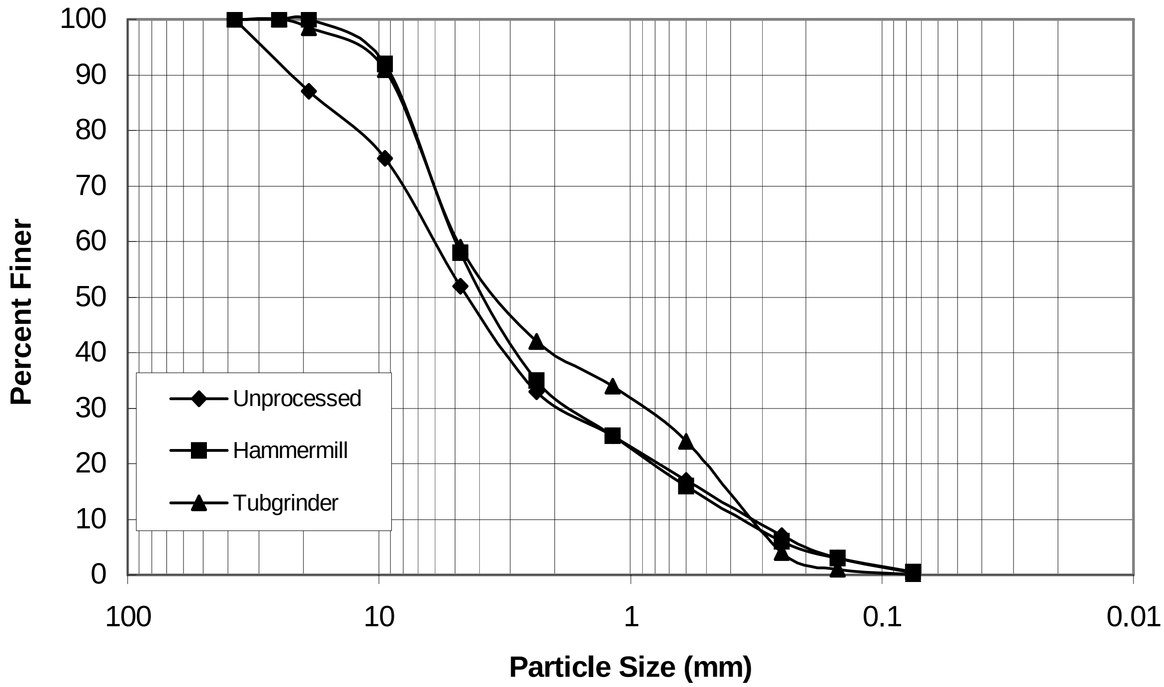

Figure 3. Particle size distribution of unprocessed and processed RAP from Florida.

Table 5. Classification of unprocessed and processed RAP from Florida.

Gradation Descriptor	Unprocessed	Hammermill	Tubgrinder
D_{10}	0.28 – 0.32	0.35	0.35
D_{30}	1.30 – 2.00	1.9	0.9
D_{60}	5.10 – 6.00	3.75 – 5.0	5.0
C_U	17.1	10.0 – 14.3	14 – 14.3
C_C	1.2 – 2.2	1.5 – 2.1	0.5
AASHTO Classification	A-1-a	A-1-a	A-1-a
USCS Classification	GW/SW	SW	SP

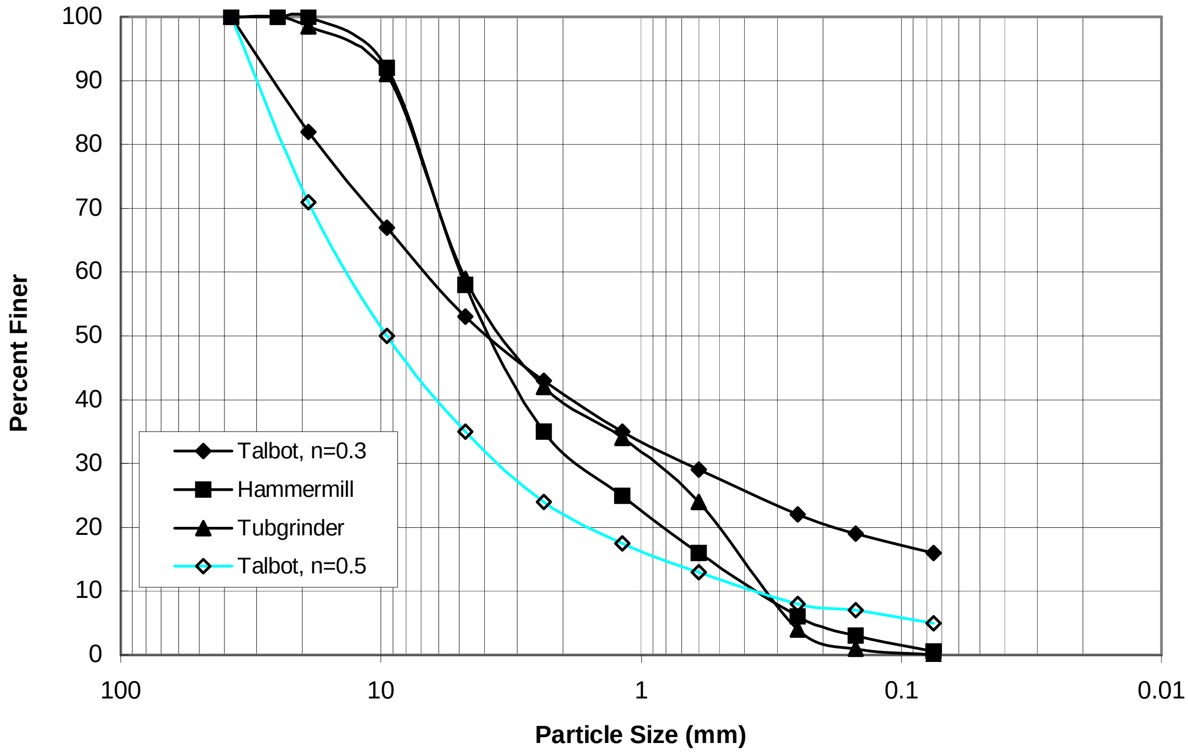

Figure 4. Comparison of hammermill and tubgrinder processed RAP to Talbot Range.

Results shown in Table 5 indicate that the tubgrinder procedure produced a coarser sand type product than the hammermill process.

RAP processed using the tubgrinder had a higher average dry density and higher strength and stiffness compared to RAP processed using the hammermill. The angle of friction of processed RAP varied between 37 to 60 degrees and was not affected by the processing type. However, the cohesion of tubgrinder samples was 4-6 psi (28-41 kPa) higher than the hammermill processed samples [22].

As such, the processing equipment selected can have a significant effect on the properties of the recycled material that are related to performance. Processing of RAP and RCP can produce a material that meets the specifications or gets rejected for a particular use.

ENVIRONMENTAL CONCERNS

There is some concern that RAP and RCP as aggregate in unbound granular layers, when subjected to intermittent wetting and drying or even constant water flow, can leach contaminants into the groundwater [9,10,13,26]. The primary concern of tests evaluating the leaching potential thus should be on leaching conditions that occur as a result of intermittent infiltration (wetting and drying and oxygen and carbon dioxide uptake) into the granular material [27].

Environmental concerns from using RAP and RCP in unbound pavement layers are not as pronounced as some materials, such as bottom and fly ash from power plants and silica fumes. States have used different methods to alleviate environmental concerns associated with using RAP and RCP in unbound pavement layers. Some states have developed a permitting process that results in a blanket approval for RAP and RCP use in the state, while, other states have developed more restrictive guidelines that lay the framework for appropriate uses of these materials [28].

Research has indicated that environmental testing (metal analysis) of virgin aggregates and RAP and RCP shows large variations of concentrations. Despite their acceptance, some traditional aggregates may have metal concentrations exceeding risk-based regulations. Therefore, allowing the use of RAP and RCP that similarly exceed risk-based levels may not represent an increased health or environmental hazard [28].

Investigation of metal leachates from virgin aggregate and RAP and RCP by the Texas DOT showed that the limits set by the Texas Risk Reduction Program for antimony (8.74 vs. 6.00), mercury (11.67 vs. 2.00), and vanadium (37.62 vs. 26.00) were exceeded by virgin aggregate. RCP exceeded the mercury limit only (5.29 vs. 2.00). On the other hand, RAP exceeded the barium (2007 vs. 2000) and lead (20.40 vs. 15.00) limits [28].

Nelson et al. [10] stated that, “on the highway surface leaching is slow, transport is rapid, and dilution is large – all leading to very low initial concentrations of potential contaminants. Furthermore, rainfall is intermittent and leaching rates decrease with time." Intermittent rain fall and fast movement of water on the pavement surface leads to slow movement of water in unbound pavement layers, making the impact on groundwater of less concern.

A testing methodology, developed to study the impact of construction and repair material on surface and groundwater, was used to estimate how highway construction and repair materials (conventional, recycled, waste) affect surface and groundwater near highway rights-of-way. Environmental impact was measured in terms of toxicity to sensitive aquatic organisms and in terms of concentrations of identified toxic substances. Freshwater green algae (Raphidocelis subcapitata) and freshwater macro invertebrate (Daphnia magna) were used as the test organisms; these represented the plant and animal species, respectively [(9)]. The research findings indicated that the vertical water movement in the highway dense-graded base materials is slow (meters per year) causing the vertical migration of contaminants to be even slower. RAP and RCP as base aggregate did not have any impact on growth inhibition of algae. The leaching and sensitivity data would have to be magnified 10,000 times and still there would not be any impact [(10)]. These findings and conclusions might not apply to drainage layers where the movement of water and infiltration is relatively faster.

RAP ENVIRONMENTAL CONCERNS

Chemical properties of RAP are dictated in large part by the chemical properties of the constituent mineral aggregate, as the aggregate component is 93 to 97 percent by weight of the total HMA mix. The remainder is hardened asphalt binder. The asphalt binder consists of asphaltenes and petrolenes. Petrolenes are resins and oils in asphalt binder [(29)]. Asphaltenes are the most viscous of the asphalt binder components and influence binder's viscosity to a large extent. Upon oxidation, oils turns to resins, which in turn convert to asphaltenes, thus increasing the viscosity of the binder further; this phenomenon is generally referred to age hardening. The important point is that none of the constituents have any chemical properties of concern.

The durability of RAP is mostly affected by the aggregate used in the original pavement. However, due to the presence of a thin asphalt film on the aggregate, the properties of the original asphalt binder will have some affect on the performance of RAP as aggregate in unbound pavement layers. Age hardening, during which asphalt binder oxidizes from oils to resins to asphaltenes, leads to higher asphalt binder viscosities and thus affect performance. Some RAP may also be obtained from pavements that have exhibited stripping. If this process continues when RAP is used as aggregate in granular base layer, then the strength of the layer as a whole may be affected. Thus, the design strength of RAP in unbound layers would need to be selected based on its potential for stripping and moisture damage.

RAP's durability does not appear to be a problem, as HMA pavements are not generally attacked chemically, so when crushed they are generally free from damaging chemical compounds [(30)]. The presence of chemicals may be a concern in pavements that have been subjected to deicing salts.

Cosentino et al. [(31)] studied the environmental concerns related to the use of RAP as aggregate in unbound pavement layers. They determined that the concentrations of heavy metals (silver, cadmium, chromium, lead, and selenium) were below the EPA standards; cadmium and lead leachate results from different tests are shown in Figure 5 and Figure 6, respectively [(31)]. This is different from the work reported by Nelson [(10,9)], as Cosentino et al. [(31)] did not use live plant and animal species to evaluate the results.

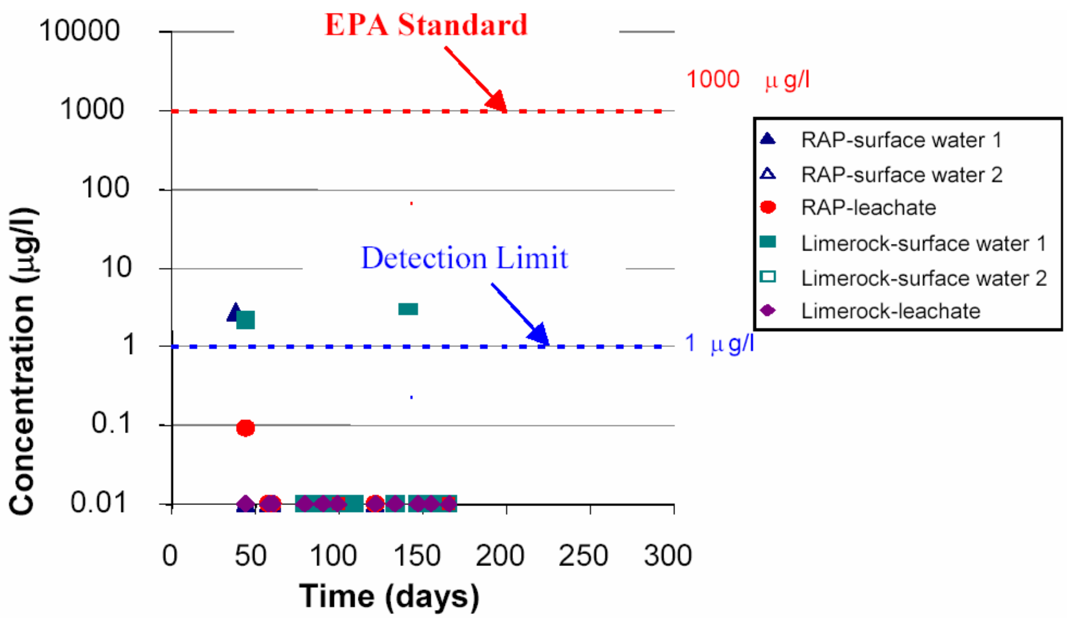

Figure 5. Cadmium concentration versus time in surface runoff and collected leachate.

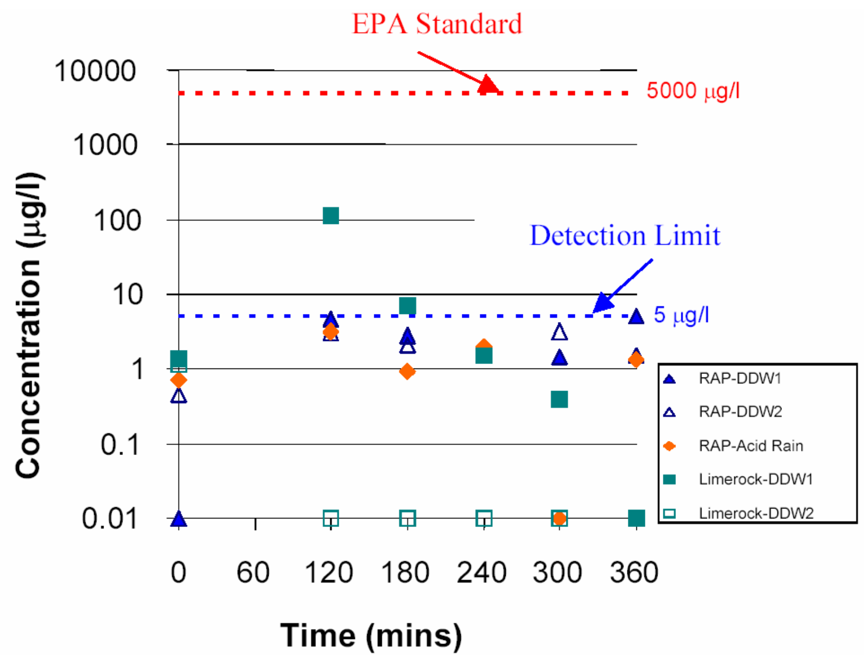

Figure 6. Concentration of lead versus time in column leaching test.

The results of the Toxic Characteristic Leachability Procedure (TCLP) tests performed on RAP indicated that RAP was not a hazardous waste. The primary chemicals investigated were volatile organic compounds, polycyclic aromatic hydrocarbons, and heavy metals. In columns tests, only lead was detected in amounts slightly above groundwater guidance concentration but even this decreased over time [32,33].

A study by the Heritage Research Group [34] on leachability of HMA samples tested for metals, volatile and semivolatile organics, and Polynuclear Aromatic Hydrocarbons (PAHs). Their results were:

- Metals: Only chrome could be detected, and even its level was 50 times below the level of hazardous under the Resource Conservation Recovery Act.
- Volatile Organics: No measurable compound above detection limits.
- Semivolatile Organics: No measurable compound above detection limits.
- Polynuclear Aromatic Hydrocarbons: Only naphthalene was detected, and it was at levels well below established guidelines.

RCP ENVIRONMENTAL CONCERNS

RCP environmental concerns are perceived as not being as pronounced as those of RAP because of the concern over the asphalt binder. Thus, few environmental tests on RCP are reported in the literature. However, this does not suggest that one material poses a higher risk to the environment than the other. Some agencies have limited the use of RCP as aggregate in unbound pavement layers because of the higher pH levels measured for RCP. However, the point of sampling is very critical in determining whether the pH levels exceed most regulatory limits.

Tests were conducted in Florida to determine the presence and amounts of heavy metals (cadmium, chromium, aluminum, nickel, iron, zinc, copper, and lead) in RCP aggregate. Only lead exceeded the EPA set limit of 5 parts per million (ppm). The source of lead in RCP samples was household paint, which is not a problem for RCP produced from crushing highway pavements [18]. RCP from old PCC pavements, before lead in gasoline was banned, may have a trace amounts of lead present [31].

RCP is a durable material and relative to RAP is less prone to containing chlorides from deicing salts due to lower permeability and higher aggregate content. However, concrete that has been subjected to alkali-silica reactivity (ASR) and sulfate attacks involve deleterious expansion that could prove to be damaging in unbound granular layers (30).

EVALUATION OF RECYCLED MATERIALS

The FHWA (7) recommends that recycled materials should be evaluated based on their relevant engineering, environmental, occupational health and safety, recyclability, and economic considerations. Saeed (35,36) also recommends that reclaimed materials be tested based on technical, environmental, societal, and economic considerations. The evaluation tests for recycled materials should be based on their intended uses (7,12,13).

Most state DOTs allow the use of RAP and RCP as aggregate in unbound base/subbase layers; RAP and RCP are subjected to the same tests and specifications as virgin aggregates. The tests and specifications are relaxed when they are not applicable. For example, the sodium sulfate in the sodium sulfate test for aggregate soundness chemically reacts with RCP; this leads to an excess disintegration of material that is not representative of the real world. Such instances are a cause for concern in the United States, as well as Europe, that many standard laboratory tests used for traditional materials do not predict the true field performance of recycled materials (37).

The general standards for using recycled materials as aggregate in base and subbase layers can be summarized as (38):

- Equal or better in engineering applications
- Environmentally acceptable
- Equal or better in economic considerations

Some of the important properties of aggregates for unbound base/subbase include gradation, particle shape and texture, stability, permeability, plasticity, abrasion resistance, and stiffness [7]. These properties impact the design parameters, construction, and performance of RAP and RCP as aggregate in unbound pavement layers. The evaluation tests could be categorized as:

- Screening tests (gradation, specific gravity, density)
- Strength tests (shear strength, CBR)
- Miscellaneous tests (toughness, durability, permeability)

HMA pavements are the most recycled product in the United States [39], and much more information is available in the literature about tests conducted on RAP than tests conducted on RCP. An estimated 85 percent of all RAP produced is recycled with about 44 states allowing their use as aggregate in unbound pavement layers [4]; 68 percent of recycled cement concrete is used as roadbase [40].

SUMMARY OF TESTS CONDUCTED TO EVALUATE RAP PROPERTIES

Screening Tests

The Illinois DOT [41] allows the use of RAP as a non-structural fill material without blending with virgin aggregate material.

Tests were conducted on 100 percent RAP and 25, 50, and 75 percent RAP blend with virgin aggregate and the results were compared to a dense graded aggregate base (DGAB) material [16]. The gradation of RAP material tested was shown in Table 1; RAP contained the least amount of fines (0.4 percent) compared to the DGAB (7.6 percent).

Strength and deformation characteristics of RAP were studied using laboratory and field tests. Field performance of RAP base was evaluated over a period of 12 months. RAP was obtained from two different sources in Florida; four different RAP materials were obtained for testing. The particle size distribution of unprocessed RAP (milling only) and post-milling processed RAP using the tubgrinder and the hammermill processes is shown in

Figure 3 and Figure 4. About 40 percent of the processed RAP falls within the range specified by the Talbot equation. The amount of processed RAP between 1.5 in (38.1 mm) and 0.15 in (4 mm) and between No. 60 (30 mm) and No. 200 (0.075 mm) needs to be increased to meet the requirements of the Talbot range [22].

McDaniel et al. [42] tested three different RAP with different stiffnesses; the stiffness determination was based on viscosity of the recovered binder. Figure 7 shows that on comparison with a typical dense graded (DGBL) and open graded base layers (OGBL) specifications, the three materials were dense graded.

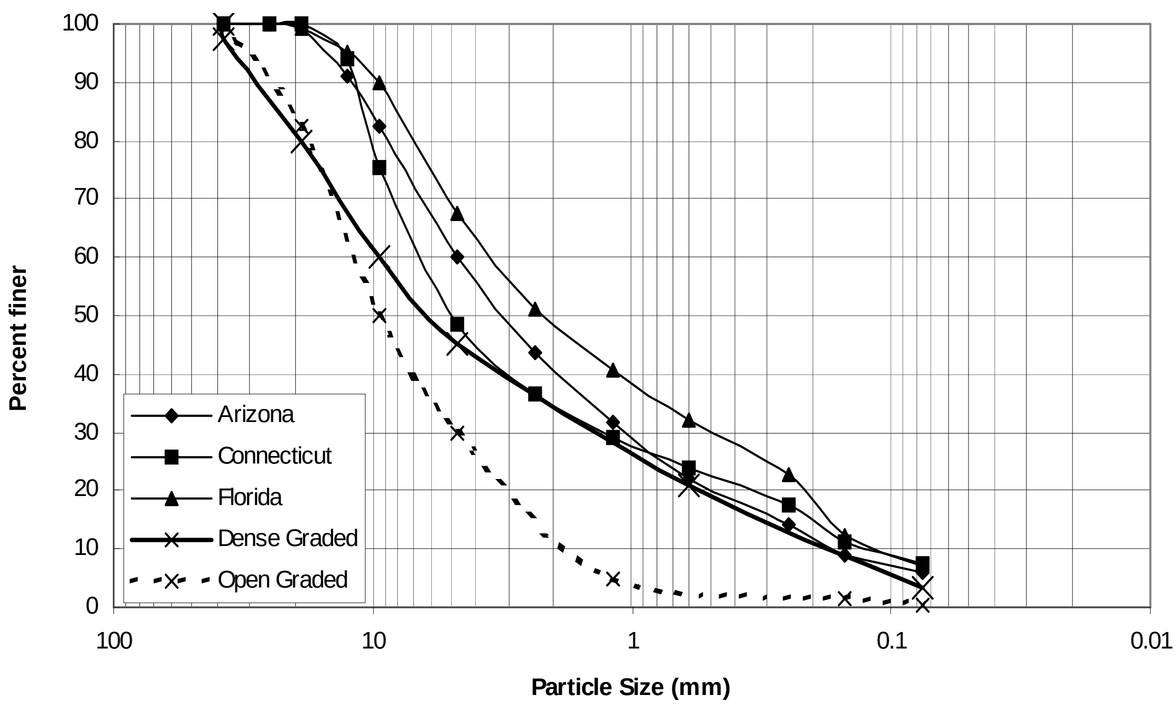

Figure 7. Comparison of RAP gradation typical base course gradations.

The Ontario Ministry of Transportation (MTO) has successfully used 100 percent RAP as granular base and shoulder material on several construction projects [43]. The typical RAP gradation, shown in Figure 8, fits in MTO's gradation band for unbound base layers. MTO also evaluated different blends of RAP with virgin aggregate material, as shown in Figure 9 [43].

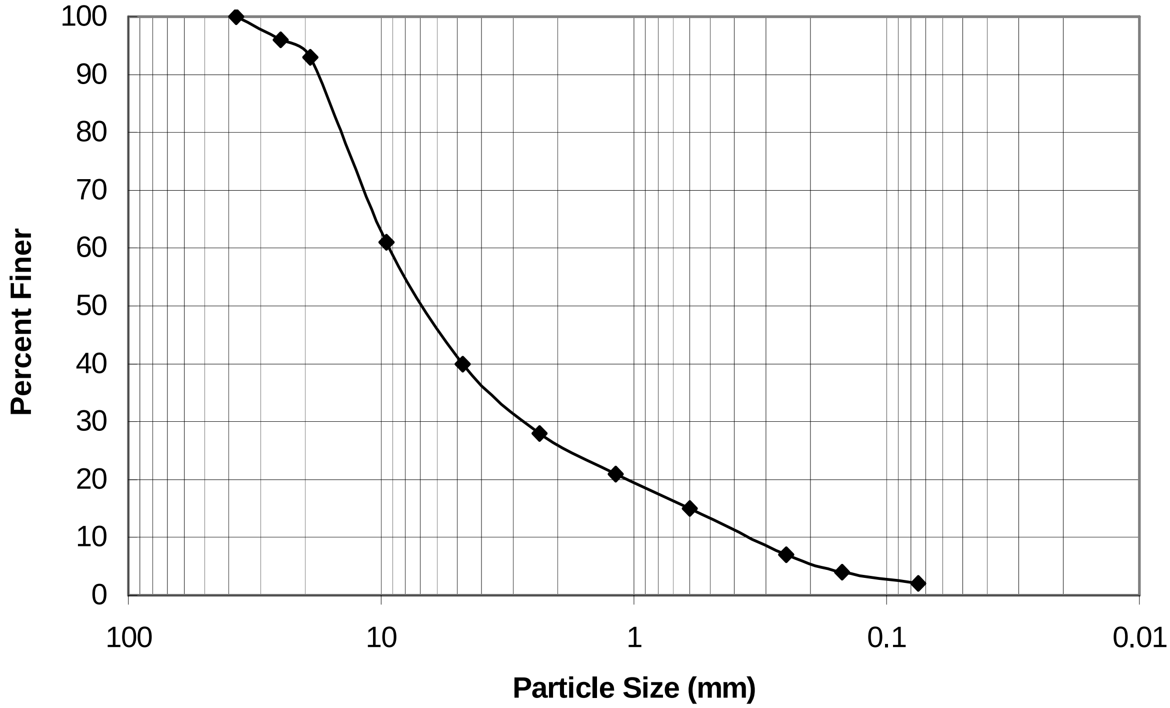

Figure 8. Typical RAP gradation used at base course in Ontario.

Compaction tests conducted by MTO indicated that RAP by itself or after blending with virgin aggregate had lower dry densities and higher moisture contents when compared to virgin aggregate material (see Figure 10).

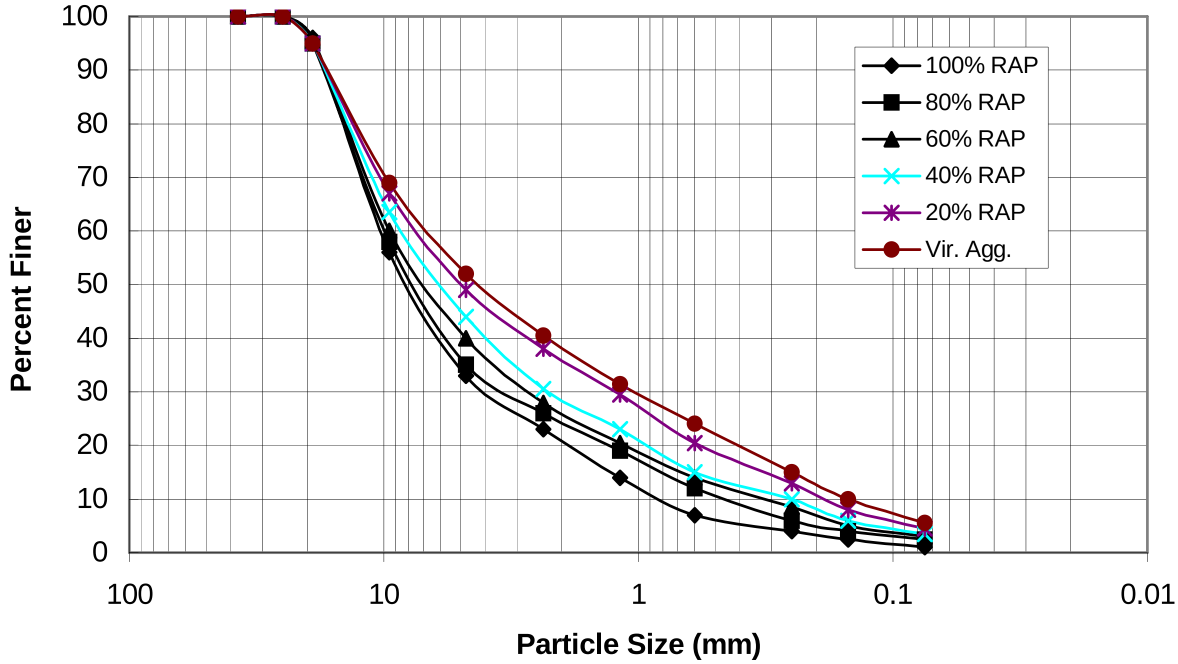

Figure 9. Gradation of laboratory blended materials tested by MTO.

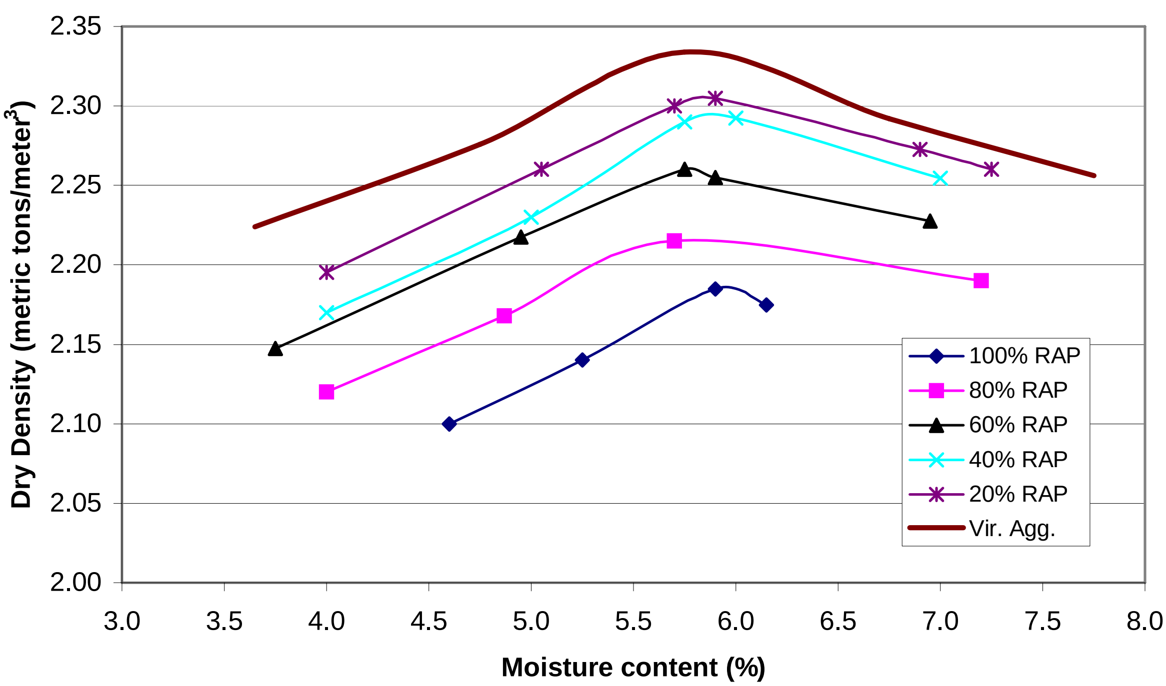

Figure 10. Laboratory compaction data on different blends of RAP.

Bennert et al. [16] conducted laboratory compaction tests on various blends of RAP with DGAB, as shown in Table 6. These values are slightly lower (10-15 lbs/ft^3) than values obtained by Hanks and Magni [43] during their tests on RAP blends with DGAB; however, the trends exhibited by RAP blended with virgin aggregate showed the same trend in both set of tests.

The Georgia DOT found that RAP only compacted 92 to 94 percent of the maximum density in the field as compared to their typical aggregate base [44].

Table 6. Maximum dry density and optimum moisture content of RAP blends.

Blended Material (%)		Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)
DGAB	RAP		
100	--	131.0	7.0
75	25	128.4	7.0
50	50	126.6	6.0
25	75	122.1	5.5
--	100	116.9	5.0

Similar results were obtained in a Texas DOT study to investigate the compaction characteristics of RAP using the Tex-113-E test method [45]. Tex-113-E uses a compaction mold (6-in [15.2-cm] diameter by 8-in [203.2-mm] high) to compact soil using a 10-lb (0.0445-kN) hammer with a sector face dropped from a height of 18 in (45.7 cm). Compacting in 4 layers, with 50 blows of the hammer applied to each layer, the sample receives a compaction energy of 22,900 ft-lb/ft^3. RAP had a slight peak in dry density at 3 percent water content, as shown in Figure 11. However, the dry density values at water contents of 2.5 percent or more were determined to be not significantly different [30]. At about 7 percent water content the dry density starts to increase again; however, increasing the moisture content beyond about 7 percent causes the excess water to drain. Based on this work, it could be stated that the largest value of dry density occurs at a smaller water content for RAP because of the influence of the bitumen coating on the particles [30].

Tests conducted on RAP samples from Florida (see Figure 12) suggest that RAP should be compacted in the field at moisture contents between 4 to 7 percent [22]. The water requirements for tubgrinder-processed RAP are relatively higher than the RAP produced using the hammermill process because the tubgrinder process produces a coarser gradation.

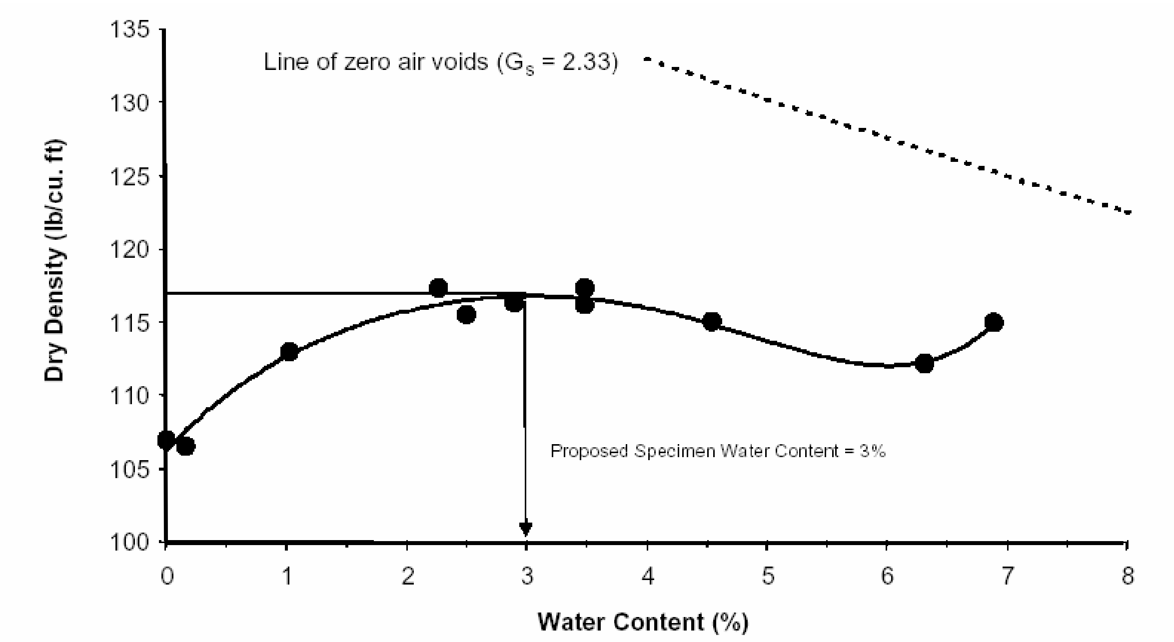

Figure 11. Compaction curve for RAP based on Tex-113-E test method.

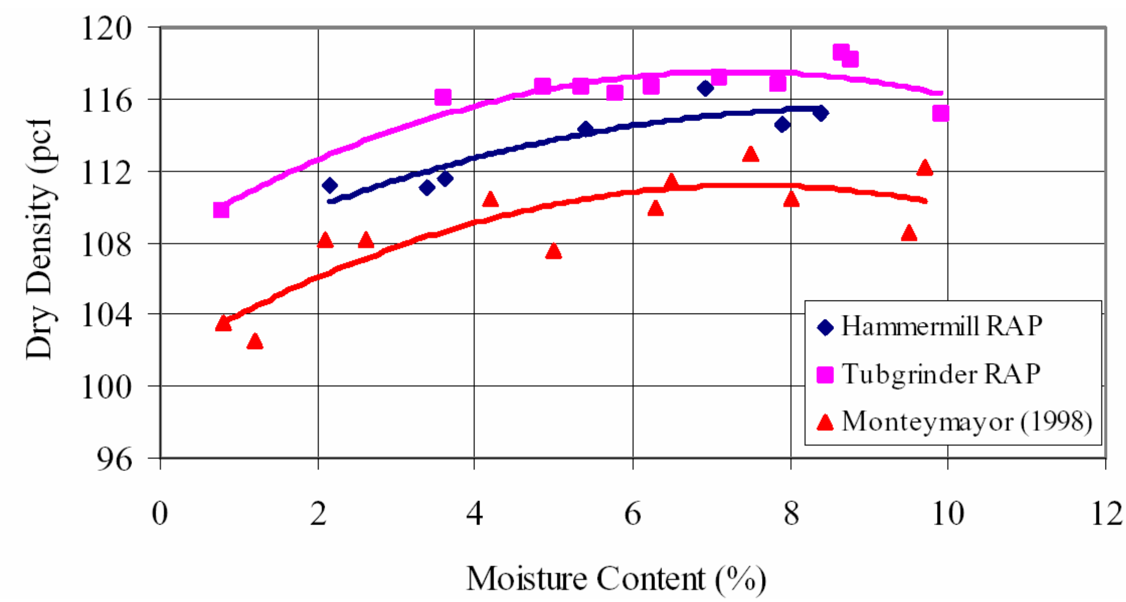

Figure 12. Modified Proctor results on Florida RAP samples.

Strength Tests

RAP blends were tested using standard laboratory tests, and different blends were analyzed under different traffic-type loading tests, such as the resilient modulus test and the cyclic triaxial test. Traditional permanent strain type tests were evaluated to determine if they are adequate in predicting the performance of RAP as DGAB and DGAB blends. Cyclic loading tests were determined to be better suited to evaluate aggregate base and subbase soils. Tests were conducted on 100 percent RAP and 25, 50, and 75 percent blends of virgin aggregate prepared at the moisture contents shown in Table 6. Results of static triaxial tests indicated that DGAB has significantly more shear strength than 100 percent RAP material [(16)].

Results on resilient modulus tests, shown in Figure 13, on non-blended RAP samples show that 100 percent RAP is significantly stiffer than DGAB. Figure 14 shows that the resilient modulus of blended RAP samples increased with an increase in the RAP percent in the test sample [(16)].

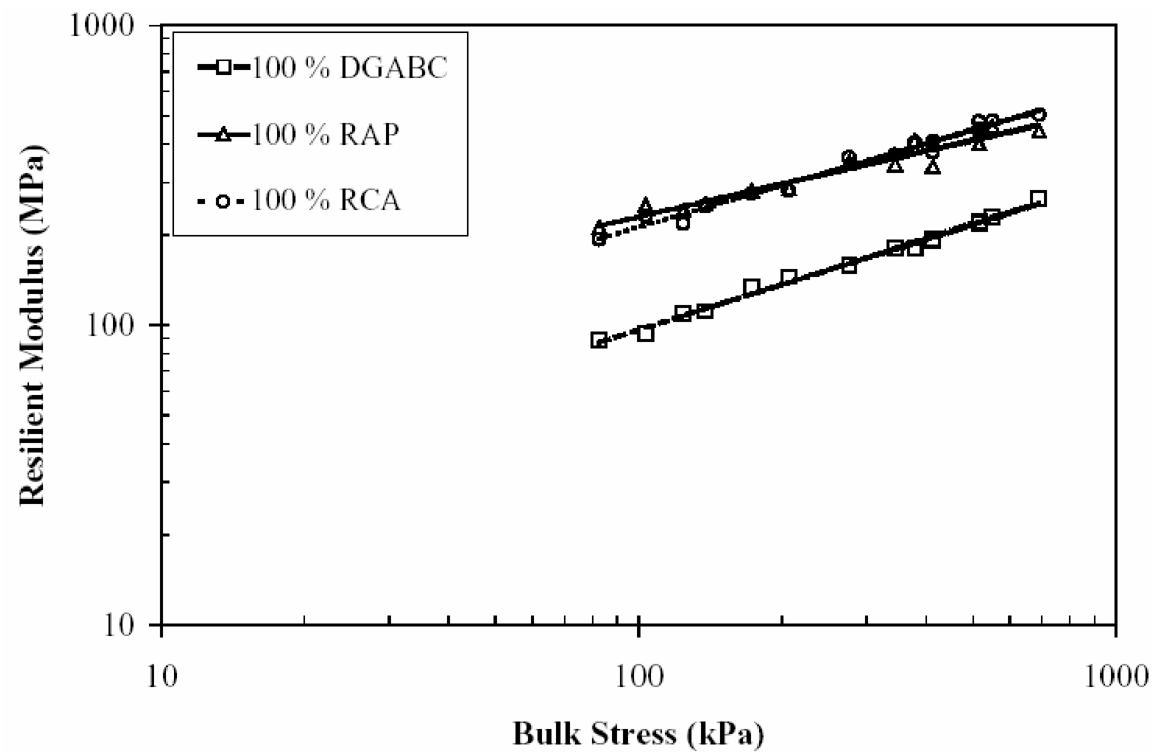

Figure 13. Resilient modulus test results on non-blended RAP and RCP samples.

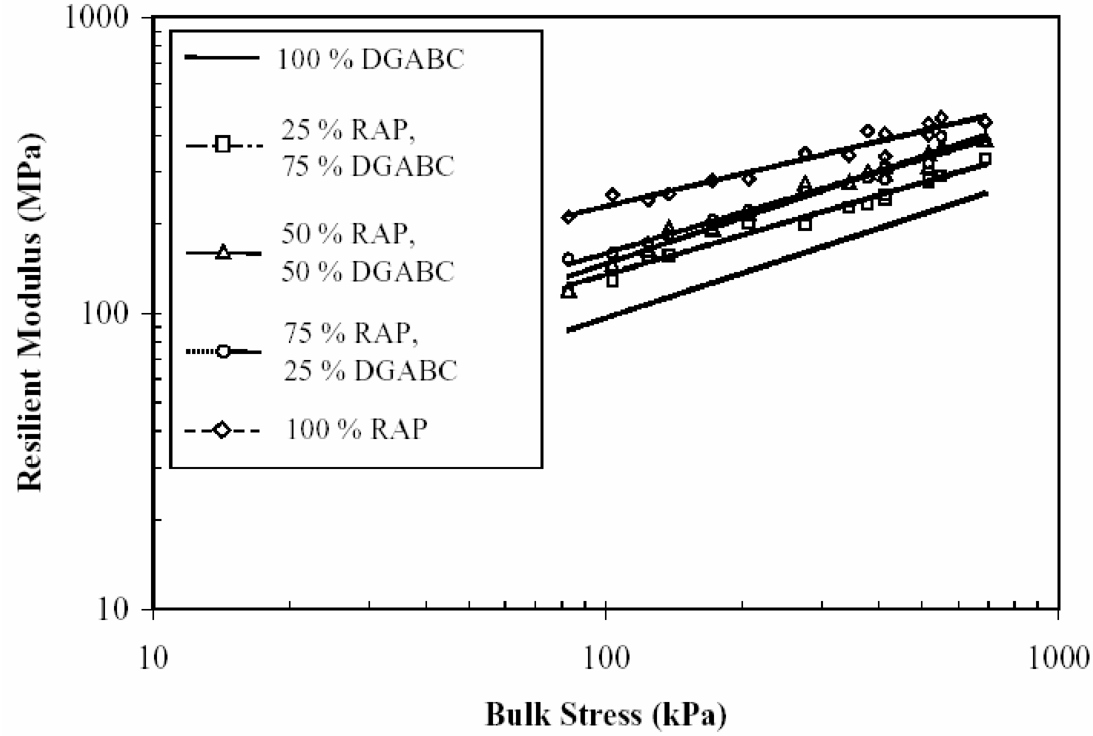

Figure 14. Resilient modulus of blended RAP increased with RAP amount in the mix.

Although the 100 percent RAP was stiffer than the DGAB material, blended and unblended RAP samples also had the highest largest permanent strains, indicating a propensity for rutting, as shown in Figure 15. The typical stress-strain relationships from this study are shown in Figure 16 (16).

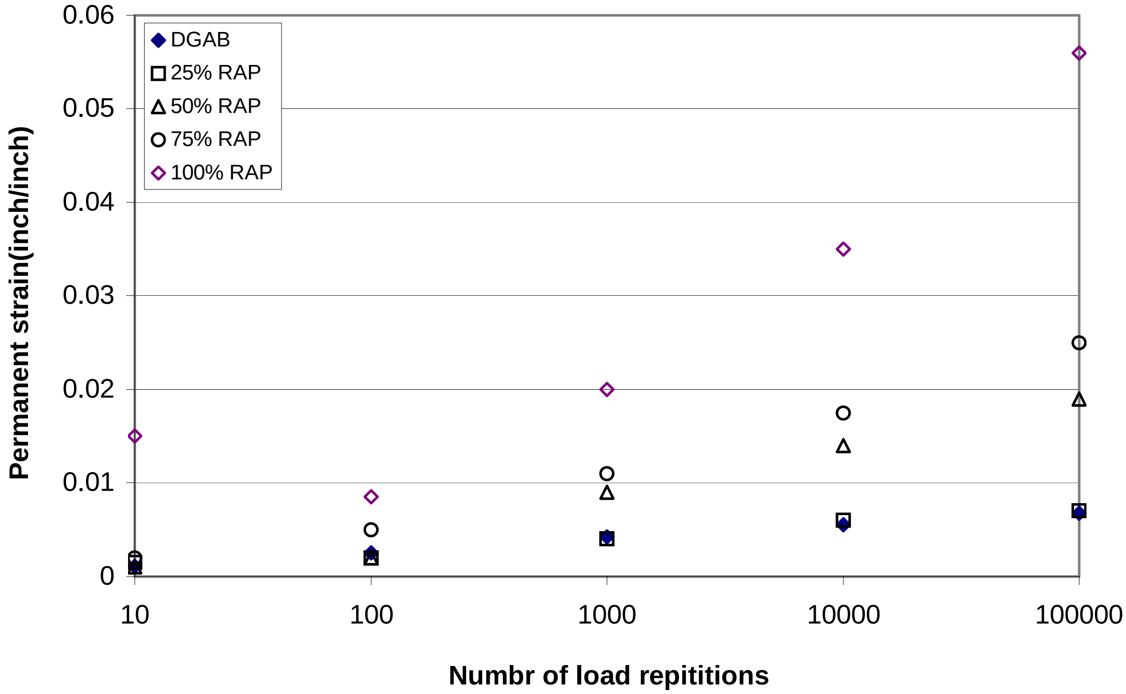

Figure 15. Result of permanent strain tests on RAP.

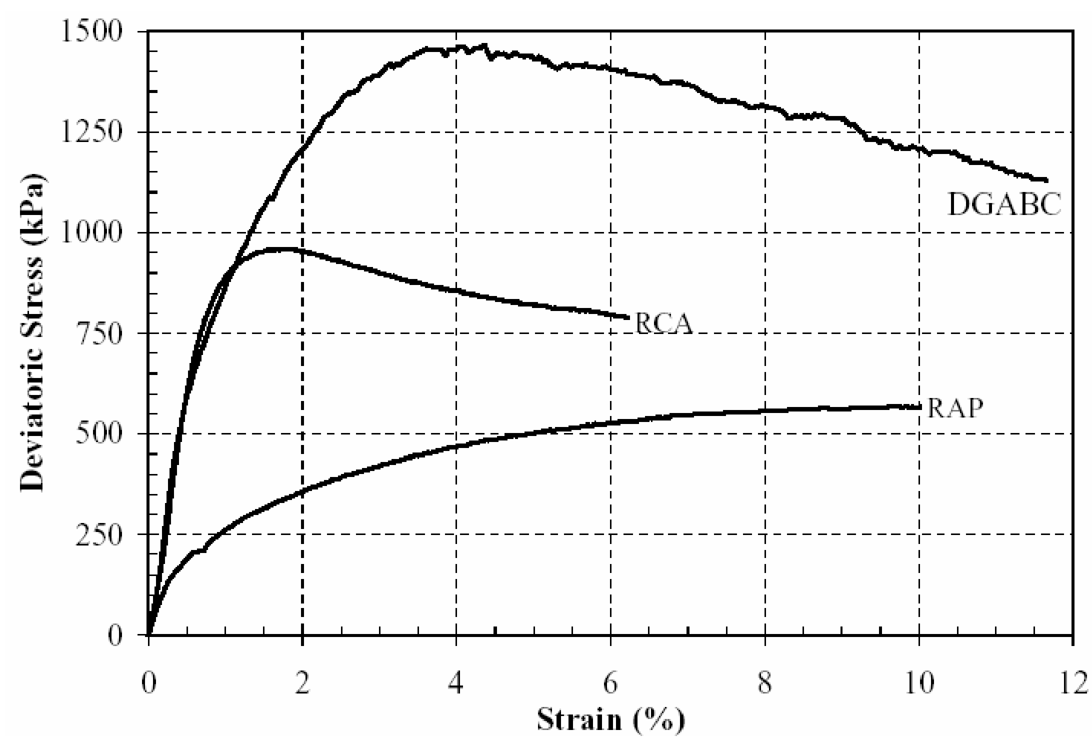

Figure 16. Behavior of 100 percent RAP/RCP samples (103 kPa conf. stress).

Resilient modulus tests on 0, 10, 30, and 50 percent RAP in base and subbase mixes used by the Massachusetts Highway Department indicated that the stiffness of the base and subbase mixes increased with an increase in the amount of RAP [46]. An increase in material stiffness increases the layer coefficient and thus the structural number of the layer. This observation is consistent with work conducted by Bennert et al. [16].

The New Jersey DOT evaluated RAP versus a DGAB using a Heavy Weight Deflectometer (HWD) [47]. The objective of this in-situ assessment was to determine if the RAP base will perform equal or better than the DGAB. This evaluation determined that RAP was 1.5 to 1.8 times stiffer than DGAB. The calculated tensile strains at the bottom of the HMA were lower for the pavement with the RAP base than those calculated for the DGAB, which means that the pavement with the RAP base will have a relatively longer fatigue life.

Florida DOT [22] studied the strength and deformation properties of RAP using laboratory tests on four RAP materials from Florida, and made the following conclusions:

- RAP was compacted using the modified Proctor, modified Marshall, vibratory, and static methods during laboratory evaluation; RAP did not display the classic moisture-density behavior for these compaction methods. At moisture contents in excess of 4 percent, the dry density was relatively constant; the slight variations observed were attributed to grinding and sample variations. Free-standing water at moisture contents in excess of 10 percent was observed for all samples (all compaction methods). In the field, RAP should be compacted at moisture contents between 4 to 7 percent.
- The triaxial properties of RAP are not affected by duration of the storage time.
- Triaxial tests conducted at three confining stresses showed an increase in strength with an increase in confining pressure (Figure 17).
- RAP was determined to be a suitable material for base/subbase construction based on its engineering properties.

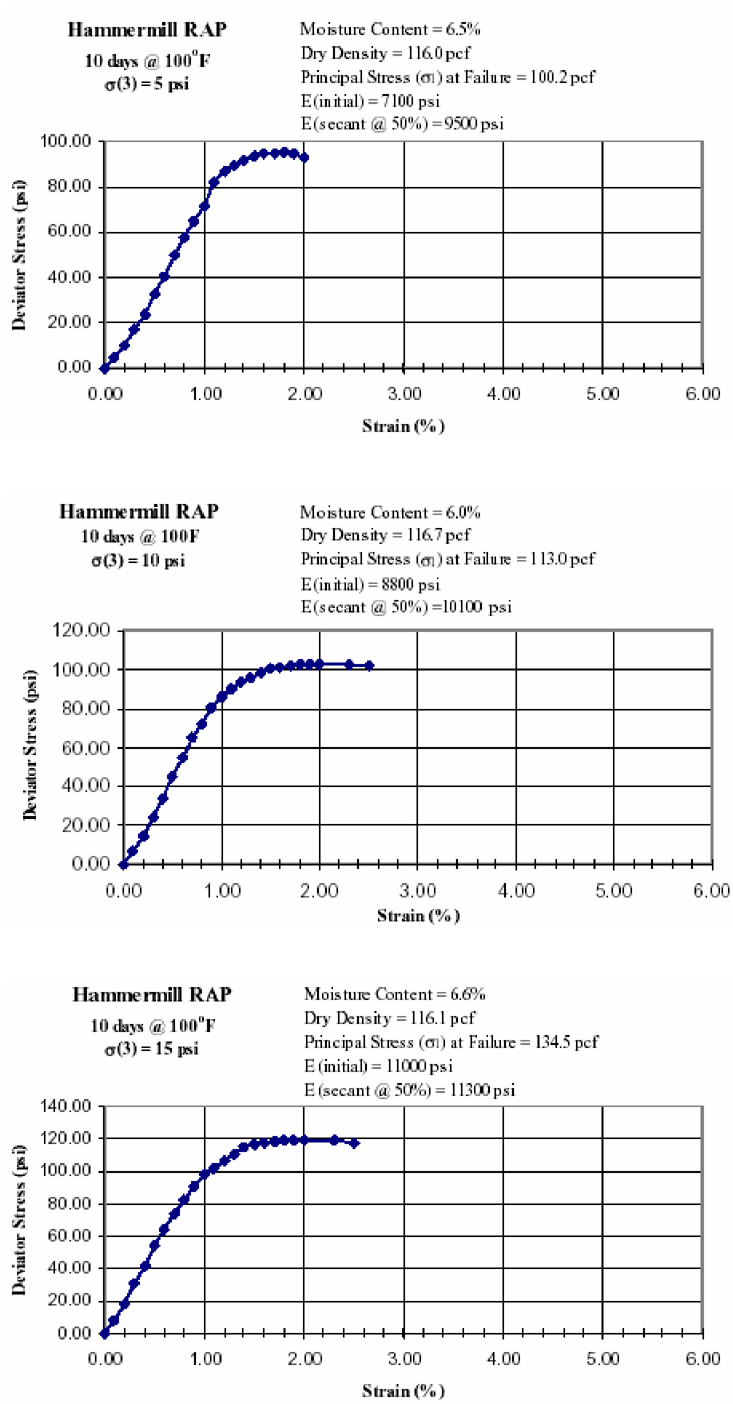

Figure 17. Triaxial test results on hammermill RAP after 10 days storage at 100 °F.

Another Florida study by Sayed et al. [48] used laboratory and field strength tests to conclude that RAP as base course saves both cost and construction time and performs well throughout a range of gradations. Laboratory and field tests indicated that RAP as aggregate in unbound pavement layers is at least equivalent (in terms of bearing strength) to limerock base. West and Murphy [49] also suggest that the chosen strength requirement of RAP should be equal to other granular bases. Similarly, Plasie [50], based on work conducted for the New Jersey DOT, stated that CBR and Falling Weight Deflectometer (FWD) test values obtained with RAP exceeded the values exhibited by DGAB material. Thus, it appears that RAP can be used successfully in place of DGAB.

Oregon DOT [51] evaluated RAP to determine layer coefficients for RAP for use with the 1986 AASHTO guide for pavement thickness design. Through the use of laboratory triaxial, diametral, and unconfined compressive strength tests, they determined that the practice of replacing virgin aggregate material with RAP appears to be a good alternative on some projects. RAP yielded relatively higher stiffness than virgin aggregate at the same stress state; however, the DOT considers RAP to be equivalent to virgin aggregate for structural design purposes.

CBR tests on different blends of RAP with virgin aggregate indicated that the CBR decreased from 129 percent for virgin aggregate materials to a low of 11.7 percent for an 80 percent RAP blend (see Table 7) [43]. Field CBR tests conducted after compaction also indicated a decrease in CBR with an increase in RAP component. These results are consistent with a Georgia DOT study that determined that RAP base CBR values were only a fraction of the CBR values for their typical aggregate base from a nearby quarry [44].

Based on CBR results conducted on RAP blends in Oman, the use of up to 100 percent RAP in subbase courses is allowed but the amount of RAP in unbound granular base courses is limited to 10 percent [52]. This is consistent with MTO and Georgia DOT evaluation results [43,44].

Table 7. Permeability and CBR test results of RAP and granular blends.

Blends	Aggregate (%)		CBR (%) 0.2” Pen	Permeability × 10^{-4} (cm/sec)
	Coarse	Fine		
Virgin Aggregate	47.8	52.2	129.0	1.04×10^{-4}
20 % RAP	51.5	48.5	95.3	-- [a]
40 % RAP	57.6	42.4	53.0	-- [a]
60 % RAP	61.2	38.8	26.7	1.04×10^{-3}
80 % RAP	63.9	36.1	11.7	-- [a]
100 % RAP	67.2	32.8	13.1	1.35×10^{-3}

[a] not tested

Permeability Tests

MTO [(43)] conducted permeability tests on virgin aggregate and compared them with a 60 percent RAP blend (40 percent virgin aggregate) and 100 percent RAP. Their results, shown in Table 7, indicated that because of the coarser gradations of RAP blends, they had a higher permeability, as would be expected.

Addition of up to 50 percent RAP has little effect on the permeability of the original base or subbase material [(46)]. The permeability of the subbase material (containing more than 50 percent RAP) increased by an order of magnitude which is very similar to tests conducted by MTO [(43)] reported in Table 7.

SUMMARY OF TESTS CONDUCTED TO EVALUATE RCP PROPERTIES

FHWA reports that, when properly processed and tested for appropriate specification compliance, RCP has demonstrated satisfactory performance as aggregate in unbound base/subbase layers. This performance assessment is based on the results of a 6-year-long study in which RCP aggregate was tested for consistency and was found to fall within a predictable range [(7)].

SCREENING TESTS

Physical and mechanical tests have been conducted to determine the properties of RCP as aggregate in unbound pavement. Properties of RCP are affected by the amount of cement paste present on the aggregate after processing [(18)]; this is a function of the original concrete and the processing used to manufacture RCP. Table 8 shows that the physical properties of RCP and the virgin aggregate required by the Florida DOT are very close.

Table 8. Physical properties of RCP compared to virgin aggregate specifications.

Property	RCP Aggregate	Virgin Aggregate
Specific gravity (SSD)	2.43	2.42
Water absorption (SSD), %	4.36	4.10
Unit weight, lb/ft^3	88.2	84.2
Los Angeles abrasion, %	33.9	32.6
Void ratio, %	41.9	--[a]

[a] Data not provided

Florida DOT tested RCP to meet the requirements of aggregates for unbound base layers and found that aggregate properties of stability, particle, permeability, plasticity index, limerock bearing ratio (LBR), particle shape, LA abrasion, and compaction were either satisfactory or excellent; sodium sulfate test results were not satisfactory because sodium sulfate is chemically unsuited to evaluate RCP [(20)]. As such, RCP can be used effectively as aggregate in unbound pavement layers when proper quality control techniques are utilized. Florida DOT reports that concrete strength is not a factor in particle breakdown during construction (placement and compaction). However, if RCP is to be utilized as aggregate in unbound pavement layers, the source of the original PCC should be ascertained to safeguard uniform quality.

The Illinois DOT [(41)] documented the usage of recycled materials in Illinois, including RCP. Due to its physical properties, such as highly angular particles, RCP is a viable substitute for aggregate and can be used as such in granular bases. The use of RCP in base layers in contingent upon the material not violating a department's material specifications. Illinois DOT has also used RCP as a drainage layer with success.

The Virginia DOT found the use of RCP as aggregate in unbound pavement layers to be very beneficial. In addition, they state that the unbound cementitious material in RCP improves the strength of the base and subbase (53). Similarly, the Michigan DOT states that RCP used as aggregate in the base and subbase can have performance comparable to virgin aggregate material (54).

Texas DOT (30) also studied the compaction characteristics of RCP using Tex-113-E test methods (45). The compaction curve shown in Figure 18 shows that the dry density increases as water content increases from 0 to 12 percent and then remains almost constant for water contents greater than 12 percent. This could be attributed to the fact that water starts draining from the bottom of the compaction mold. The RCP compaction curve does not exhibit the distinct peak that is typical for soils.

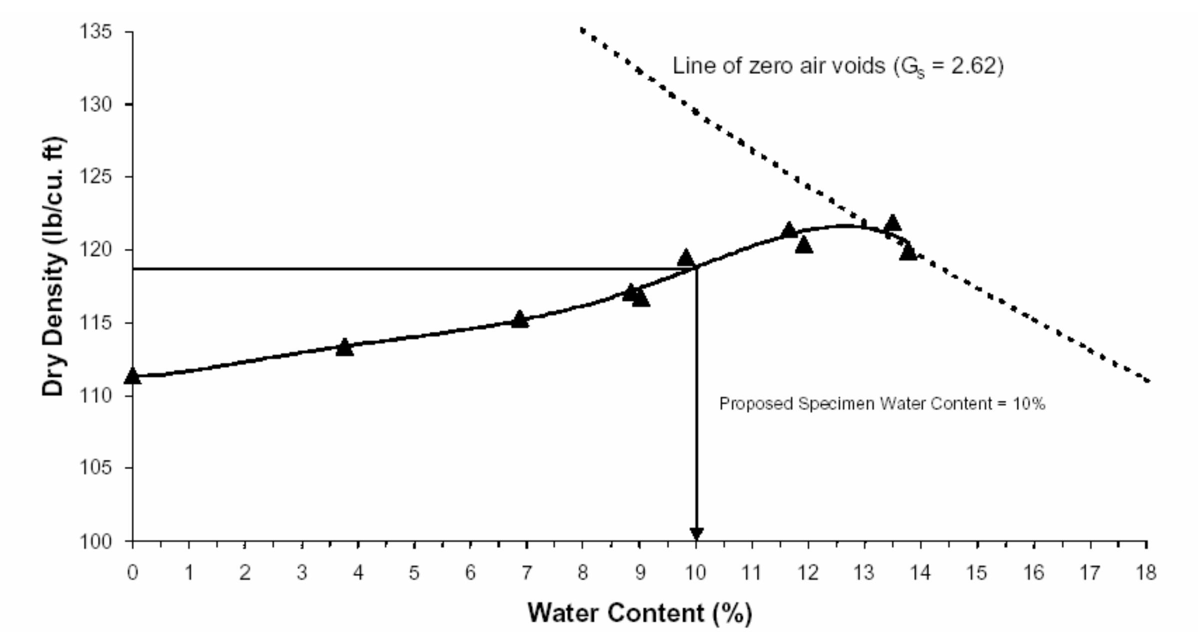

Figure 18. Compaction curve for RCP using Tex-113-E test method.

Florida DOT [18], while investigating the compaction and moisture characteristics of RCP samples, determined that there was little inter-laboratory variation in compaction test results. For example, compaction tests conducted at the University of Central Florida had a RCP unit weight of 113.5 lbs/ft^3 (17.9 KN/m^3) at an optimum moisture content of 11.2 percent were considered very close to dry density of 114.8 lbs/ft^3 (18.1 KN/m^3) at an optimum moisture content of 12.1 percent determined at Florida DOT laboratories.

Bennert et al. [16] determined the optimum moisture content of several blends of RCP with virgin aggregate, as shown in Table 9. RCP optimum moisture contents are slightly higher than those of RAP (shown in Table 6) due to the presence of cement paste on RCP.

Table 9. Maximum dry density and optimum moisture content of RCP blends.

Blended Material (%)		Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)
DGAB	RCP		
100	--	131.0	7.0
75	25	128.6	5.0
50	50	125.9	6.0
25	75	124.9	7.0
--	100	123.9	7.5

Strength Tests

Bennert et al. [16] also studied RCP using standard laboratory tests, analyzed 100 percent and 25, 50, and 75 percent blends under the resilient modulus test and the cyclic triaxial test, and evaluated its performance as DGAB. The gradation of RCP material tested was shown in Table 3. Results of static triaxial tests, shown in Figure 19, indicated that DGAB has significantly more shear strength than 100 percent RCP material.

The 100 percent RCP and its blends were stiffer than the DGAB material (see Figure 13). Unlike tests conducted on RAP samples, RCP samples did not show any large permanent strains indicating future rutting potential. Figure 20 shows that the stiffness of RCP increased with an increase in the amount of RCP in the mix.

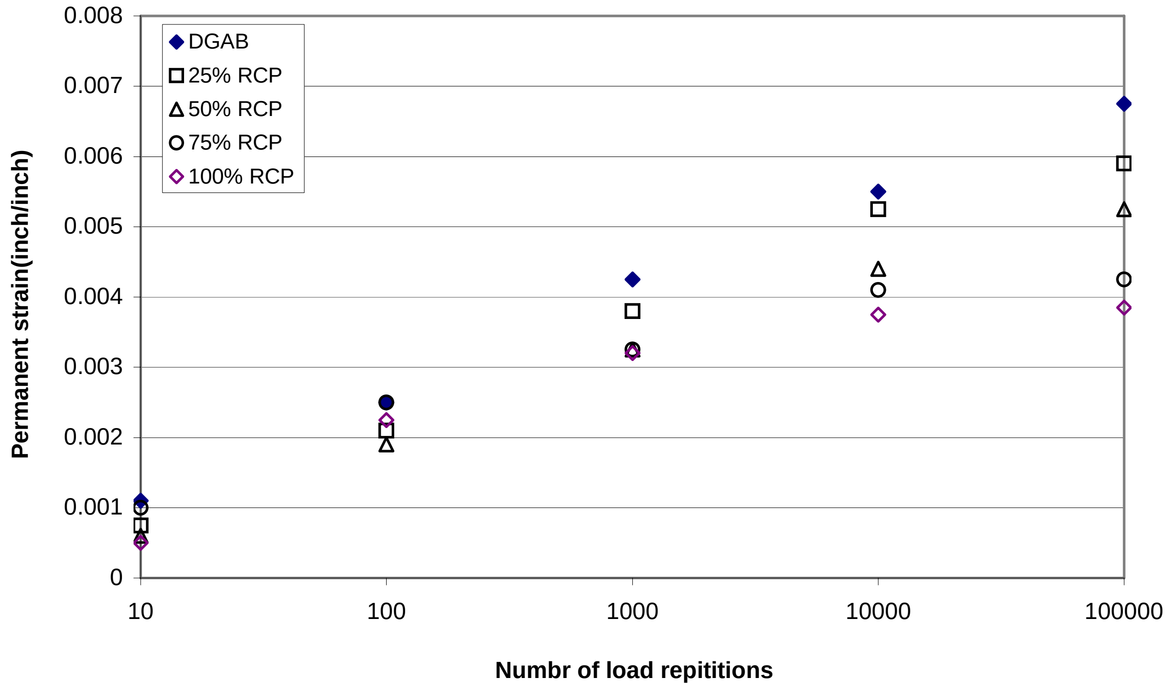

Figure 19. Result of permanent strain tests on RCP.

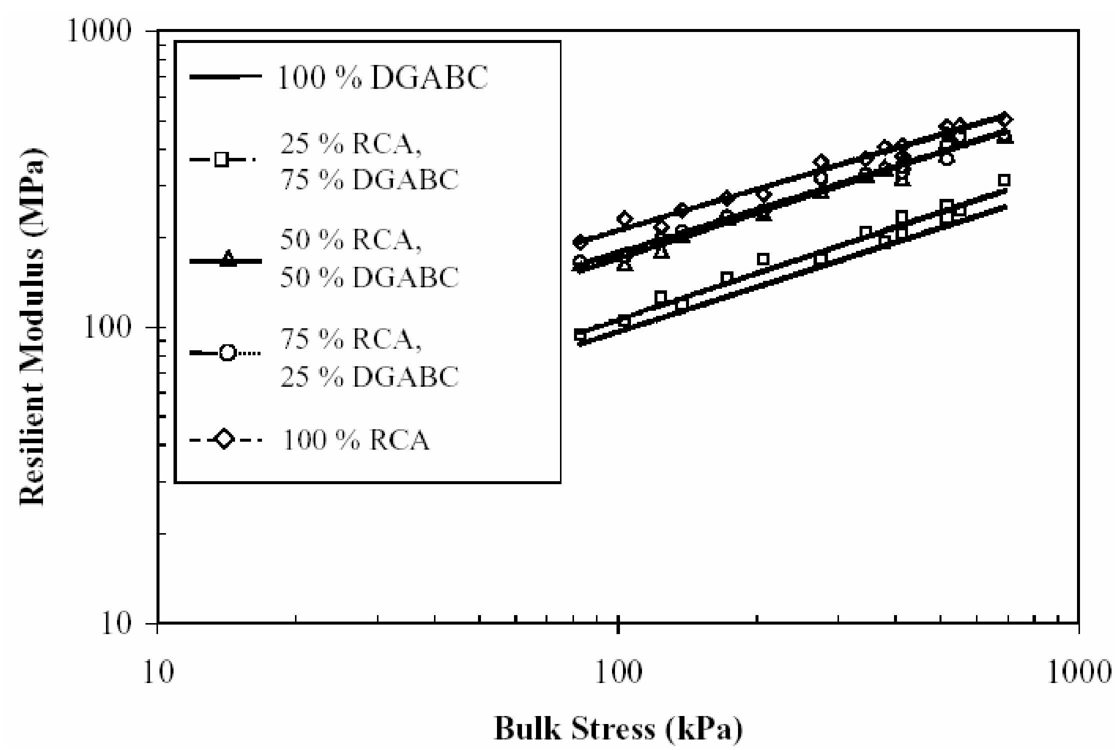

Figure 20. Resilient modulus increased with percent of RCP in the blend.

Resilient modulus tests on RCP showed a larger stiffness value (resilient modulus) at higher bulk stresses, whereas RAP shows a higher stiffness under lower bulk stresses [16]. An example of stiffness tests conducted at VTI in Sweden, shown in Figure 21, shows the same trend [37].

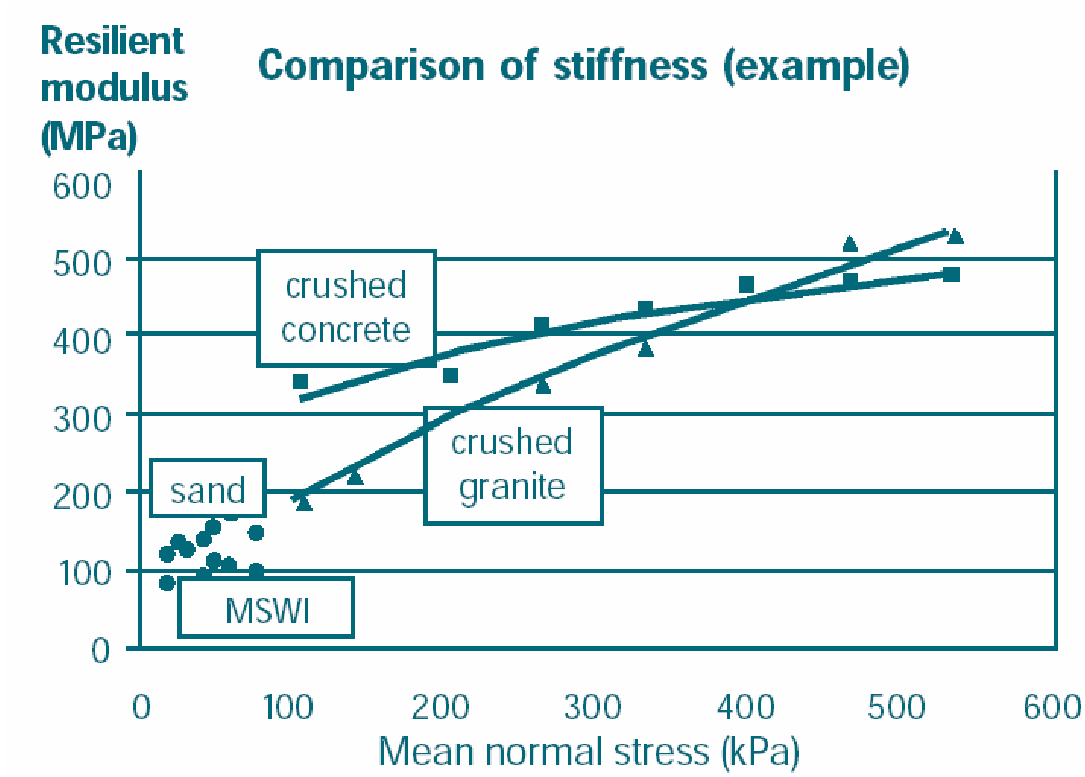

Figure 21. Triaxial testing data from Sweden.

LBR tests were conducted on RCP samples from seven Florida DOT districts every month for one year to evaluate the variability in RCP strength characteristics [18]. The LBR test evaluates an aggregate's overall bearing and shearing strength relative to lime rock, which has an LBR of 800 psi (5.5 MPa). The LBR test [55] sample is prepared by compacting the base material in a 6-inch (15.2-cm) diameter and 6-inch-high mold using a 10-lb (0.0445-KN) piston hammer dropped from a height of 18 inches (45.7 cm) [56]. Load readings are recorded for each 0.01-inch (0.25-mm) penetration of a 1.95-inch (49.5-mm) piston, and the load versus penetration results are plotted. The load at 0.1-inch penetration as a percentage of the standard LBR strength is termed as the LBR strength of the material. Almost all RCP samples met the Florida DOT specifications for LBR of 100 percent or more. A comparison of average LBR with Florida DOT LBR specification is shown in Figure 22.

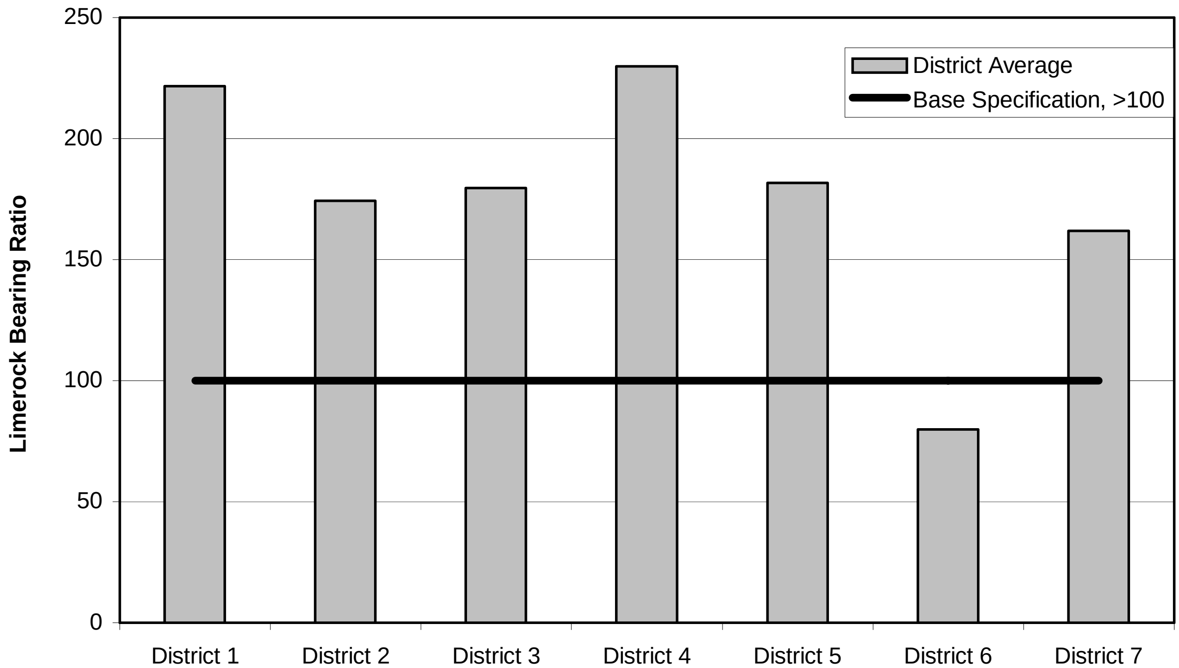

Figure 22. Average LBR for all districts in the Florida DOT study.

Arm [57] studied the self-cementing properties of RCP in unbound pavement layers using triaxial and field tests. The 2-year study included repeated load triaxial tests on manufactured samples after different storage time and FWD tests on test sections; the results showed a clear increase in resilient modulus (Figure 23) and backcalculated layer modulus (Figure 24). This increase is large initially and then levels off with time.

Permeability Issues

Minnesota DOT reviewed 11 field and laboratory studies to determine the effect of using RCP as aggregate in unbound base/subbase layers on performance of drainage systems by possible impairment due calcium carbonate deposits and other fines in the RCP [58]. The environmental concern was that the drainage system discharge was relatively high in pH level. They stated that the amount of participate was directly related to the amount of exposed cement mortar surface.

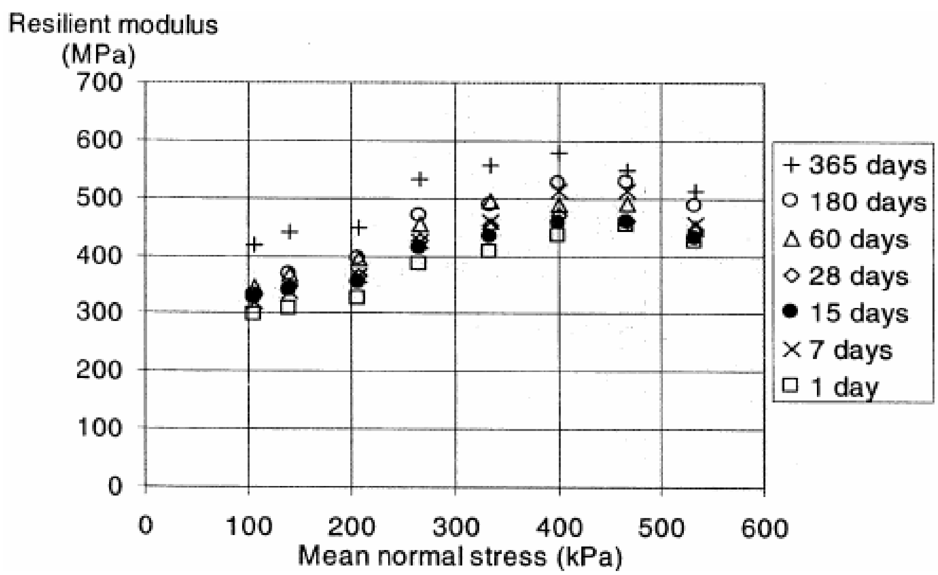

Figure 23. Growth in resilient modulus of crushed concrete with age.

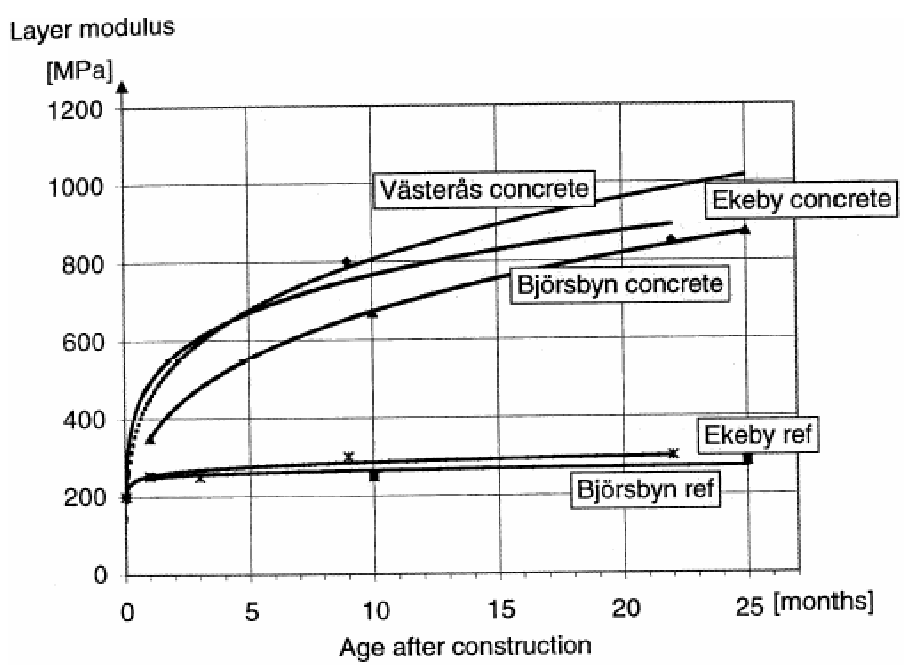

Figure 24. Increase in stiffness (backcalculated modulus) with time for unbound RCP layer.

Washing RCP aggregate before construction reduces the accumulation of crusher dust and other fines (non carbonate residue) in and around pavement drains. The use of filter fabrics with high initial permittivity has also been suggested, as these allow accumulation of precipitate and other fines without causing a significant reduction in drainage function. Selective grading and blending with virgin aggregate reduces but does not eliminate the precipitate problem. The pH level is not high enough to have a significant environmental impact. It is quickly diluted by the surface runoff [58, (59)].

Toughness Tests

LA abrasion tests conducted on RCP samples from seven districts in Florida over a one-year time period indicated that most of the LA abrasion values were well within the acceptable range for virgin aggregate material, as shown in Figure 25 [(18)].

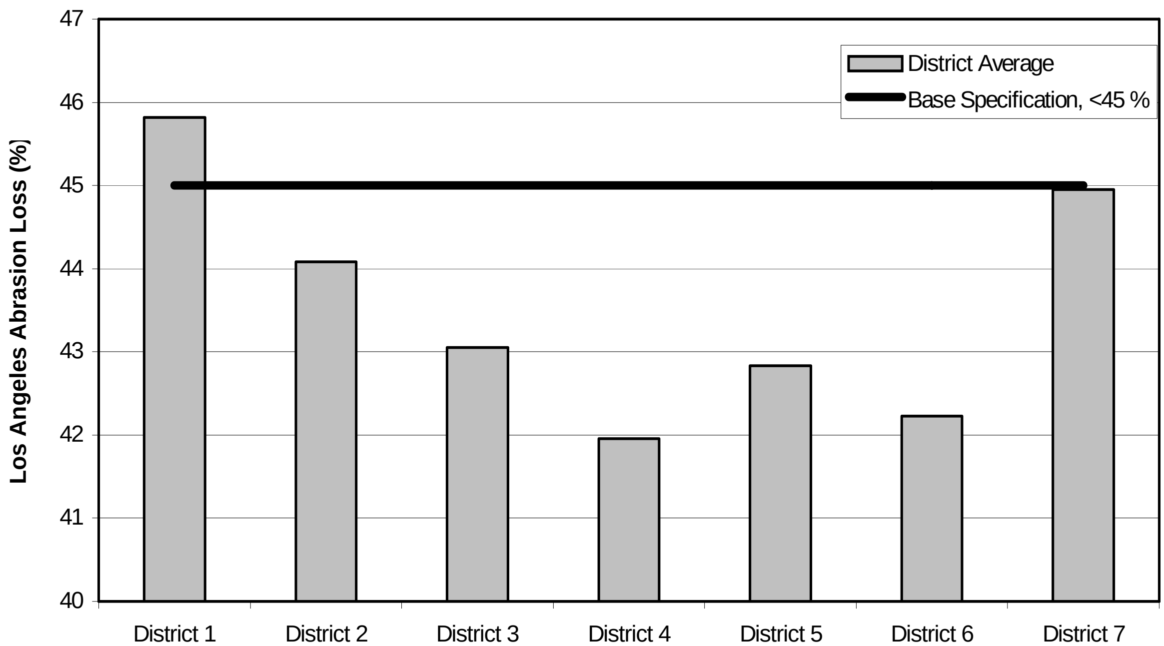

Figure 25. Average RCP LA abrasion loss in the Florida DOT study.

Sodium sulfate soundness tests indicated an average loss in excess of 52 percent; well above the Florida DOT specification of 15 percent. The sodium sulfate test disintegrates the concrete during the tests; thus, it is usually waived on recycled aggregates [(18)].

EVALUATION SUMMARY

In summary, there are consistent findings in many of the studies reviewed regarding the use of RAP and RCP as aggregate in unbound pavement layers. However, there are also many inconsistencies between the studies covered regarding the volumetric and structural properties of unbound base/subbase layers with RAP and RCP and their effect on pavement performance. Many of these inconsistencies might be explained by the use of different materials test methods, specimen preparation procedures and test protocols. These inconsistencies were considered when updating the Phase II work plan.

INTERVIEWS WITH STATE DOTS

Interviews were conducted with state DOT to obtain information regarding their policies, practices, experiences (including past studies), and perspectives on RAP and RCP recycling in unbound pavement layers, and to seek insights and information from other institutions (public or private) engaged in these issues. The state DOTs that were contacted during this research effort are shown in Table 10, a total of 22 state DOT provided information. Results of work conducted at Minnesota Road Research Program [(60)] provided data for 13 additional state DOTs. The states included in the final analysis are shown in Figure 26. The information sought during the phone interviews included the following:

- Policy on using RAP/RCP in unbound pavement layers
- Pavement design
- Material specifications
- Construction and constructability issues
- Performance observations

Table 10. State DOTs contacted by the NCHRP 4-31 team for phone interviews.

Reclaimed Asphalt Pavement	Reclaimed Concrete Pavement
Arizona DOT	Florida DOT
Florida DOT	Georgia DOT
Georgia DOT	Illinois DOT
Illinois DOT	Iowa DOT
Louisiana DOT	Kansas DOT
Maine DOT	Michigan DOT
Mississippi DOT	Minnesota DOT
Nebraska Department of Roads	Mississippi DOT
New Hampshire DOT	Missouri DOT
New Jersey DOT	North Dakota DOT
North Dakota DOT	Oklahoma DOT
Rhode Island DOT	South Dakota DOT
South Dakota DOT	Wisconsin DOT
Texas DOT	
Virginia DOT	
Wisconsin DOT	

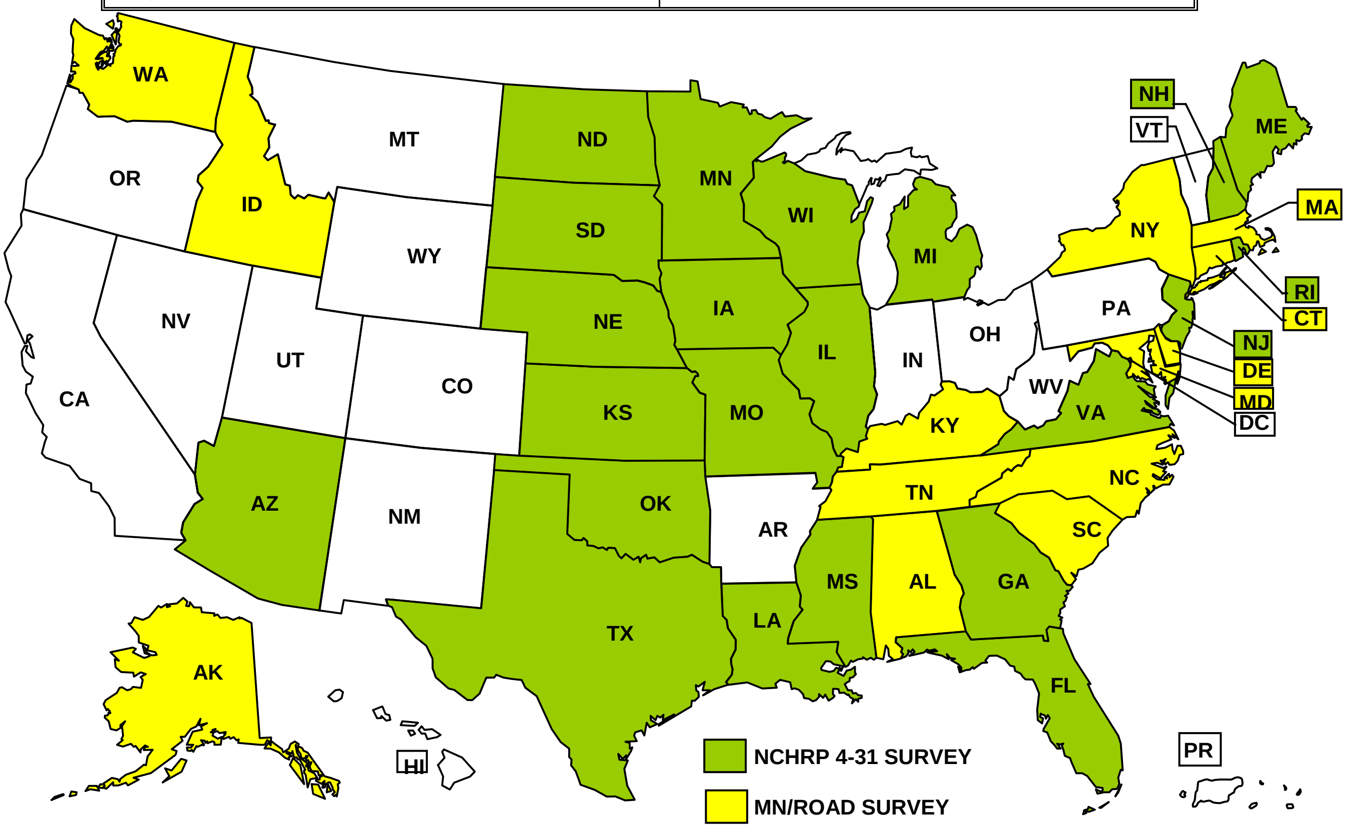

Figure 26. State DOTs included in the final analysis for Subtask 1.B.

Policy on Using RAP/RCP as Aggregate in Unbound Layers

Almost all State DOTs contacted allow RAP and RCP as aggregate in unbound pavement layers, as shown in Figure 27.

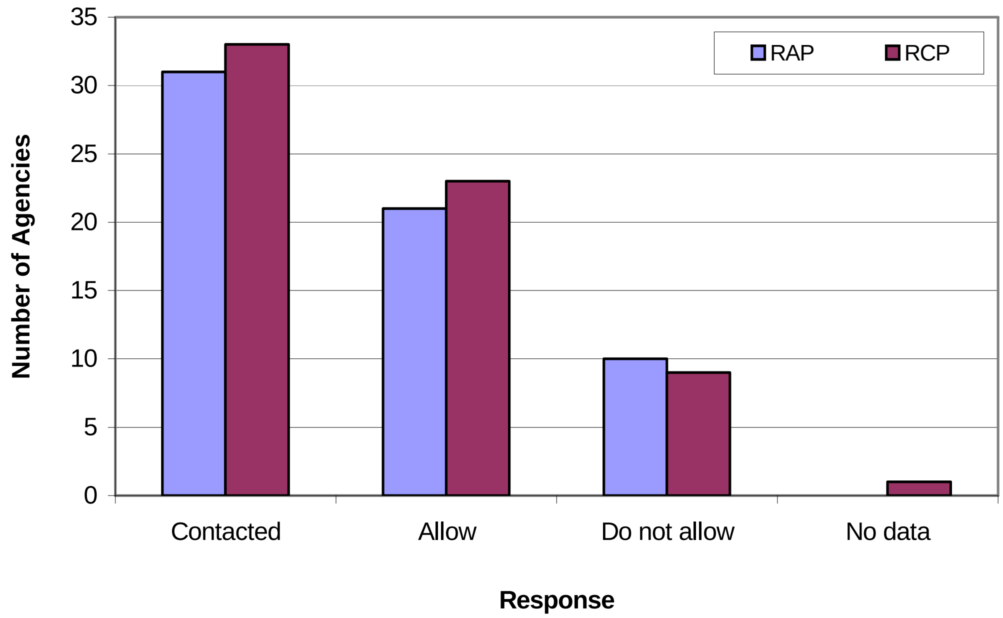

Figure 27. Number of agencies that allow RAP/RCP as aggregate in unbound layers.

Material availability and economic savings was the most cited reason for using RAP and RCP (see Figure 28); however, most of the times the choice whether to use RAP/RCP was left to the contractor. North Dakota DOT allows the use of RAP and RCP as unbound pavement layers as a policy; however, this policy based use is only when recycled materials are available from the same project and only on highways with low to medium traffic volumes. Georgia DOT restricts the use of RCP to unbound base courses and does not permit the use of RAP in base courses. Most respondents indicated that RAP and RCP material has to satisfy virgin aggregate material specifications, however, some requirements (such as LA abrasion loss, sodium sulfate test) are often relaxed.

Pavement Design

Twenty-one of the contacted DOTs allow the use of 100 percent RCP as aggregate in unbound pavement layers; 16 DOTs allow the use of 100 percent RAP. Only 2 DOTs restrict the amount of RCP in unbound pavement layers to less than 50 percent; 5 DOTs restrict the use of RAP to 50 percent or less. Nine DOTs use specific test values (stiffness, layer coefficients) for RAP in structural designs. Only 6 DOTs have evaluated RCP to provide input to their structural design procedure. The reason for this is that RAP is generally considered slightly weaker or nearly the same strength as virgin aggregate as is evaluated to determine its strength/stiffness characteristics for structural design purposes. RCP, on the other hand, is generally considered stronger than virgin aggregate and the strength/stiffness values for standard virgin aggregate are often used for structural design purposes.

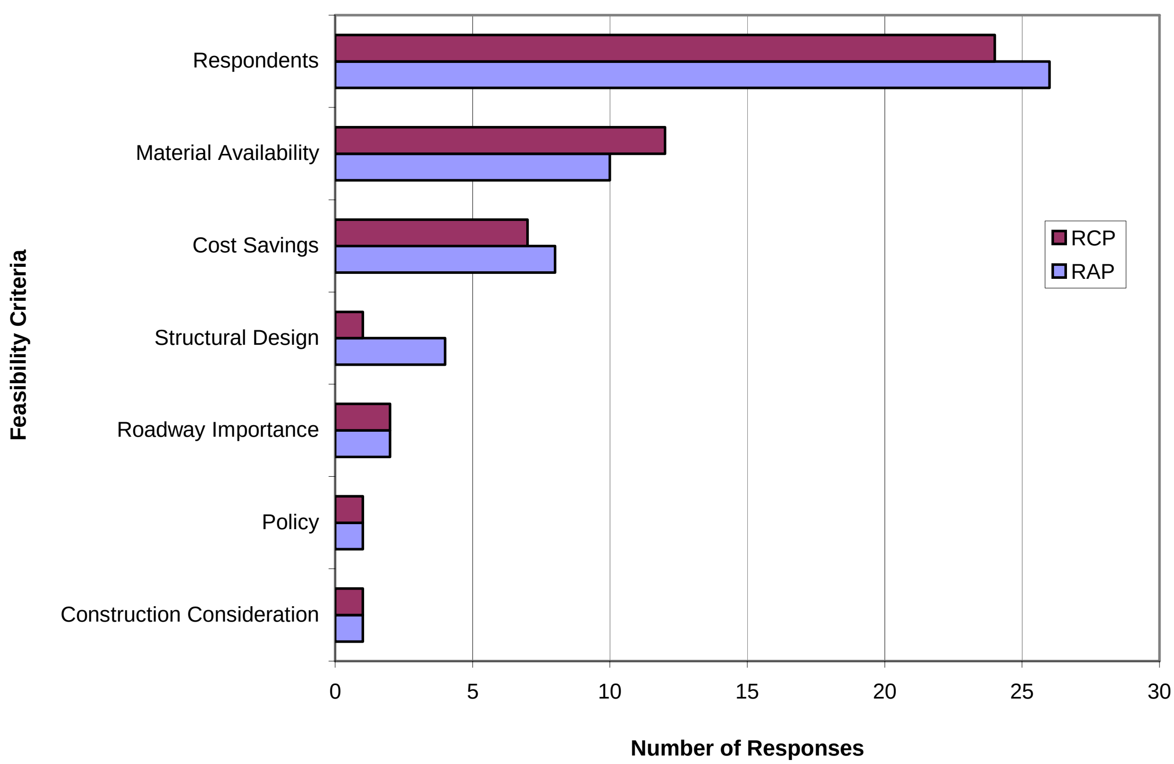

Figure 28. Criteria to determine feasibility of using RAP and RCP at the project level.

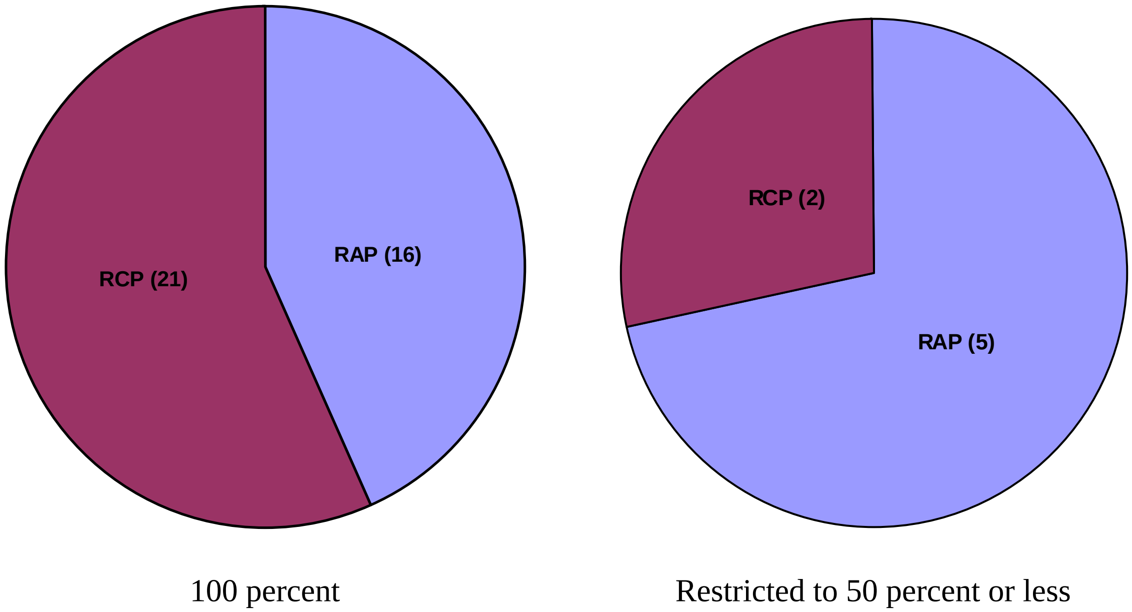

Figure 29. State DOTs allowing 100 percent and less than 50 percent RAP and RCP.

Material Specifications

Twenty-one of the responding state DOTs have specifications for the use of RAP or RCP as aggregate in unbound pavement layers. Two state DOTs use special provisions for RCP modifying the virgin aggregate base course specifications on a project-by-project basis.

Connecticut, Florida, New Jersey and Texas DOTs require environmental tests on RAP. Connecticut, Louisiana, North Dakota, and Texas require that environmental tests be conducted on RCP before use as unbound aggregate in base/subbase pavement layers. Only Illinois DOT requires environmental tests for source approval of virgin aggregate materials. Florida DOT does not allow the use of RAP below the water table. New Jersey requires environmental tests on RAP and virgin aggregate if suspecting petroleum contamination.

Construction and Constructability Issues

Most of the state DOTs contacted had no constructability related issues with using either RAP or RCP as aggregate in unbound pavement layers. One state DOT indicated that the base layer containing RAP was tender immediately after placement; the solutions that worked well to alleviate this problem included delaying the compaction operation, and using thin lifts. One state mentioned that contractors preferred construction with RAP to virgin aggregate for unbound pavement layers. Two states noted that RAP required relatively more compactive effort during construction.

Only three of the responding state DOTs reported any constructability issues with RCP. Two state DOTs indicated that RCP required more water during construction. Crushed concrete is relatively drier, and the presence of cement paste and crushed faces make crushed concrete more absorptive. One state DOT has concerns about segregation of the crushed RCP material.

Milling and crushing were the predominant methods to produce RAP; crushing was the predominantly used to produce RCP (Figure 30). Crushing is generally done at an off-site facility and requires hauling ripped HMA and PCC to the processing facility. After crushing, the material is either stockpiled for later use or hauled immediately to the job site. A mobile plant is sometimes used if the material is to be used at the same job site.

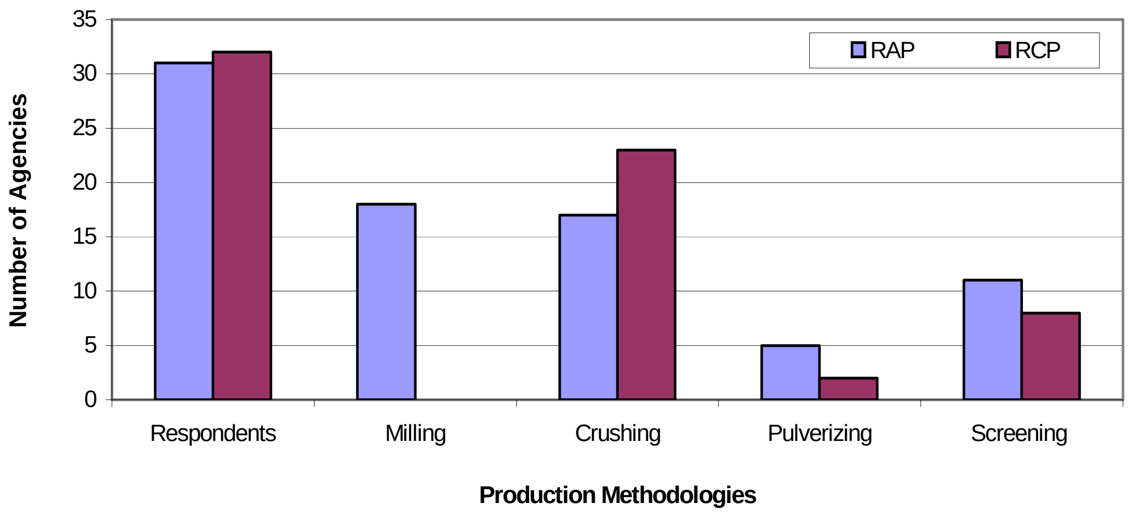

Figure 30. Processes used in the production of RAP and RCP.

Performance Observations

All state DOTs contacted indicated no problems with the performance of RAP and RCP based on empirical evidence; Figure 31 shows agencies' experience with RAP and RCP as aggregate in unbound pavement layers. A total of eleven respondents (four for RAP and seven for RCP) indicated that they have recently started using RAP and RCP as aggregate in unbound pavement layers; no problems have been noted, but they have no history to make a judgment at this stage.

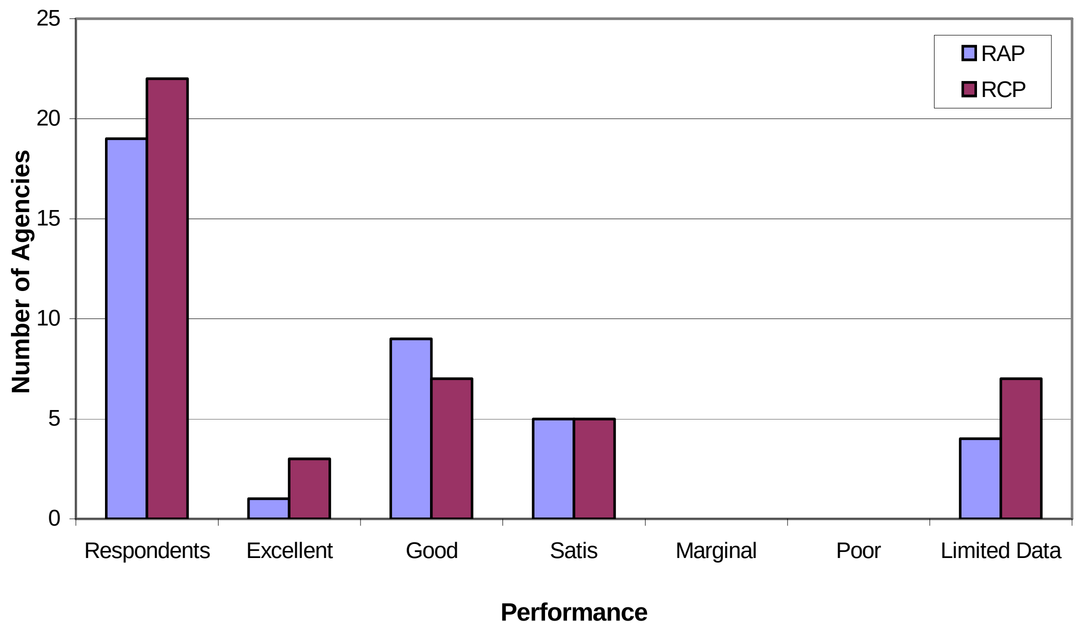

Figure 31. Agencies' experience with RAP and RCP as aggregate in unbound layers.

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APPENDIX B

RECOMMENDED NEW AGGREGATE TESTS

DISCLAIMER

The proposed test methods are the recommendations of the NCHRP Project 4-31 staff at Applied Research Associates, Inc. These methods are not approved by the NCHRP or any AASHTO committee or formally accepted for the AASHTO specifications.

PROPOSED STANDARD METHOD OF TEST FOR SHEAR STRENGTH OF AGGREGATE BY THE REPEATED LOAD TRIAXIAL TEST

1. Scope

1.1 This method covers procedures for preparing virgin and recycled materials and testing using the repeated load triaxial test for shear strength.

2. Reference Documents

2.1 AASHTO Standards:

T 27 Standard Method for Sieve Analysis of Fine and Coarse Aggregates
M 92 Standard Specification for Wire-Cloth Sieves for Testing Purposes
T 180 Standard Method for Moisture-Density Relations of Soils
T 307 Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials

3. Apparatus

3.1 Axial Loading Device.

The axial loading device shall be capable of applying axial force to the specimen using controlled stress. The device shall be capable of applying a uniform cyclic (haversine waveform with 0.1 second pulse duration followed by a 0.9 second rest period) force above an initial static force on the piston. The device shall be capable of applying a maximum force of at least 5,000 lbf. and shall have the capability of controlling the static axial force to within ± 0.5 percent of the desired axial force and the dynamic force to within ± 1.0 percent of the desired cyclic axial force.

3.2 Axial Force Measurement Device.

The axial force measuring device shall be an electronic load cell located between the actuator and the chamber piston rod having the capability or measuring axial force to within ± 1 percent of the applied axial force.

3.3 Pressure and Vacuum Control and Devices.

The chamber, back pressure, and vacuum control devices shall be capable of applying and controlling pressures or partial vacuums to within ± 0.25 psi.

3.4 Pressure and Vacuum Measurement Devices.

The chamber, back pressure, and vacuum measurement devices shall be capable of measuring pressures and partial vacuums to within ± 0.25 psi.

3.5 Volume Change Measurement Devices.

The volume of water entering or leaving the specimen during the permeability phase of the test shall be measured with an accuracy of within ± 0.05 percent of the total volume of the specimen. The volume measurement devices shall be two burettes. One burette shall be attached to a line from the specimen cap and the other to the line from the specimen base.

3.6 Axial Deformation Indicator.

Movement of the piston relative to the top of the cell shall be measured by an LVDT (linear variable differential transformer). Axial deformation will be assumed to be the measured piston movement. The piston travel shall be measured with an accuracy of at least ± 0.02 percent of the initial height of the specimen. The LVDT shall have a range of travel of at least 15 percent of the initial height of the specimen.

3.7 Recorders.

Applied axial forces and axial deformation during repeated loading shall be recorded by electronic analog or digital recorders. It shall be necessary to calibrate the measuring devices through the recorder using known input standards. Resolution of each variable should be within the accuracy requirements for the deformation and force measurement devices (see AASHTO T 307, Notes 2 and 3 and paragraphs 6.3.3.2 and 6.7 for quality assurance/quality control requirements).

3.8 Specimen Size Measurement Devices.

Devices used to determine the height and diameter of the specimen shall measure the respective dimensions to within ± 0.001 inch. A circumferential measuring tape has been found to be the best device for measuring specimen diameters.

3.9 Triaxial Cell.

The triaxial chamber should be made of clear lucite or acrylic in order to aid in attachment to the piston to the specimen cap and to observe the specimen during testing. The chamber must be sufficiently thick to safely perform tests at cell pressures up to 100 psi. The top and bottom of the cell shall be constructed to seal the ends of the chamber and to ensure proper alignment of the loading piston with the specimen axis. The loading piston should have a minimum diameter of ¾ inch and have provision for a threaded boss at one end (for connecting the piston to the specimen cap) and a spherical surface at the other end for transferring the axial load applied by the load actuator. The connection of the piston to the top cap shall be by straight threads. A teflon washer may be used to avoid over-tightening. The top of the cell shall have a piston guide containing two linear ball bushings to maintain alignment of the piston. The piston seal may be a rubber O-ring having an unstretched inside diameter of approximately 90 percent of that of the piston. The top of the cell shall also have a vent valve to provide for quick reduction of the confining pressure. The bottom of the cell shall have an inlet through which the confining liquid is supplied to the cell and inlets leading to the specimen base and to provide for connection to the cap to allow saturation and drainage of the specimen.

3.10 Specimen Cap and Base.

Aluminum caps and bases may be used. Provision should be made for drainage of the specimen through both the cap and the base. The diameter of the cap and base should be equal to that of the specimen. Radial grooves shall be made in the cap and base to guide water passing through the plates to a central hole in the cap and base. Holes in the bearing plates should be aligned with the grooves. Bronze porous plates shall be used between the test specimen and the bearing cap and base in lieu of standard porous stones to readily facilitate both saturation and drainage.

3.11 Compaction Mold.

A split compaction mold equipped with a collar and provided with a means to attach the mold and collar to the cell base shall be used to prepare specimens. A latex membrane shall be installed and used as a liner in the mold for compaction. The mold shall be constructed so that the O-ring placed around the membrane to seal it against the specimen base will bear against an inner surface of the mold. In addition, the mold shall be constructed so the collar will be supported by a flange on the outside of the mold so a space can be made to keep the collar from bearing on the membrane after it is pulled over the top of the mold. A metal piston with a flange shall be used to complete compaction of the last layer of the specimen to ensure a flat top surface that is parallel to the bottom surface and perpendicular to the long axis of the specimen.

3.12 Membranes.

The specimen will be encased in two latex membranes. The inner membrane shall be 0.025 inch thick and have a diameter of 90 to 95 percent of that of the specimen. This membrane will form the inner surface of the mold and the aggregate will bear against it during compaction (note that this membrane will be punctured repeatedly during the compaction process, but can be used repeatedly for subsequent testing as the inner membrane). The outer membrane shall be 0.025 inch thick and have a diameter of 90 to 95 percent of that of the specimen. It will be placed around the specimen after the mold has been removed and the specimen is being supported by a partial vacuum of 5 psi. The purpose of the outer membrane is to seal holes formed in the inner membrane during compaction. Prior to placing the outer membrane around the specimen, an ice pick may be used to punch additional holes in the inner membrane to assure removal of any air trapped between the membranes. Membranes shall be sealed to the specimen cap and base using rubber O-rings having unstressed inside diameters between 75 and 85 percent of the diameter of the cap and base.

3.13 Vibratory Compactor

Vibratory compaction shall be provided using electric rotary or demolition hammers with a rated input of 750 to 1250 watts and capable of 1800 to 3000 blows per minute. The compactor head shall be at least 0.5 in (13 mm) thick and have a diameter of not less than 5.75 in (146 mm).

Anticipating that some material possess gradations, angularity and texture that may bridge the compactive efforts provided by full-sector face vibrations, use of controlled-blow modified Proctor energy (10-lb rammer with 18-inch drop) is acceptable.

4. Specimen Preparation

Specimens shall have a nominal diameter of 6 in and have a height-to-diameter ratio between 2 and 2.5. The maximum particle size shall be 1 in.

Specimens shall be compacted in six equal weight and height layers using a vibratory compaction device (or drop rammer). The top of each layer shall be scarified prior to the addition of material for the next layer.

Material for each layer shall be prepared just prior to compaction by combining air-dry gravel with previously prepared minus No. 4 sieve material batched at the water content of the minus No. 4 material in a total sample at optimum water content. Air-dry gravel for each layer shall be prepared according to the desired gradation of the gravel fraction in the total sample. Slightly more than the required wet weight of minus No. 4 material for the total specimen shall be prepared in a single batch and allowed to cure overnight prior to compaction. The required wet weight of minus No. 4 material per layer shall be based on the required dry weight and the batch water content. The combined layer weights shall be the initial wet weight of the specimen.

To prepare the specimen, place the required amount of prepared material for one layer in the mold; avoid spillage. Using a spatula, draw the material away from the inside edge of the mold to form a small mound at the center. Insert the vibrator head and vibrate the material until the required layer thickness is achieved. This may require the removal and insertion of the vibrator several times until experience is gained in gauging the vibration time that is required.

A moisture content determination will be made using leftover material after specimen preparation.

After completion of the triaxial test, the specimen will be laid flat on its side and divided into three equal portions. Moisture content will be determined for the top, middle, and bottom 1/3rd using the divided specimen. Care must be exercised to properly label each portion of the specimen. The final moisture content reading reported should include initial portion weight of the specimen to facilitate calculation of a weighted average.

5. Procedure

5.1 Specimen Measurement.

Base the initial specimen conditions on measurements taken after the mold has been removed (with a partial vacuum of 5.0 psi applied to the specimen). Take three uniformly spaced diameter measurements along the axis of the specimen and measure the specimen height at four locations.

5.2 Prior to Shear.

Assemble the cell with a completely dry specimen drainage system (cap, drainage lines, and burettes). Set the axial deformation indicator so it will have sufficient travel to perform the test and record an initial reading. Simultaneously, decrease the 5.0-psi partial vacuum acting on the specimen to atmospheric pressure while increasing the confining pressure to 5.0 psi. Air shall be used as the confining fluid for all of the testing. If the test is to be a "dry test," proceed to the consolidation phase of the test.

5.3 Seepage Saturation.

If the test is to be a "wet test," fill the burette to the bottom of the specimen with de-aired water and allow the top of the burette access to atmospheric pressure. Open valves so the top of the specimen has access to atmospheric pressure through the burette to the top of the specimen. Next, open valves so that the water in the burette will slowly enter the bottom of the specimen. Allow water to seep through the specimen until it appears in the burette to the top of the specimen. It may be necessary to refill the burette to the bottom of the specimen several times before water appears in the other burette. If the seepage process is proceeding too slowly, apply a partial vacuum of 2.0 psi to the top of the specimen. When water appears in the burette to the top of the specimen or after approximately 8 hours of seepage, close the drainage valves to the specimen and fill the burette to the top of the specimen with de-aired water.

5.4 Back-Pressure Saturation.

After filling the burette to the top of the specimen with de-aired water, open valves in the drainage system so water in the burette under atmospheric pressure has access to both the top and bottom of the specimen. The cell pressure should still be 5.0 psi. When the water level in the burette stabilizes, simultaneously increase the confining pressure and the back pressure acting on the burette to the top of the specimen in increments of 10.0 psi until the total back pressure is 40 psi and the cell pressure is 45 psi. Remember to increase the force acting on the loading piston by an amount equal to the cell pressure times the piston cross-sectional area each time the cell pressure is increased. Allow each increment of back pressure (total of four) to remain on the specimen for approximately 15 minutes. When the water level in the burette stabilizes under the total back pressure of 40 psi, proceed to the consolidation phase of the test. A falling-head permeability test may be performed prior to consolidation. Procedures for performing falling head permeability tests using triaxial test equipment are given in ASTM Test Method D 5084. There is presently no AASHTO test method for this test.

5.5 Consolidation

A single confining pressure of 15.0 psi will be used for both wet and dry tests. Dry test specimens shall be consolidated in the same manner as the standard test specimens. Wet test specimens shall be allowed to stabilize under the 15.0-psi confining pressure overnight with the specimen drainage valves closed. Drainage valves will be opened for a period of 1 hour prior to testing the wet test specimens.

5.6 Axial Loading

Repeated loads shall be applied to both wet and dry specimens in stages. Each stage, characterized by a certain deviator stress, shall consist of 1000 repetitions of axial load applied to the specimen using a haversine waveform consistent with AASHTO T307 with respect for load duration and frequency (0.1 second load duration followed by 0.9 second rest period) and control. A contact load equal to 1 psi (approximately 30 lbs for a 6-inch diameter cylindrical test specimen) shall be maintained at all times during the cyclic loading and rest/height measurement portion of the test. The triaxial cell piston rod static weight and uplift forces acting on the piston rod shall be accounted for in the design control per AASHTO T307, paragraph 8.3.2.1. Deviator stress for the first two stages will be 10 and 20 psi and will increase by 20 psi thereafter until specimen failure (see Table 1). Specimen failure is defined as reaching an axial strain of 10 percent or the load-frame limit, whichever comes first. Sufficient time shall be allowed for the specimens to stabilize between stages. Drainage valves shall remain open during repeated loading.

Table 1 – Stress Control for Repeated Load Test

Sequence No.	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	No. of Cycles	Comments
PC	15	1	10	50	Record 0-point height measurement
1	15	1	10	1000	Note A
2	15	1	20	1000	Note A
3	15	1	40	1000	Note A
4	15	1	60	1000	Note A
5	15	1	80	1000	Note A
6	15	1	100	1000	Note A
7	15	1	120	1000	Note A
8	15	1	140	1000	Note A
9	15	1	160	1000	Note A
10	15	1	180	1000	Note A, Note B

Note A: acquire data for resilient modulus determination at cycles 96-100. Obtain a height measurement following every 100 cycles.

Note B: a 5,000-pound load cell can accommodate a load equivalent to about 180 psi of axial stress on a nominal 6-inch diameter test specimen (approximately 5,110 pounds).

Control software shall be programmed such that continuous readings of the load and 2 independent LVDT's can be recorded and used to compute the resilient modulus (see AASHTO T307) at each deviator stress during cycles 96 – 100 of the 1000 cycle stress loading. A data acquisition rate of 500 data points per second shall be used to record values.

The average height recorded from 4 height measurements (Step 5.1) will be the gauge length for all strain computations. The device shall have the capability to record a baseline position value (referred to as 0-point) following 50 pre-conditioning cycles at the initial deviator stress value of

10 psi. Subsequent position values shall be acquired every 100 cycles during the performance of the test, and these values used to compute accumulated axial strain during the test.

5.7 Calculations.

The difference between the height measurement taken at the end of any 100 cycles of load and the 0-point height measurement shall be divided by the initial sample height to compute axial strain at any time during the test. When this value exceeds 10 percent, the test specimen is considered failed and the test may cease.

Calculations for resilient modulus can be performed in accordance with formulas provided in AASHTO T307.

5.8 Report.

The report shall consist of pertinent sample ID and physical characteristics of the test specimen, including but not limited to wet and dry density and moisture content (page 1), resilient modulus summary information (page 2), a plot of resilient modulus versus bulk stress fitting the bulk stress constitutive model for $M_r = K_1 \theta^{K3}$ (page 3), and plots showing axial strain accumulation during the test (page 4).

PROPOSED STANDARD METHOD OF MEASURING THE DIELECTRIC VALUE OF AGGREGATE BY THE TUBE SUCTION TEST DEVICE

1. Scope

1.1 This method covers a procedure for measuring the dielectric constant value of aggregates using the tube suction test apparatus.

2. Reference Documents

2.1 AASHTO Standards

T 27 Standard Method for Sieve Analysis of Fine and Coarse Aggregates
M 92 Standard Specification for Wire-Cloth Sieves for Testing Purposes
T 180 Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18 in) Drop

3. Apparatus

1. Molds - Standard plastic molds of 6-inch diameter and 12-inch height.

2. Soaking pans.

3. Distilled water.

4. Drill - Electric drill with 1/16-inch drill bit.

5. Sieves - 1-inch sieve.

6. Dielectric probe - A capacitance-based 60-mm diameter surface probe generating a 50 MHz electrical field between a central node and an outer ring arranged coaxially.

7. Multimeter - A hand held or bench top multimeter capable of measuring capacitance.

8. Drying oven - a thermostatically controlled drying oven capable of maintaining a temperature of 230 ± 9 ^{o}F for drying moisture samples.

9. Balances - A balance or scale conforming to the requirements of AASHTO M 231.

4. Procedure

4.1 Mold Preparation.

At 1/4 inch above the outside bottom of the mold, drill 1/16-inch diameter holes around the circumference of the mold at a horizontal spacing of 1/2 inch. This equates to 38 or 39 holes around the cylinder base. In addition, drill one 1/16-inch-diameter hole in each quadrant of the circular bottom of the mold, with each hole about two inches from the center. Weigh the mold.

4.2 Sample Preparation

1 Thoroughly dry in an oven approximately 30 pounds of the aggregate to be tested. Maintain the oven at a temperature of 230 degrees Fahrenheit.

2 After removing the aggregate from the oven, allow it to cool to a temperature at which it can be comfortably handled.

3 Sieve the aggregate through the 1-inch sieve screen and discard all material retained on the screen.

4 Mix the aggregate at optimum moisture as determined by Modified Proctor.

5 In the prepared plastic mold, compact the aggregate in four lifts of 2 inches each at Modified Proctor. Compact each lift with 50 blows. Use PVC wraps or a metal sleeve around the mold as necessary to prevent failure of the plastic walls during compaction.

6 After compaction, carefully smooth the sample surface. Remove or reposition any coarse aggregate protruding from the sample surface. Fill all large voids at the surface with fines, but avoid a full cover of fines to help preserve the uniformity of the particle size gradation throughout the sample.

7 Measure the final height of the sample and record its weight.

8 Place the sample in an oven maintained at a temperature around 100 degrees Fahrenheit for drying. Dry each sample for a minimum of 72 hours.

4.3 Sample Testing

1 Record the weight of each aggregate sample, including the mold.

2 Use the probe and multimeter set up to take six capacitance readings on the surface of each sample. Take five around the perimeter of the sample and the sixth in the center. Press down on the probe with a force of about twenty pounds to ensure adequate contact of the probe on the sample surface. Use minimal twisting as needed to seat the probe. Follow this pattern for each sample each time dielectric readings are made. The change in capacitance due to probe contact with the material under investigation is used to determine the dielectric value according to the following relationship (1):

$$\Delta C = C_a (\varepsilon_r - 1)$$

3 Where ΔC is the measured change in capacitance, C_a is the active probe capacitance, and ε_r is the dielectric value.

4 Place each sample in the empty soaking basin.

5 Use distilled water at 77 degrees Fahrenheit to fill the soaking basin to a depth of ½ inch and record the time. Maintain the water bath at this temperature throughout the testing period.

6 Take additional capacitance or dielectric readings at the recommended time intervals of 1/2 hour, 1 hour, 2 hours, 4 hours, 8 hours, 12 hours, 24 hours, and 24 hours thereafter until testing is completed. These equate to total test times of 1/2 hour, 1-1/2 hours, 3-1/2 hours, 7-1/2 hours, 15-1/2 hours, 27-1/2 hours, 51-1/2 hours, 75-1/2 hours, and so forth.

7 If the water content is also to be monitored through time, record the weight of each sample at the same or similar time intervals. Wipe the bottom of the mold dry before weighing.

8 The test is completed when the elapsed time exceeds 240 hours. Take final capacitance or dielectric readings and record the final weight.

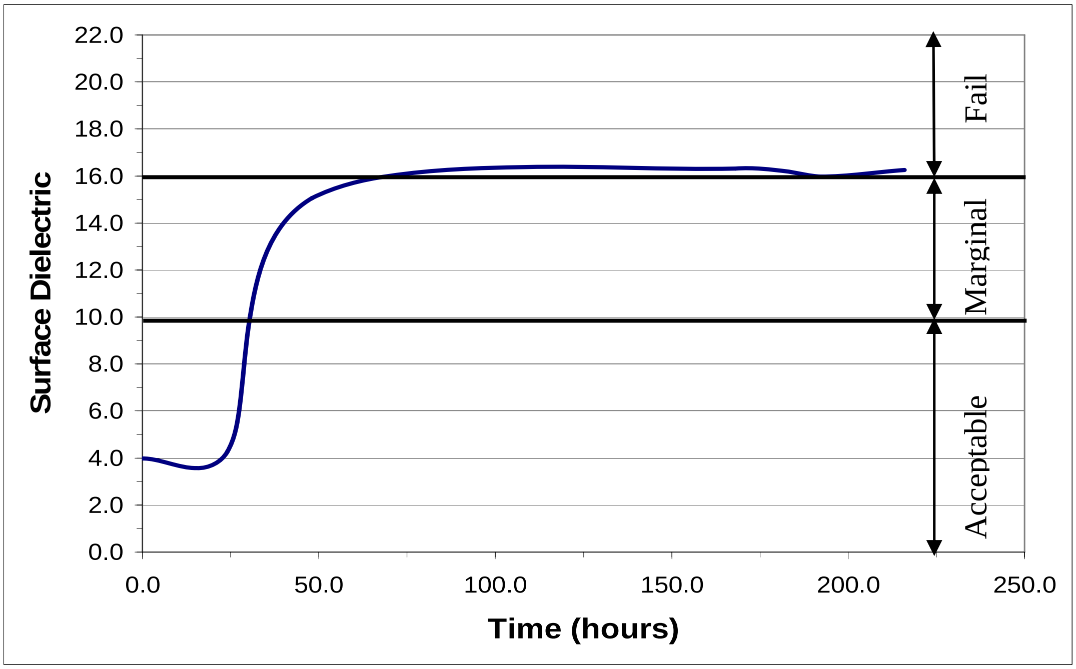
9 If the actual dry density of each sample is to be calculated, place the samples in an oven for complete drying. The oven should be maintained at a temperature of 230 degrees Fahrenheit. Record the dried weight.

5. References

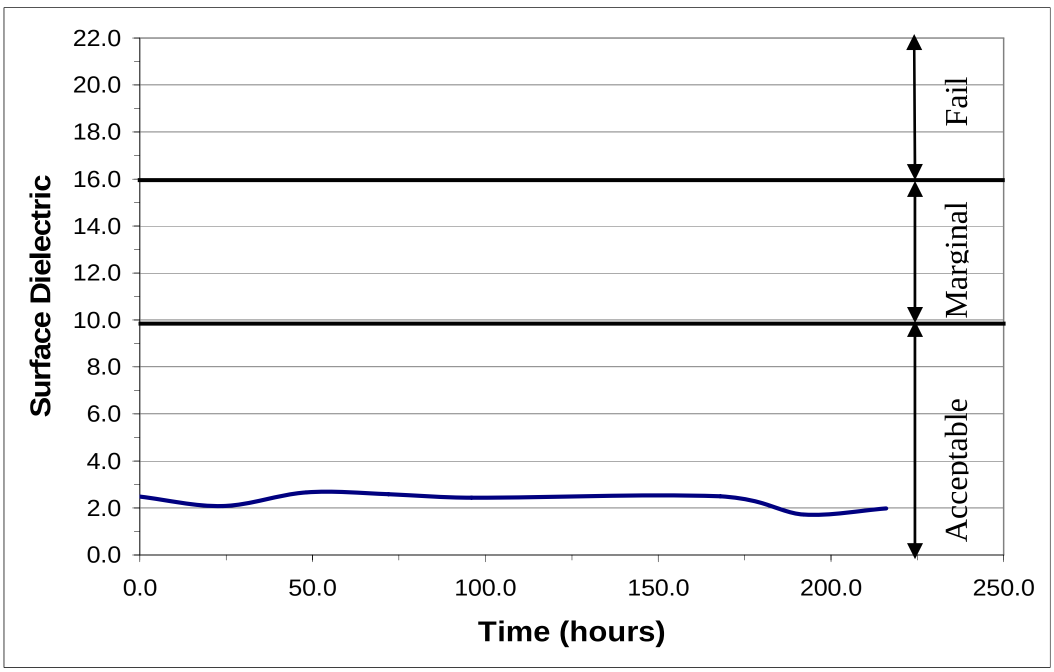
(1) Guthrie, W.S., P.M. Ellis, and T. Scullion. Repeatability and Reliability of the Tube Suction Test. In *80th Annual Meeting Preprint CD-ROM*, Paper No. 01-2486, Transportation Research Board, Washington, D.C., January 2001.

APPENDIX C

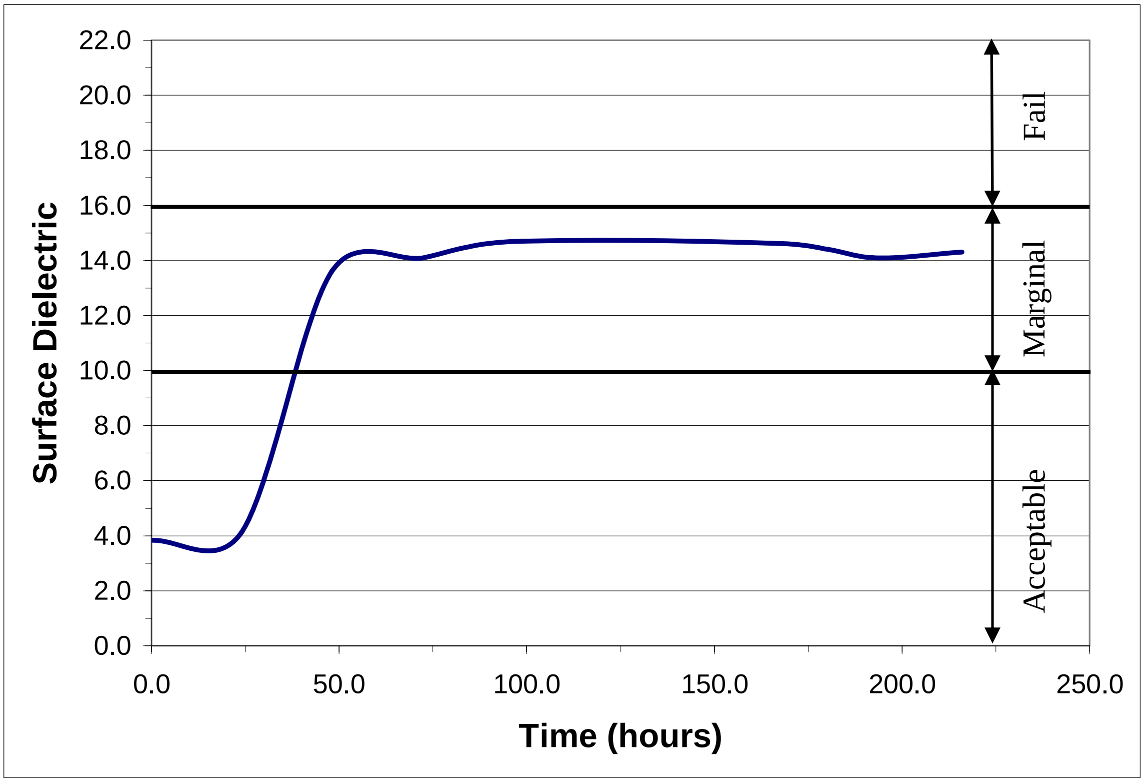
PLOTS OF SURFACE DIELECTRIC VALUES WITH TIME FOR TESTED MATERIALS



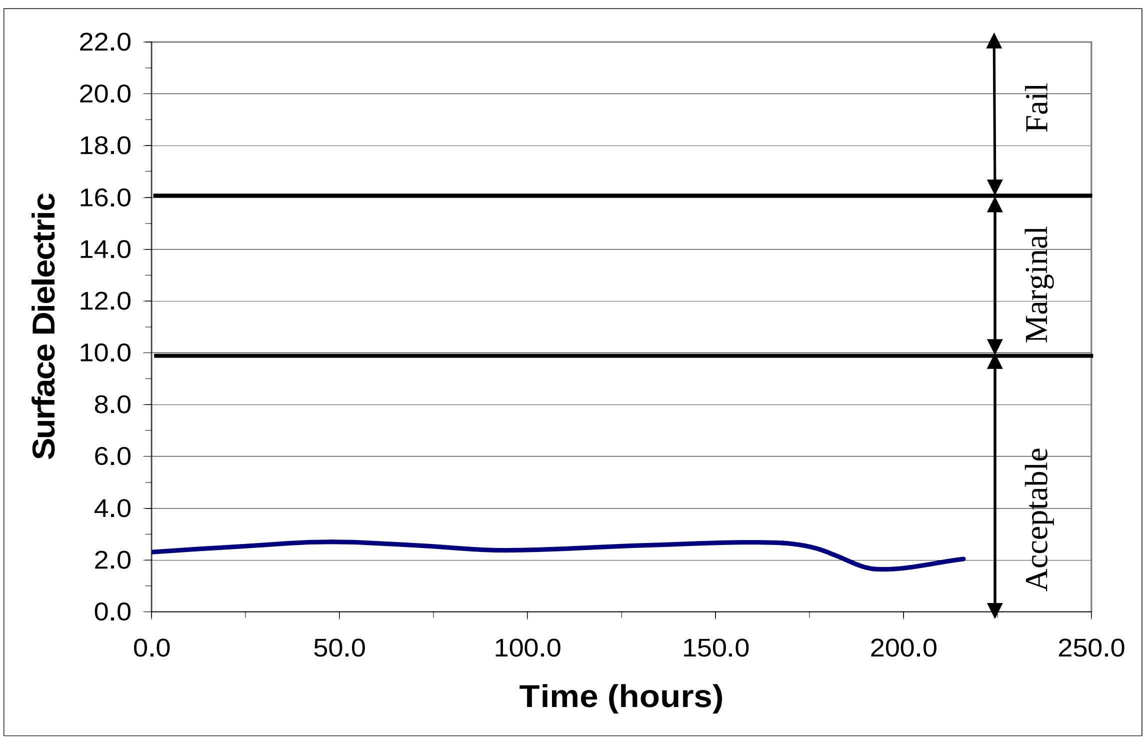
Dielectric Curve with Time for RCP-LS (IL) (#814)



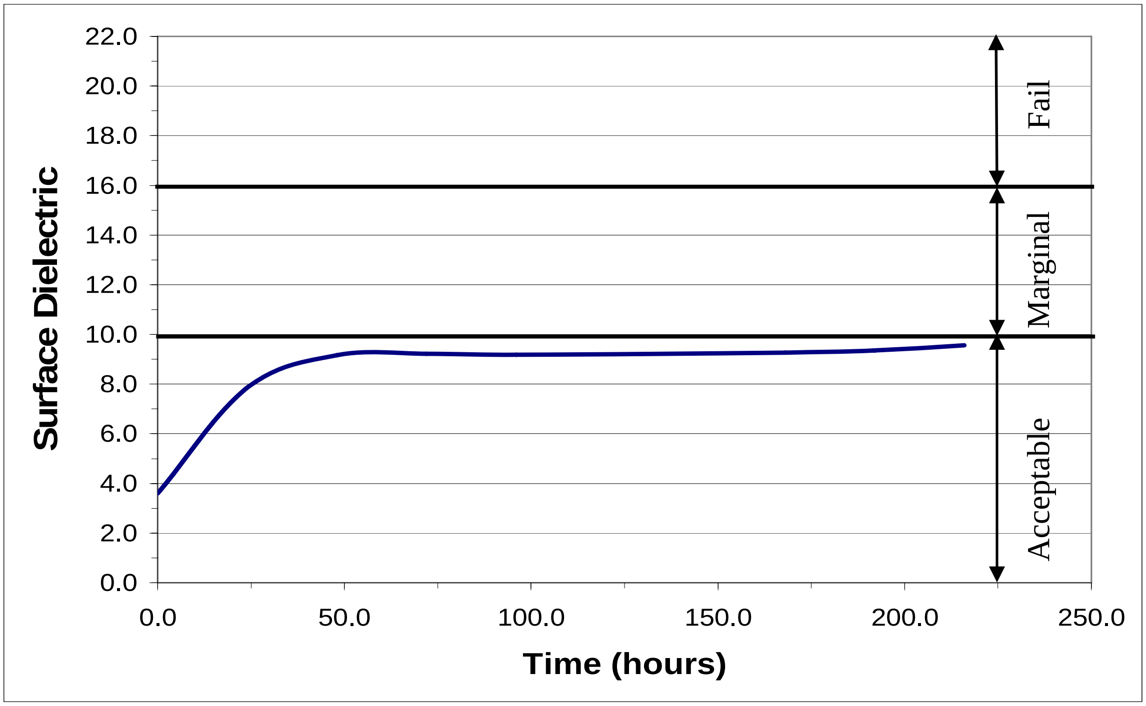
Dielectric Curve with Time for RAP-GV (LA) (#831).



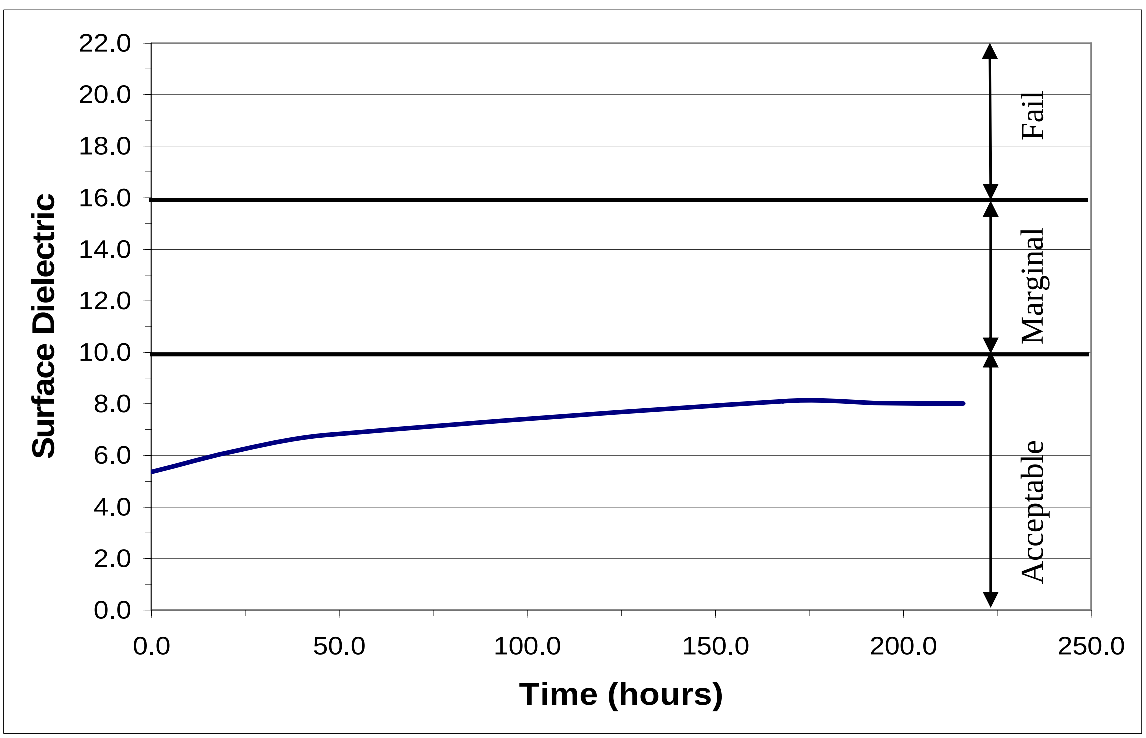
Dielectric Curve with Time for RCP-GV (LA) (#832).



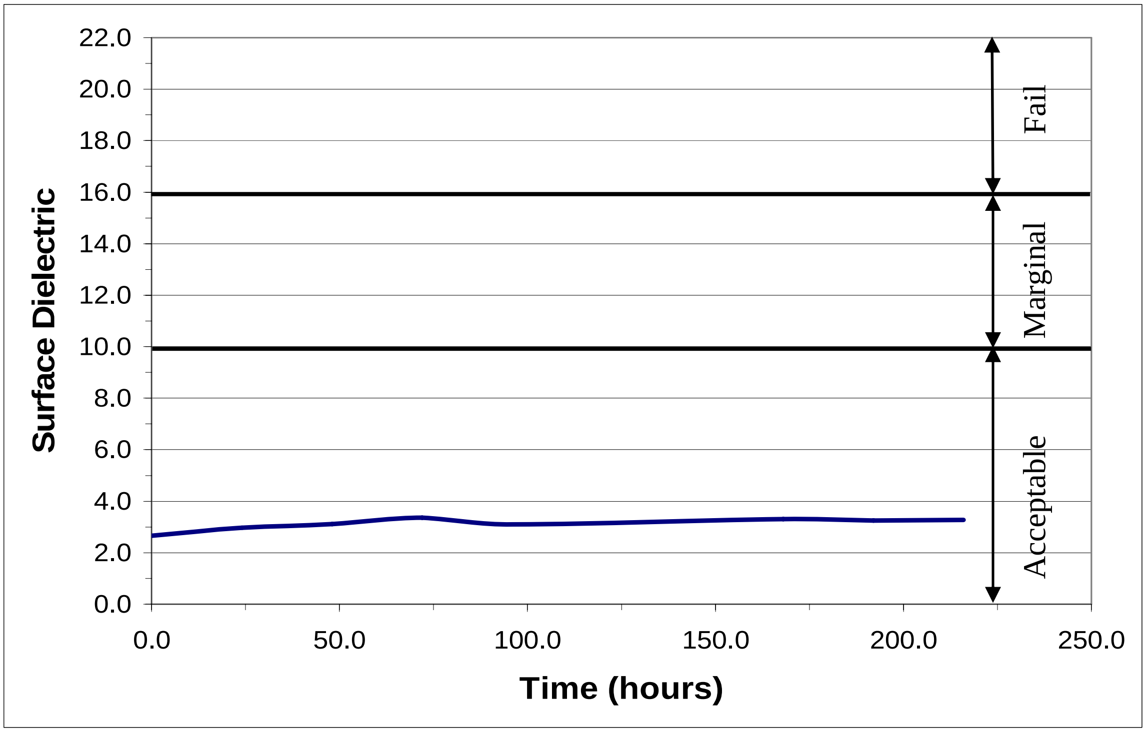
Dielectric Curve with Time for RAP-LS (MS) (#838).



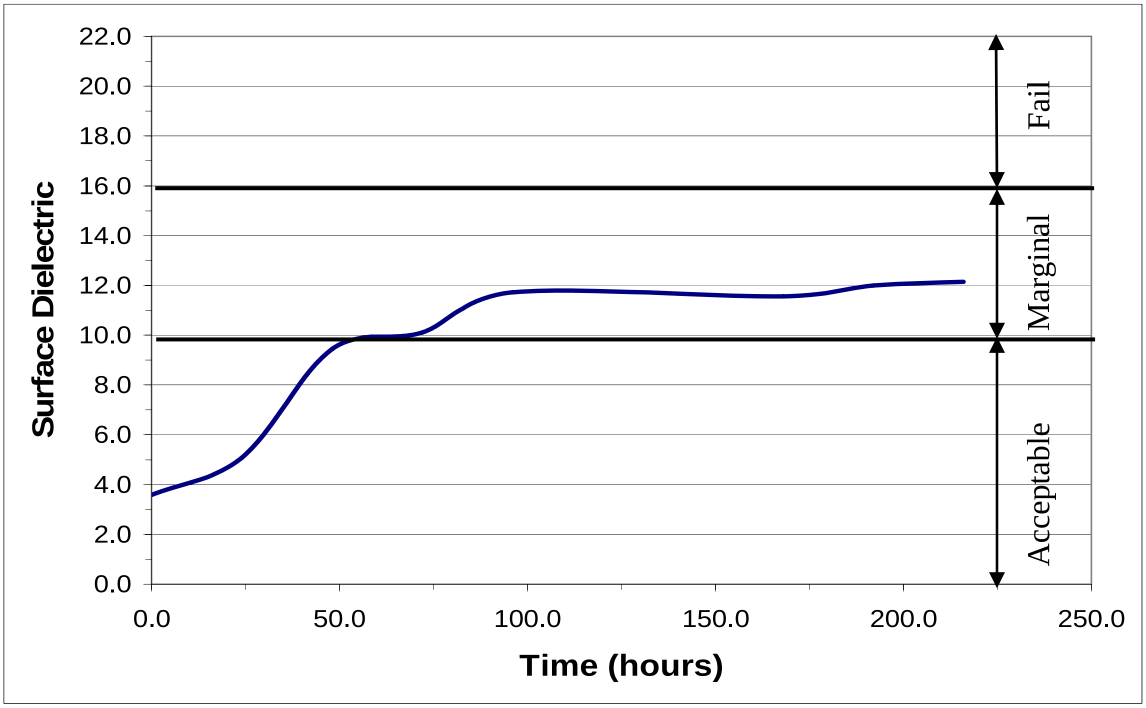
Dielectric Curve with Time for Virgin DGBL Blend 1 (#894).



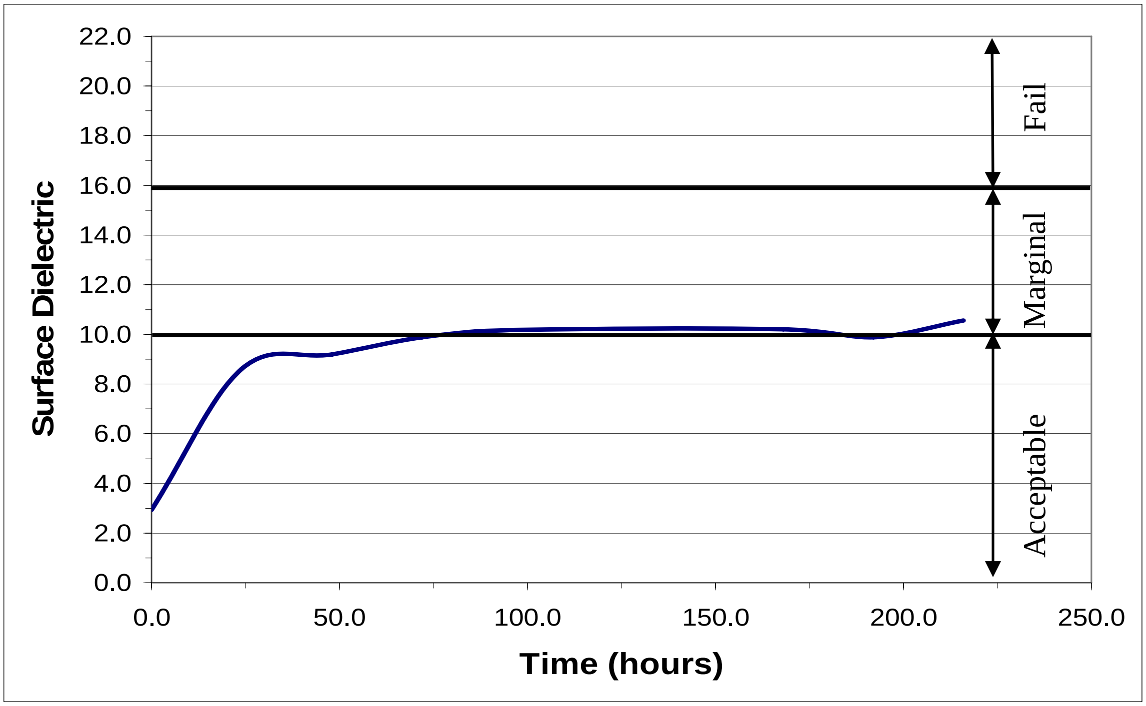
Dielectric Curve with Time for Virgin OGDL Blend (#895).



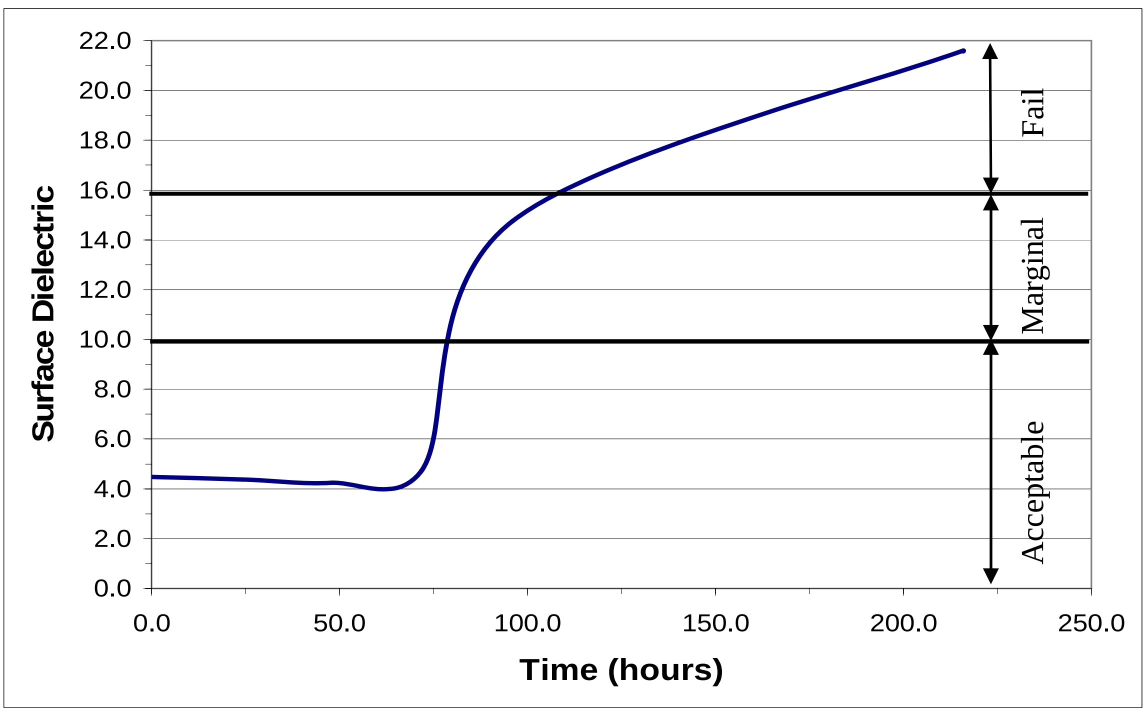
Dielectric Curve with Time for RAP-GR (CO) (#944).



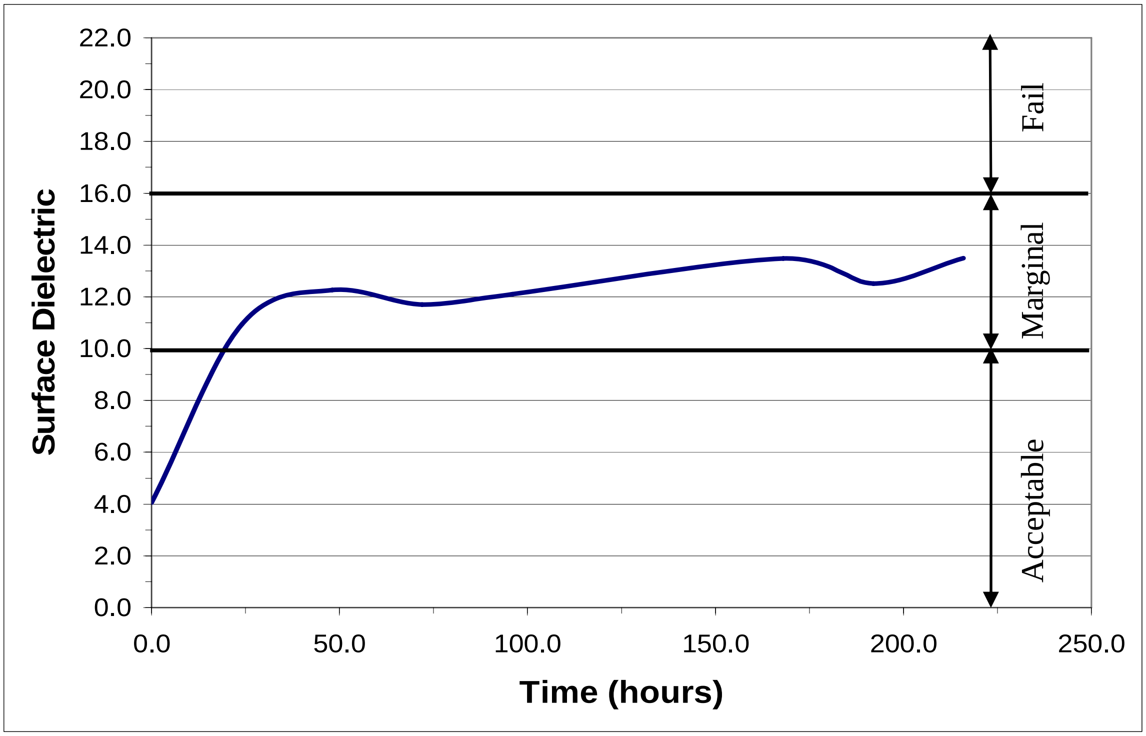
Dielectric Curve with Time for RCP-GR (SC) (#945).



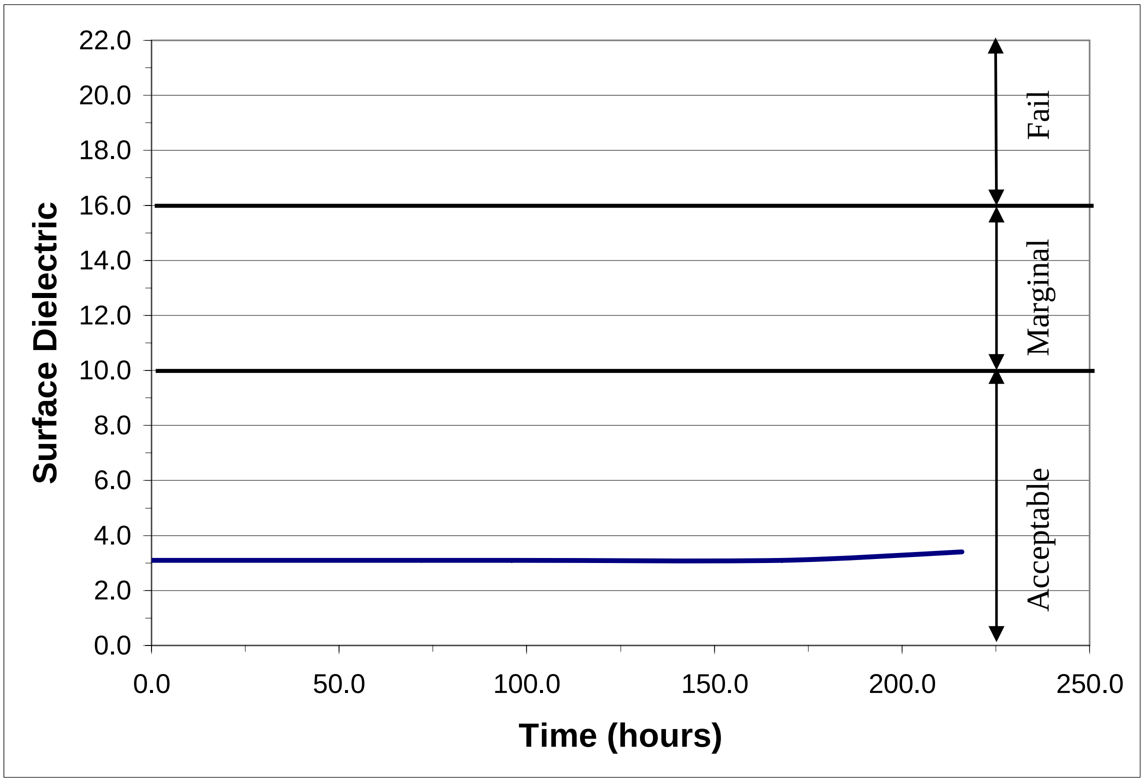
Dielectric Curve with Time for Virgin DGBL Blend 2 (#961).



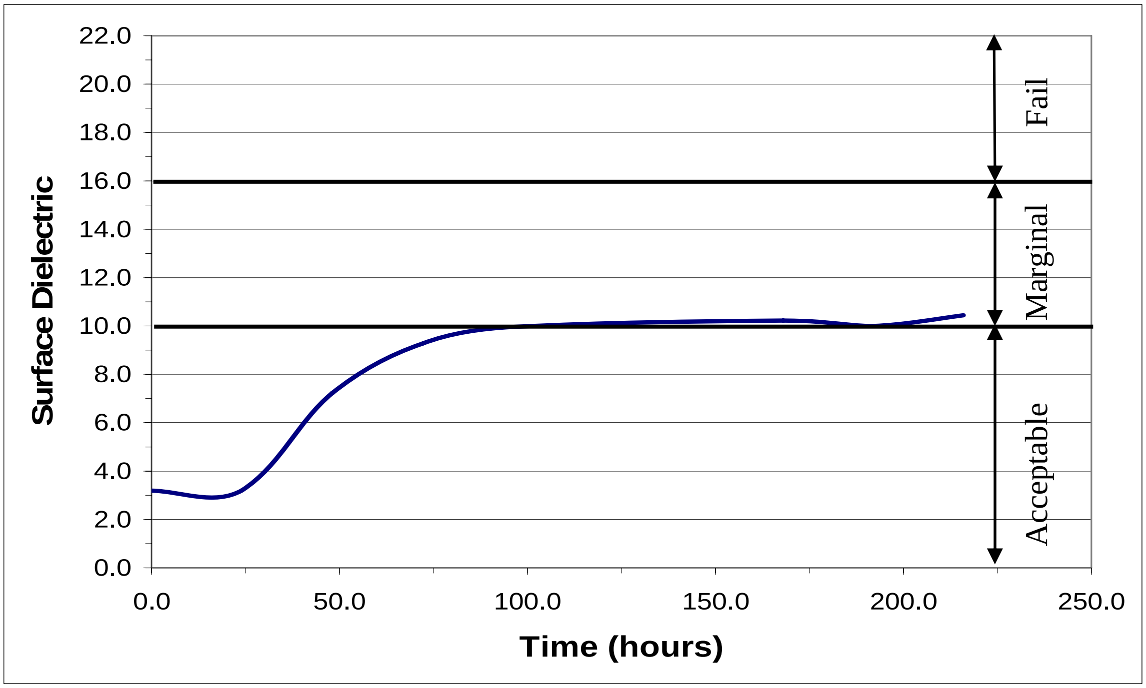
Dielectric Curve with Time for 50/50 RCP-LS (IL) (#962).



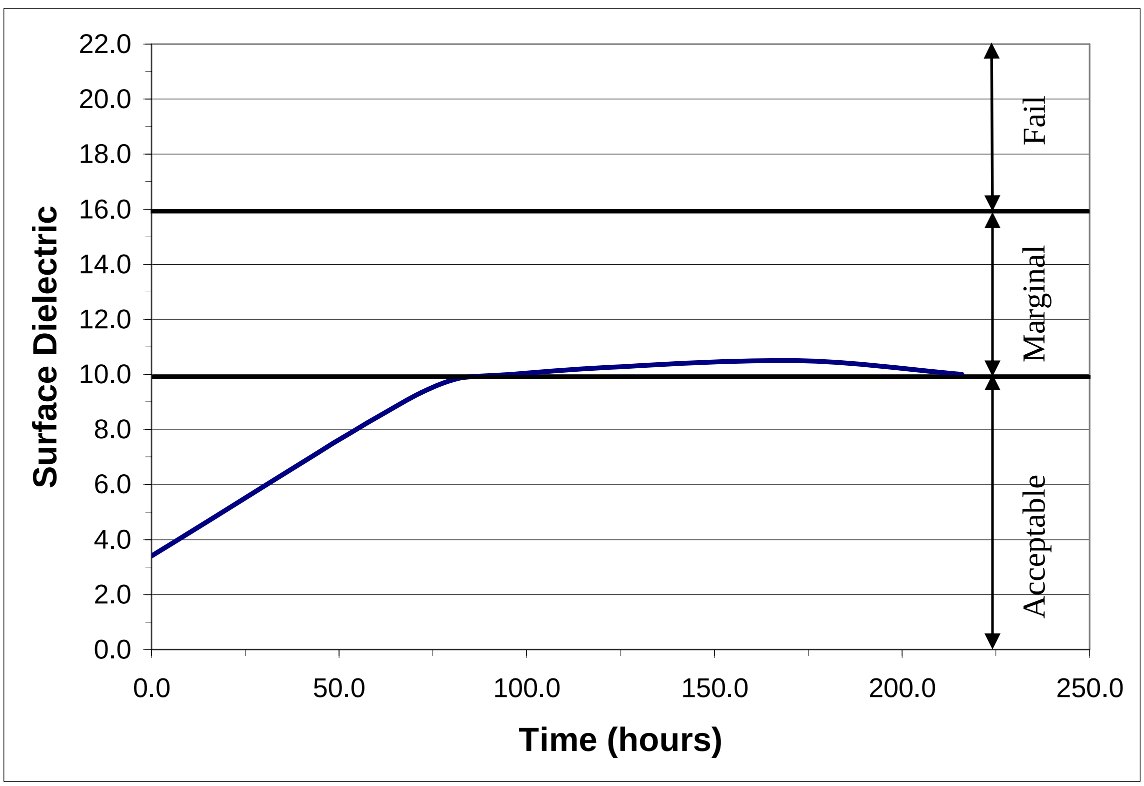
Dielectric Curve with Time for 50/50 RCP-GV (LA) (#963).



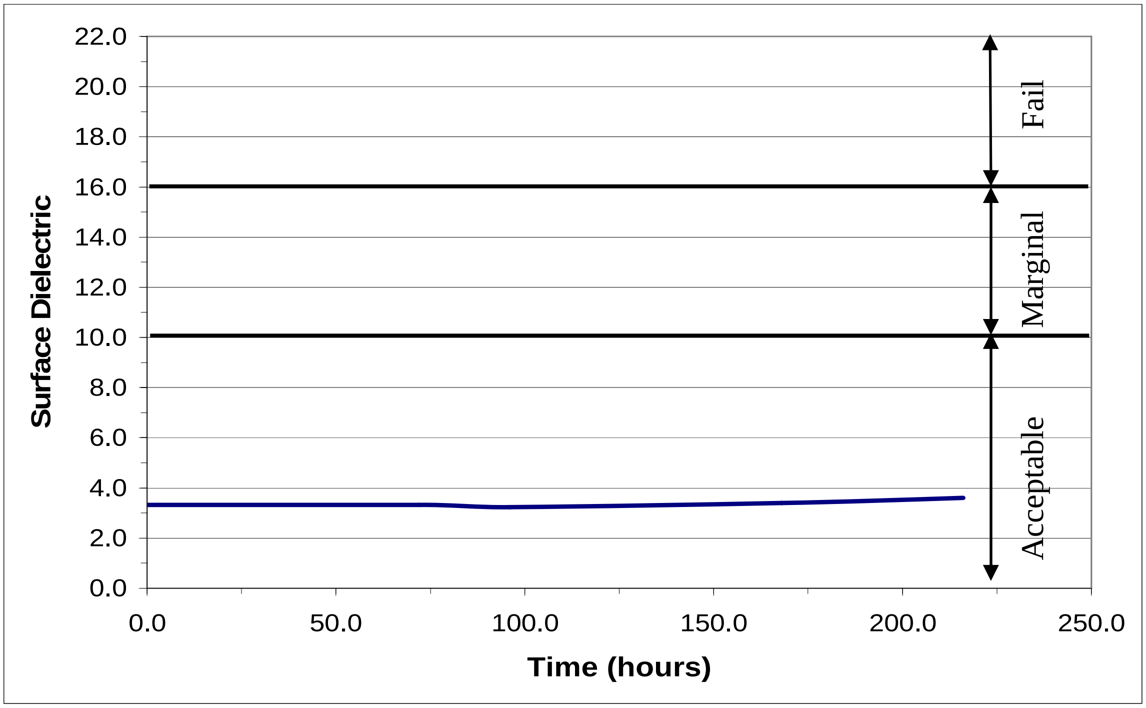
Dielectric Curve with Time for RAP-GR (CO) 100% OGDL Re-blend (#964).



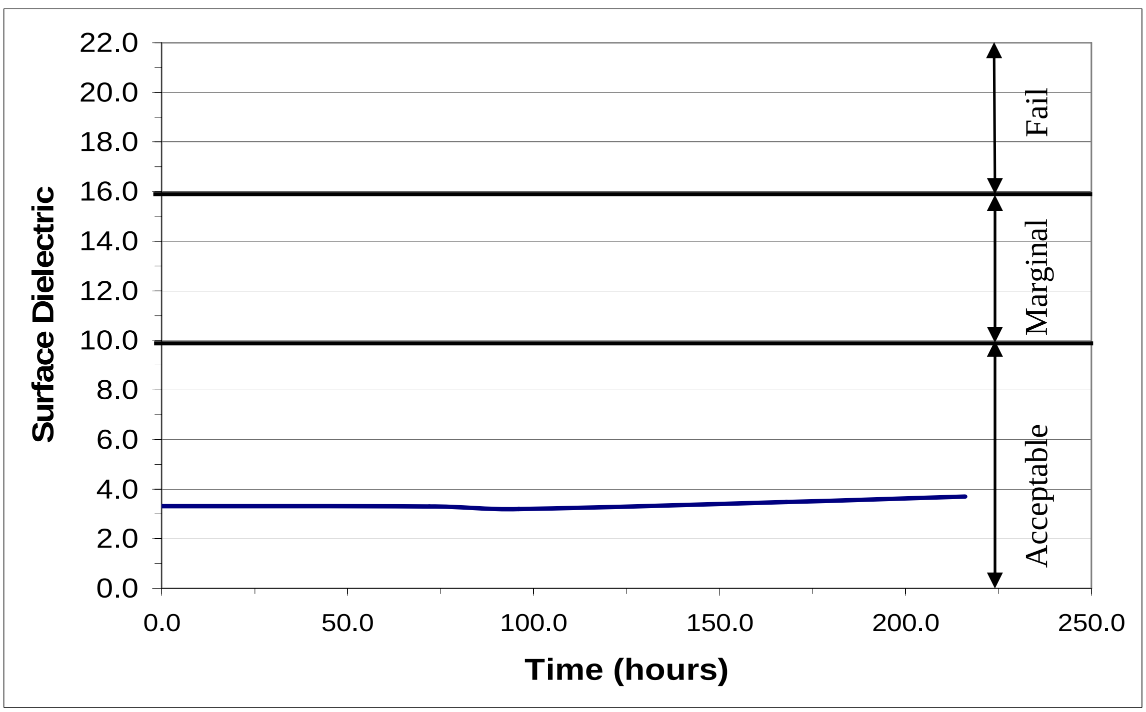
Dielectric Curve with Time for RCP-GR (SC) 100% OGDL Re-blend (#965).



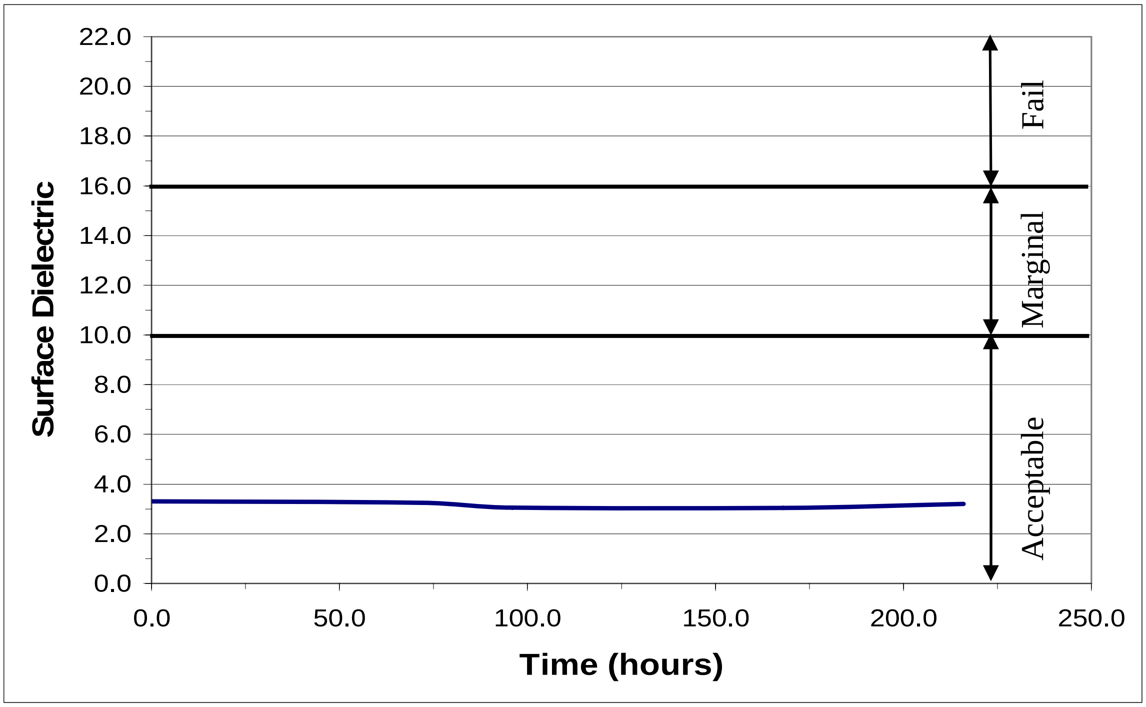
Dielectric Curve with Time for 50/50 RCP-GR (SC) (#984).



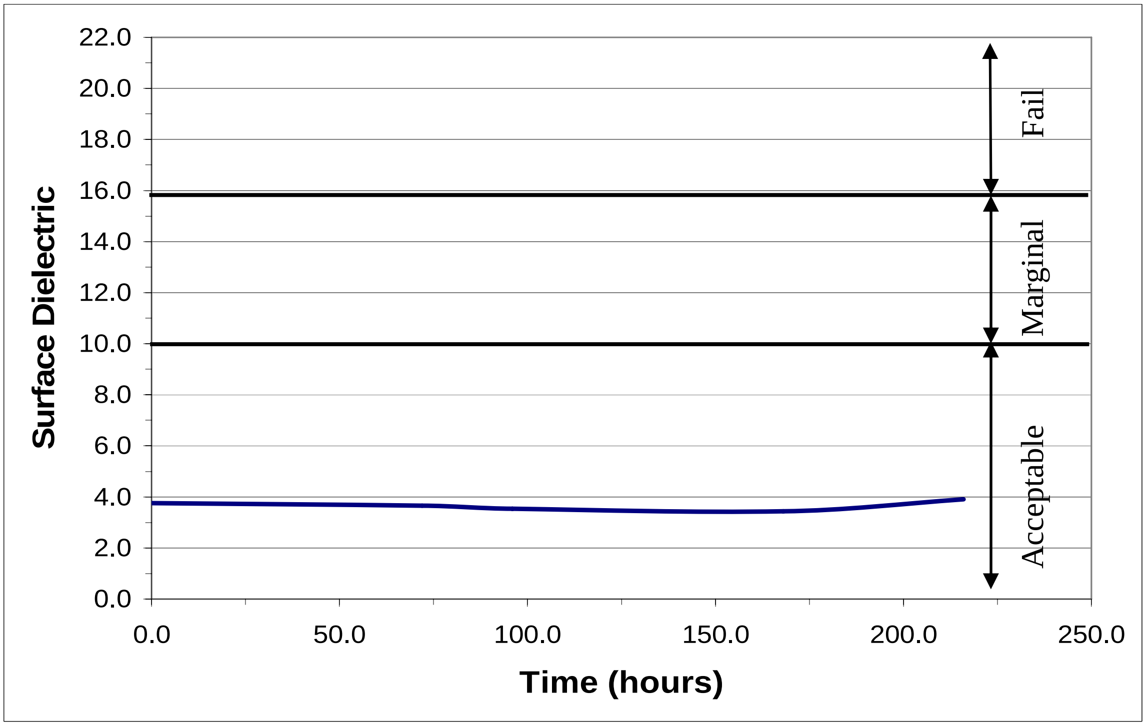
Dielectric Curve with Time for 50/50 RAP-GV (LA) (#985).



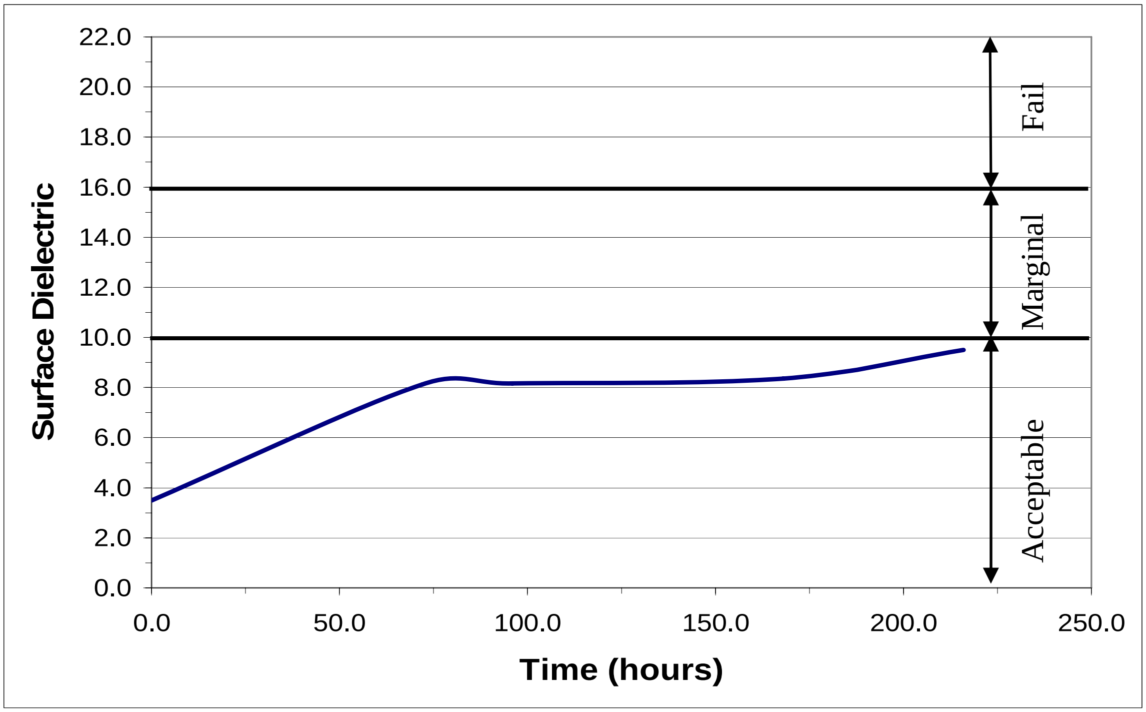
Dielectric Curve with Time for 50/50 RAP-GR (CO) (#986).



Dielectric Curve with Time for 50/50 RAP-LS (MS) (#987).



Dielectric Curve with Time for RAP-GR (CO) 50/50 OGDL Re-blend (#988).



Dielectric Curve with Time for RAP-GR (SC) 50/50 OGDL Re-blend (#989).