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Summary Report—Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results

August 2008

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Partnered Pavement Research Center (PPRC) Strategic Plan Element No. 4.16: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types

PREPARED FOR:

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DOCUMENT RETRIEVAL PAGE **Summary Report:** UCPRC-SR-2008-01

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Abstract:
This report summarizes a detailed report presenting the first and second year of field and laboratory measurements and statistical analyses and performance estimates for tire/pavement noise, permeability, ride quality, distress development, and friction properties of four types of asphalt pavement surface types used by the California Department of Transportation: open-graded asphalt concrete (OGAC), rubberized open-graded asphalt concrete (RAC-O), rubberized gap-graded asphalt concrete (RAC-G) and dense-graded asphalt concrete (DGAC). Tire/pavement noise was measured using the on-board sound intensity method (OBSI). A factorial experiment was developed and executed that considered these surface types, rainfall, traffic and age, with sections selected in the following age groups: less than one year old, one to four years old, and four to eight years old. A partial factorial was included for another type of open-graded mix, called F-mix. In addition, special sections placed by various Caltrans pilot and research projects were also included in the plan for field monitoring and laboratory testing. The report summarizes the measured performance and presents summary statistics for the results. Statistical analyses were performed, including single-variate regression to identify significant variables, multivariate regression, survival analysis, and principal components regression, depending on the type of data, in order to estimate performance. The performance models were used to estimate the life of the various surface types for the conditions in the experiment. The median noise reduction across the population included in the experiment is approximately 2 dB(A) for OGAC and approximately 3 dB(A) for RAC-O mixes compared to the DGAC mixes for the Standard Reference Test Tire (SRTT), with values converted from the *Aquatred* tire measurements used in the project. The *Aquatred* results are slightly different prior to conversion to the SRTT values, indicating slightly less noise benefit from open-graded mixes and less difference between OGAC and RAC-O.

Keywords:
Open-graded asphalt concrete, noise, OBSI, permeability, friction, ride quality

Proposals for implementation:
Continue use of open-graded mixes for noise reduction as RAC-G does not offer comparable noise reductions after the first several years of service.

Related documents:

- Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results (UCPRC-2007-03)
- Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements (UCPRC-RR-2007-13)
- State of the Practice in 2006 for Open-Graded Asphalt Mix Design (UCPRC-TM-2008-07)

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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PROJECT OBJECTIVES

The research presented in this report is part of the Caltrans Quieter Pavement Research (QPR) Work Plan. The central purpose of this research is to support the Caltrans Quieter Pavement Research (QPR) program Road Map and Work Plan with goals and objectives that address identification of asphalt pavement surfaces that are both quieter and safer. The research conforms with FHWA guidance provided to state Departments of Transportation (DOTs) that conduct tire/pavement noise research.

Results from this research are intended to identify best practice for selecting asphaltic surfaces based on performance trends identified from field measurements for noise, permeability, friction, and durability. This goal will be met after completion of the following objectives:

1. Develop a database for lifetime performance trends to identify best practice. The database is to be developed based on field and laboratory measurements of current Caltrans asphalt surface mixes. Trends will be determined for California open-graded (OGAC), rubber asphalt open-graded (RAC-O), rubber asphalt gap-graded (RAC-G), and dense-graded asphalt concrete (DGAC) mixes with regard to sound intensity, durability (as measured by amount of raveling, rutting, and cracking), friction, and permeability. Performance trends will be analyzed as a function of aggregate gradation, binder type, traffic (speed, average annual daily traffic [AADT], average annual daily truck traffic [AADTT], Equivalent Single Axle Loads [ESALs]), climate (rainfall and temperature), and roughness (International Roughness Index [IRI]).

2. Gather and summarize information on laboratory tests that are correlated with these performance measures (sound intensity, durability, friction, and permeability); gather information on mix design methods; and identify best practices that can potentially be used in California.
3. Evaluate current practice and research in other states and in Europe on the lifetime performance of their open-graded mix types with respect to sound intensity, durability, friction, and permeability. Gather and summarize performance data and identify promising mixes that can be used for the traffic and climates of California.
4. Determine whether a relation can be established between the laboratory noise absorption test performed on field cores using the impedance tube, and field sound intensity measurements.

This summary report completes the work of PPRC SPE 4.16.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	millimeters	0.039	inches	in
M	meters	3.28	feet	ft
Km	kilometers		mile	mile
AREA				
Mm^2	square millimeters	0.0016	square inches	in^2
M^2	square meters	10.764	square feet	ft^2
VOLUME				
M^3	cubic meters	35.314	cubic feet	ft^3
MASS				
Kg	kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

1 INTRODUCTION

1.1 Background

In recent years traffic noise has become a growing public concern. In recognition of this concern, design and construction of quieter pavement to reduce noise has received increasing attention in California as well as nationally and internationally over the past several years. With the short-term benefits of quieter pavements at least partially documented, recent attention has focused on developing a better understanding of their long-term acoustic benefits.

The California Department of Transportation (Caltrans) has initiated several studies to evaluate the acoustic properties of pavements and the role of pavement surface characteristics relative to tire/pavement noise levels. The research presented in this report is part of one of these studies and is an element of the Caltrans Quieter Pavements Research (QPR) Work Plan.

The Caltrans QPR study is intended to examine the impact of quieter pavements on traffic noise levels and to establish which pavement characteristics have the greatest impact on tire/pavement noise. The Caltrans QPR study is also intended to identify surface types, materials, and construction methods that will result in quieter pavements that are also safe, durable, and cost-effective. The information gathered in the study will be used to develop quieter-pavement design features and specifications for noise abatement throughout the state. For the flexible pavement part of the QPR study, Caltrans identified a need for research in the performance areas of acoustics, friction, ride quality, and durability of asphalt pavement surfaces. Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.16, titled "Investigation of Noise, Durability, Permeability and Friction Performance Trends for Asphaltic Pavement Surface Types" was initiated in November 2004 in response to that need.

1.2 Research Objectives.

The objectives of this investigation have included the following:

1. Develop a database for lifetime performance trends to identify best practice. The database is to be developed based on field and laboratory measurements of current Caltrans asphalt surface mixes. Trends will be determined for California open-graded (OGAC), rubber asphalt open-graded (RAC-O), rubber asphalt gap-graded (RAC-G), and dense-graded asphalt concrete (DGAC) mixes with regard to sound intensity, durability (as measured

by amount of raveling, rutting, and cracking), friction, and permeability. Performance trends will be analyzed as a function of aggregate gradation, binder type, traffic (speed, average annual daily traffic [AADT], average annual daily truck traffic [AADTT], Equivalent Single Axle Loads [ESALs]), climate (rainfall and temperature), and roughness (International Roughness Index [IRI]).

2. Gather and summarize information on laboratory tests that are correlated with these performance measures (sound intensity, durability, friction, and permeability); gather information on mix design methods; and identify best practices that can potentially be used in California.
3. Evaluate current practice and research in other states and in Europe on the lifetime performance of their open-graded mix types with respect to sound intensity, durability, friction, and permeability. Gather and summarize performance data and identify promising mixes that can be used for the traffic and climates of California.
4. Determine whether a relation can be established between the laboratory noise absorption test performed on field cores using the impedance tube, and field sound intensity measurements.

This summary report completes the work of PPRC SPE 4.16.

2 APPROACH

This report presents a summary of the results of the two-year research study designed and conducted to address the Objectives 1, 2, and 4 listed in Section 1.2. This report provides a summary of the results presented in Reference (1) (termed the "Source Report").

To complete Objective 3, a review of U.S. and European literature for asphalt pavement surfaces pertinent to permeability, skid resistance (tire/pavement friction), roughness/ride quality, durability, together with pavement surface, mix, and age characteristics affecting noise levels is included in the Source Report (1), and additional literature survey information is included in Reference (2). This information was used to develop the work plan for the performance database associated with Objective 1 as well as to identify promising mixes for further evaluation in projects expected to follow PPRC SPE 4.16.

A series of pavement sections from throughout the State with commonly used surface types were selected for evaluation of the characteristics listed above. These sections were subjected to a range of tests in the field, and cores were taken for laboratory tests. Results of both the field and laboratory data were subjected to statistical analyses and were used to develop models, the results of which are summarized in this report.

Information regarding the relationship between laboratory sound absorption using the impedance tube and on-board sound intensity (OBSI) measured in the field is included in the Source Report and a more detailed frequency based analysis is included in Reference (3).

2.1 In-Service Pavement Sections

The field performance studies included the following asphalt pavement surface types: (1) open-graded asphalt concrete with conventional asphalt binders (OGAC)[*], asphalt rubber binder (RAC-O), and Oregon F-type with conventional and rubber asphalt binders; (2) rubber asphalt, gap-graded (RAC-G); and (3) dense-graded asphalt concrete (DGAC). Field data were collected for two sets of test sections. The first set consisted of pavements containing all the surfacing types listed above and are referred to as QP sections. The second set of 18 sites and 23 sections consisted of sections developed by the Caltrans

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[*] The mix nomenclature used in this summary report was changed in November 2007 with the introduction of the revised Section 39, Caltrans Standard Specifications. For example, DGAC is now termed hot mix asphalt (HMA) and rubber asphalt, gap-graded is designated rubber hot mix asphalt, gap-graded (RHMA-G). For consistency with previous documents from this project, the mix nomenclature used prior to November 2007 has been used in this report.

Division of Environment Analysis (DEA) for noise monitoring and other special test sections developed for durability monitoring by other divisions of Caltrans; these have been termed the ES sections.

The QP sections were established to evaluate age, traffic, and climate effects on mix types commonly used in California. The 60 sections in this set were distributed according to mix type as follows: OGAC, 13 sections; RAC-O, 15 sections; RAC-G, 11 sections; DGAC, 16 sections; and F-type, 5 sections. They were grouped into three age categories (less than 1 year, 1 to 4 years, 4 to 8 years); two traffic categories (high, two-way AADT > 32,000; low, < 32,000), and two rainfall categories (high, average rainfall > 620 mm [24.4 inches]; low, < 620 mm).

The ES set (also referred to as the California Noise Monitoring Sites) of 23 sections included OGAC, RAC-O, DGAC, dense- and gap graded mixes with terminal blend asphalt rubber, and two special surfacings (termed bonded wearing course [BWC] and European gap-graded [a Colas product]). These sections contain ranges in: surface course thicknesses (20–90 mm); yearly precipitation (210–754 mm); temperatures (including some with freeze-thaw cycles); and AADTT (4,300–134,000).

2.2 Field Measurements

For this two-year study, data were collected twice in two years, with one rainy season in between data collections.. In each field measurement year, data were obtained both during traffic closures and at highway speeds. During the traffic closures, condition surveys and tests (permeability, friction, and air and pavement surface temperature measurements) were performed; at the same time pavement cores were also obtained. Data collection at highway speeds included: on-board sound pavement intensity (OBSI), International Roughness Index (IRI), pavement macrotexture, and air and pavement surface temperatures. Details of the test program are included in the source report.

Field test equipment included:

- Falling head permeameter (NCAT method [4]) for water permeability, shown in Figure 1;
- British Pendulum (ASTM E303) for surface friction, shown in Figure 2[†]; and
- Sound intensity car with on-board sound intensity equipment (OBSI-California Method), shown in Figure 3. The sound intensity car was also equipped with a laser profilometer to measure International Roughness Index (IRI) (ASTM E1926) and macrotexture defined by mean profile depth (MPD) (ASTM E1845), as shown in Figure 4.

[†] During friction testing thermocouples were used to measure air and pavement surface temperatures.

A circular texture meter (CTM) and dynamic friction tester (DFT) were used on some sections but were not available for use on all sections in both years, and were therefore not included in the statistical analyses.

Figure 1: Falling-head permeameter.

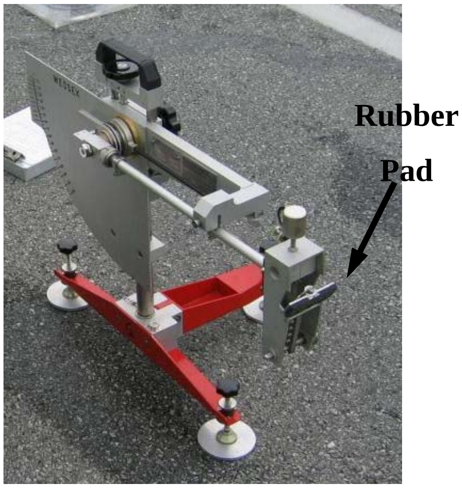

Figure 2: British Pendulum skid-resistance tester.

Figure 3: On-board sound intensity (OBSI) microphone setup.

Figure 4: Laser profilometer beam.

2.3 Laboratory Test Program

The laboratory program consisted of tests on cores obtained at the time of the field tests. In the first year of the study, 12 cores were obtained from each section, six (6) from the outer wheelpath and six (6) from between the wheelpaths. During the second year, only six cores were taken, half from the outer wheelpath and half from between the wheelpaths, immediately next to six of the previous coring locations.

Laboratory tests on cores during the first year included:

- Sound absorption using an impedance tube (ASTM E1050), as shown in Figure 5;
- Extent of clogging using computed tomography (CT Scan)[‡], as shown in Figure 6;
- Layer thickness measurements: Air-void determination based on bulk specific gravity (G_{bulk}) measurements using the Corelock® and Parafilm™ procedures and maximum specific gravity (G_{mm}) determinations using Caltrans Test Method CT 309;
- Aggregate gradations by sieve analysis (CT 202) from aggregate specimens obtained by extraction using an ignition oven (ASTM D4125).

The second laboratory test program on cores was limited to air-void content determinations as described above.

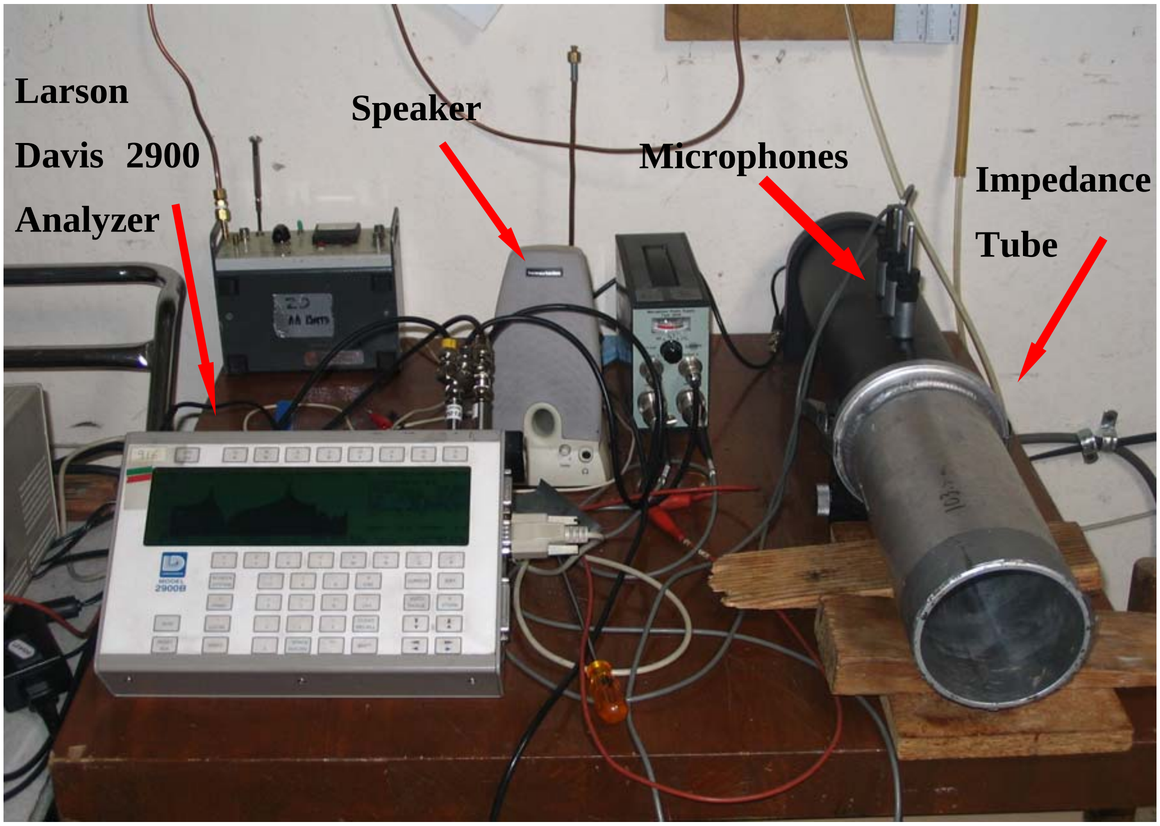

Figure 5: Impedance tube system.

[‡] The CT Scans were performed at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) by A. Ongel on cores from a reduced set of sections.

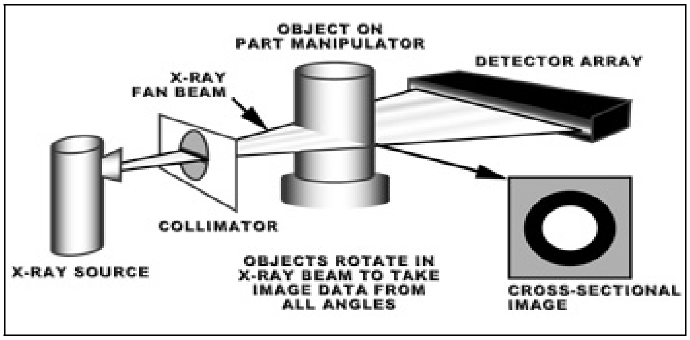

Figure 6: Computed tomography (CT) scanner (5).

2.4 Nomenclature and Analysis Procedures

Independent variables were defined from the data obtained from the field and laboratory test programs together with pavement construction, traffic, and climate information collected from various sources. Abbreviations to represent these variables were then used in a series of regression analyses considered suitable to evaluate the collected data for selected performance characteristics. Prior to these analyses, descriptive statistics for the variables, Table 2, were determined to identify the presence of skewness in the data. Also, matrix plots were used identify the multicollinearity (high degree of linear correlation) between the independent variables. These determinations were considered essential since skewness and multicollinearity may influence inferences from the regression analyses.

Selected measures of performance for the asphalt mixes included: permeability and air-void content; skid resistance (friction); roughness; and acoustical properties., The selection of key influencing factors for each of these measures of performance was based on the following: (1) summary of the expected trends obtained from the literature survey, (2) descriptive statistics for the variables, and where data were considered sufficient, and (3) statistical models.

Some examples of the statistical models used to provide the results included in Section 3 of this summary are as follows:

1. Permeability, k in a logarithmic expression, where Log k was found to be a function of age, mix type, air-void content, and fineness modulus [FM]).
2. Friction, using the British Pendulum Number (BPN), whereLog BPN was found to be a function of AADTT, age x NDT> 25°C. (AADTT is average annual daily truck traffic, age x NDT> 25°C is the interaction of years since construction and the number of days where the air temperature was greater than 25°C since construction.)

3. Roughness, in terms of International Roughness Index (IRI) expressed as 1 / (IRI)0.5 was found to be a function of rubber inclusion, age x annual rainfall, NDT > 30°C. (Rubber inclusion is whether the mix has a rubber asphalt binder, age x annual rainfall is the interaction term of years since construction and average annual rainfall, and NDT > 30°C is the number of days where the air temperature was greater than 30°C since construction.)
4. On-board sound intensity, (OBSI) was found to be a function of Log k, mean profile depth [MPD], the presence of raveling, and the mix type.

2.5 Database

The data used to prepare the report are included in a relational database delivered to Caltrans separately. Specific data in this database include:

1. British Pendulum Number (BPN) and macrotexture data including Mean Profile Depth (MPD) and Root Mean Square Profile (RMS). MPD and RMS data affect skid resistance and can be used to calculate parameters for the International Friction Index (IFI);
2. On-board sound intensity (OBSI), a measure of tire/pavement noise, corrected for air temperature, speed, and tire type;
3. Sound intensities for different frequencies;
4. Ride quality in terms of International Roughness Index (IRI);
5. Surface distresses, including bleeding, rutting, raveling, transverse cracking, and wheelpath cracking;
6. Asphalt mix data, including air-void content, permeability, aggregate gradation (calculation results), and layer thickness; and
7. Age, climate, and traffic data.

Table 2: Descriptive Statistics for the Independent Variables

Variable[§]	Mean	Standard Deviation	Minimum	Maximum	Number of Sections with Data
IRI (m/km)	1.5	0.7	0.7	3.8	71
Air-Void Content (%)	12.4	5.0	4.1	21.6	71
Mean Profile Depth (MPD) (microns)	975	328	406	1807	71
Root Mean Square (RMS)	651.4	196.1	282.3	1,121.6	71
British Pendulum Number (BPN)	57.0	7.8	41	75	72
Surface Area (m^2/kg)	23.9	8.0	10.8	45.6	70
Fineness Modulus	5.0	0.5	3.8	5.9	70
Coefficient of Curvature (C_c)	3.4	1.9	1.0	8.0	70
Coefficient of Uniformity (C_u)	21.1	14.9	2.9	58.0	70
Age (years)	3.8	2.7	0.0	13.6	71
AADTCL	9,315	7,418	1,289	29,818	71
AADTTCL	1,215	1,534	6	6,454	71
ESALs (annual)	521,890	794,199	1,000	3,481,320	71
A.A.Prec (mm)	632.0	480.5	144.5	2,105.2	71
ΔPrec (mm)	488.1	384.3	37.1	1396.2	64
Age · A.A.Prec (mm)	2,127.0	2,090.0	2.0	9,773.0	71
A.A.Wet Days	80	56.4	0.0	335.0	71
ΔWet Days	98	66.4	24	265	64
Age · A.A.Wet Days	267.4	235.4	0.0	1,007.0	71
N.D.Prec. > 10mm	65	66.9	0.0	310	71
ΔN.D. Prec. > 10 mm	12	11	0.0	43	64
Age · N.D.Prec. > 10mm	18	14.1	0.0	58	71
N.D.Prec. > 20mm	31	36.4	0.0	179	71
Age · N.D.Prec. > 20mm	9	8.8	0.0	35	71
A.A. Max D.T. (°C)	23.0	2.6	15.8	28.9	71
ΔA.Max D.T. (°C)	22.9	2.3	14.3	27.6	64
A.A. Min D.T. (°C)	8.7	2.2	4.2	13.9	71
ΔA.Min D.T. (°C)	8.2	1.8	3.9	11.9	64
N.D. T > 25°C	137	56.5	1	237	71
ΔN.D. T > 25°C	127	50	0	204	64
Age · N.D. T > 25°C	502	389.4	2	1,356	71
N.D. T > 30°C	77	51.7	0	156	71
ΔN.D. T > 30°C	71	45	0	204	64
Age · N.D. T > 30°C	285	254.0	0	877	71
A.D.D > 30°C	2,672.0	1,835.0	0.0	5,422.0	71
ΔA.D.D > 30°C	321.3	223.7	0.0	666.5	64
Age · A.D.D > 30°C	9,832.0	8,882.0	0.0	30,005.0	71
A.A.T.H.M. (°C)	31.8	4.8	18.1	38.5	71
A.A.T.C.M. (°C)	3.6	2.4	–0.4	13.9	71
Average Annual Freeze-	14	14	0	50	72

[§] Refer to the Source Report for the definitions of the variables.

Variable[§]	Mean	Standard Deviation	Minimum	Maximum	Number of Sections with Data
Thaw Cycles					
Min T (°C)	–3.59	3.36	–8.9	13.9	71
ΔMin T (°C)	–4.71	3.01	–12.8	0.0	64
Average Daily Temp Difference (°C)	14.19	1.79	8.62	17.78	71
Maximum Daily Temp Difference (°C)	26.25	3.58	15.50	32.20	71
N.D. T < 0°C	7	3.60	0	14	71
ΔN.D T < 0°C	23	17	0	63	64
N.D. T < 5°C	16	4.49	0	23	71
Surface Layer Thickness (mm)	43.8	22.1	10.4	112.5	71
Total Pavement Thickness (mm)	225.8	74.9	71.6	438.0	71
Underlying Layer Thickness (mm)	181.4	63.6	54.0	409.8	71

2.6 Addendum

Results of the sound intensity study for the two-year period reported in Reference (1) and summarized herein were obtained using an *Aquatred* tire mounted on the UCPRC noise car. At completion of the second year of testing in 2007 the *Aquatred* tire was replaced with the *Standard Reference Test Tire* (SRTT) for subsequent tire/pavement noise measurements. A study was conducted in spring 2008 to permit sound intensity results from the *Aquatred* tire used for the first two years to be converted to equivalent *SRTT* tire values. Some results of that conversion study are included as an Addendum to this summary report.

3 RESULTS

As stated at the outset, the purpose of the study has been to evaluate the performance of a range of asphalt mix types used in surface courses in terms of noise, ride quality, friction, and durability. More specifically the objectives have included:

- Evaluation of the durability and effectiveness of open-graded mixes to increase friction, minimize surface distress, and reduce noise compared to other asphalt surfaces;
- Determination of pavement characteristics which affect tire/pavement noise;
- Correlation of sound absorption and tire/pavement noise; and,
- Evaluation of the performance of a few new mixes compared to the asphalt mixes currently used in California.

The following sections attempt to briefly summarize the results of this two-year study in terms of the above objectives. None of the test sections in the experiment had extensive distresses at the end of the second year of measurements. Nearly all of the mixes included in the study had good friction values.

3.1 Performance of Open-Graded Mixes

The results showed that Caltrans open-graded mixes constructed over the past eight years (OGAC and RAC-O) reduce tire/pavement noise as measured by OBSI compared to the dense-graded mixes included in the study by almost 2 dB(A) on average for all sections over the nine-year range of ages, which, according to the literature survey, is near the limit of what the human ear can discern. Twenty-five percent of the open-graded mixes provided noise reduction above 3 dB(A) compared to the average noise level of a DGAC mix, which is 104 dB (A) for the sections tested. Over the entire set of sections including all ages, the open-graded mix noise levels were between 1 dB (A) greater and 4 dB (A) less than the average DGAC noise level. The noise levels of the DGAC mixes in the study were similar across all ages of pavement.

Noise reductions between 2 dB (A) and 6 dB (A) were reported in the literature for open-graded mixes compared to DGAC mixes. Greater noise reductions such as these are expected when new open-graded mixes are compared with older DGAC surfaces that have widespread, severe distresses. It must be remembered that the noise levels in this report were compared between open-graded mixes and DGAC mixes of similar ages.

It should also be noted that increasing air-void content, permeability, and macrotexture was found to reduce the noise levels at frequencies greater than 1,000 Hz. Since open-graded mixes have higher air-void content and macrotexture, they may reduce the noise levels at those higher frequencies. If the human ear perceives that pavements that are quieter at these frequencies are less annoying (debatable among acousticians), then open-graded mixes might be perceived as being quieter than dense-graded mixes, even though the overall A-weighted noise levels are not significantly different from each other.

Open-graded mixes exhibit higher permeability and friction than dense-graded and RAC-G mixes; therefore, they can reduce hydroplaning and spray and splash and thereby improve safety. Based on the results of the conditions surveys for pavements less than nine years old included in this study, they also may be less prone to transverse cracking. Sections with greater rainfall and with PCC below the asphalt layer are more likely to have transverse cracking. Although it could not be revealed statistically in this study, it is expected that open-graded mixes would be more prone to raveling since their high permeability would be expected to increase the oxidation rate of the binder, in comparison to the less permeable DGAC and RAC-G mixes. Overall, very few mixes showed bleeding or rutting, except for the F-mixes, three out of five of which showed bleeding. Although the data was not statistically significant in this study, rubberized mixes tended to have better cracking performance, which would be expected to slow the rate of increase in noise in later years. More significant differences in performance between OGAC and RAC-O mixes are expected as the surfaces in the experiment are measured over several more years and their deterioration becomes more pronounced.

Regression analysis of the presence of raveling confirmed the earlier findings that older sections and sections with greater rainfall and higher truck traffic are more likely to show raveling. The combined effects of rainfall, age, and traffic also increase the presence of raveling. All OGAC F-mixes showed a significant amount of raveling after eight years. Therefore, raveling is a problem for F-mixes without rubberized binders. After the second year of data collection, the oldest RAC-O F-mix (five years old) had raveled, while the two newer RAC-O F-mixes (two and four years old) had not.

Open-graded mixes lose their noise-reducing properties with time mainly due to clogging and because of the presence of distresses on the pavement surface. The model developed in this study from field data predicts their noise levels to reach those of dense-graded mixes within seven years. Clogging occurs at the top part of the surface layer and reduces its permeability. There is also some indication that thicker mixes, above 50 mm, may be less clogged and hence have higher permeabilities than thinner mixes. The longevity of benefits provided by open-graded mixes varies with mix properties, rainfall, and presence of raveling.

From this small sample of pavements in California, there does not appear to be a major difference in performance between RAC-O and OGAC mixes with respect to noise and permeability benefits across the age ranges as measured using the Aquatred tire. However, the rate of increase in IRI is slower for rubberized mixes.

3.2 Performance of RAC-G Mixes

It appears from the data that RAC-G mixes provide some noise benefit compared to DGAC mixes. Most of the noise benefits from RAC-G appear to come from the fact that they have higher air-void contents and permeabilities than DGAC mixes when they are built (compaction of RAC-G mixes included in this study followed a method specification, in which the compaction method is specified rather than a minimum relative density). Permeabilities of RAC-G mixes appear to be reduced to those of DGAC mixes within several years, likely due to compaction under traffic. In contrast, open-graded mixes lose permeability at a much slower rate, which in turn influences their noise-reducing properties. Based on the statistical analyses, the noise levels from RAC-G mixes appear to approach those of DGAC within four years. The sound intensity regression model overpredicts the noise levels of RAC-G mixes; therefore, this model cannot be used to estimate the lifetime of RAC-G mixes in terms of noise reduction.

The cumulative distributions of OBSI noise reduction compared to DGAC (104 dB(A) average across all ages) for each of the other three mixes in the main factorial are shown in Figure 7.

3.3 Variables Affecting Tire/Pavement Noise

The study showed that tire/pavement noise is significantly influenced by pavement surface characteristics including aggregate gradation, macrotexture, age, and presence of distresses. Coarser gradations and increasing air-void contents reduce the overall noise levels; the presence of distresses and increasing macrotexture and age increase the overall noise levels, confirming the previous findings of other researchers. This study found, however, that the overall A-weighted noise levels are insensitive to changes in air-void content for open-graded mixes with air-void content above 15 percent. This insensitivity occurs because air-void contents above 15 percent are usually associated with higher macrotexture (MPD) values. This study indicates that large texture depths increase tire vibrations, which increases noise levels and offsets the influence of increased air-void contents in reducing noise levels. This suggests that if air-void contents and permeabilities can be increased without using larger maximum aggregates sizes (the cause of increased MPD for this set of mixes), then overall noise levels can likely be reduced.

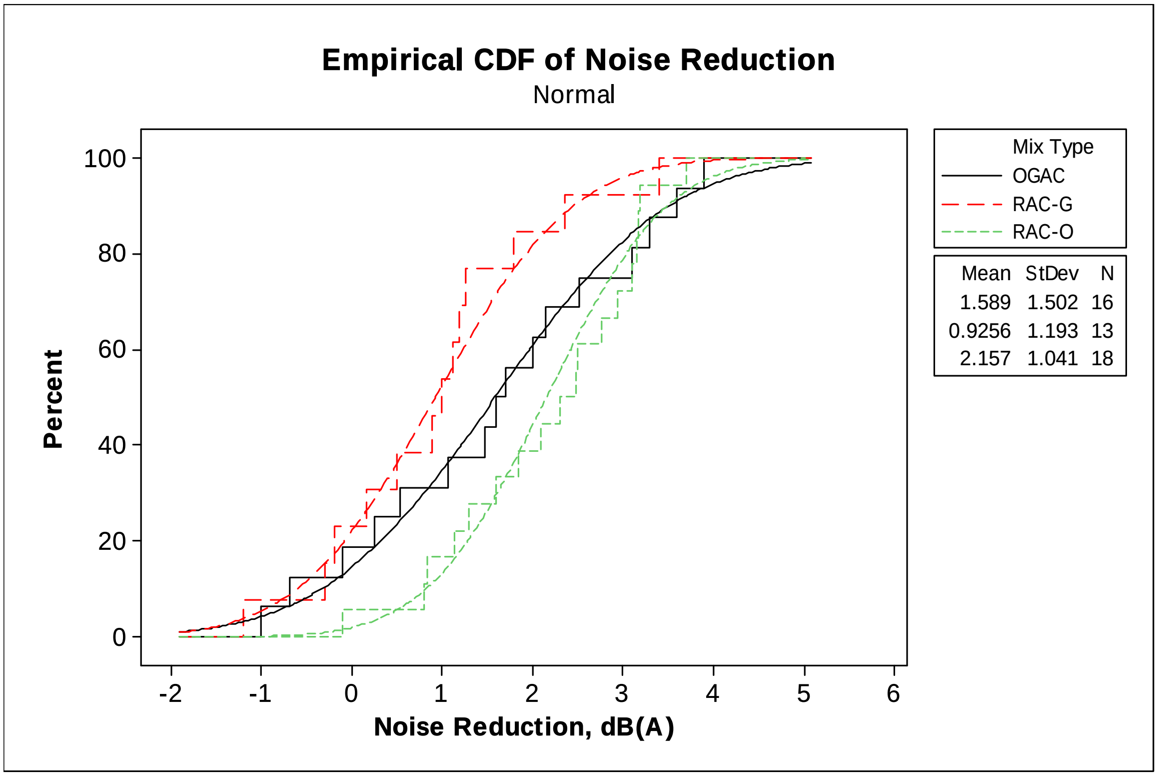

Figure 7: Cumulative distribution function of noise reduction of OGAC, RAC-O, and RAC-G mixes compared to DGAC (104 dB(A) average across all ages) across an eight-year range of ages (positive value indicates a reduction in noise).

Since California mixes are placed in thin layers (around 30 mm), thickness was not found to affect the noise levels of the sections studied. There is some indication, however, that increasing thickness may lower the noise levels for thicknesses above 50 mm (2 in.).

Pavement temperature was found not to significantly affect the noise levels. This is a very preliminary finding, since only a small number of same sections have been repeatedly tested at different temperatures.

Use of rubber asphalt binders did not significantly influence noise levels, although the noise levels of RAC-O mixes were somewhat less than those of OGAC mixes.

The low frequencies of tire/pavement noise were found to be governed by tire vibrations due to high macrotexture while the higher frequencies were found to be governed by air-pumping mechanisms that can be reduced by the presence of air voids on the pavement surface, as best measured by surface permeability. This result confirmed the findings of previous researchers on noise-generation mechanisms. However, increasing air-void content was found to increase the noise levels at a given macrotexture at lower frequencies, probably due to increased tire vibrations.

At frequencies around 800 to 1,000 Hz, where tire/pavement noise is highest; air-pumping cannot be reduced by increasing air-void content above 15 percent since tire vibrations govern the noise generation for mixes with high air-void content and high macrotexture values. This trend can also be seen in the overall noise levels. At frequencies above 1,000 Hz, however, higher air-void content and higher macrotexture values reduce the air-pumping noise. Therefore, open-graded mixes have significantly lower noise levels at frequencies above 1,000 Hz compared to DGAC.

Figure 8 provides examples of open-graded mixes compared with DGAC and RAC-G examples in each of the three age groups which illustrate the statistical findings described above. It can be seen in the figure that open-graded mixes tend to have higher noise levels at low frequencies (below 1,000 Hz) and much lower noise levels at higher frequencies (above 1,000 Hz) compared to DGAC and RAC-G mixes. As mixes age, both types of mixes increase their noise levels at both low and high frequencies, however, overall (average dB(A)) the increases in noise for the open-graded mixes are greater than those of DGAC/RAC-G resulting in similar noise levels to DGAC/RAC-G mixes after about eight years on average.

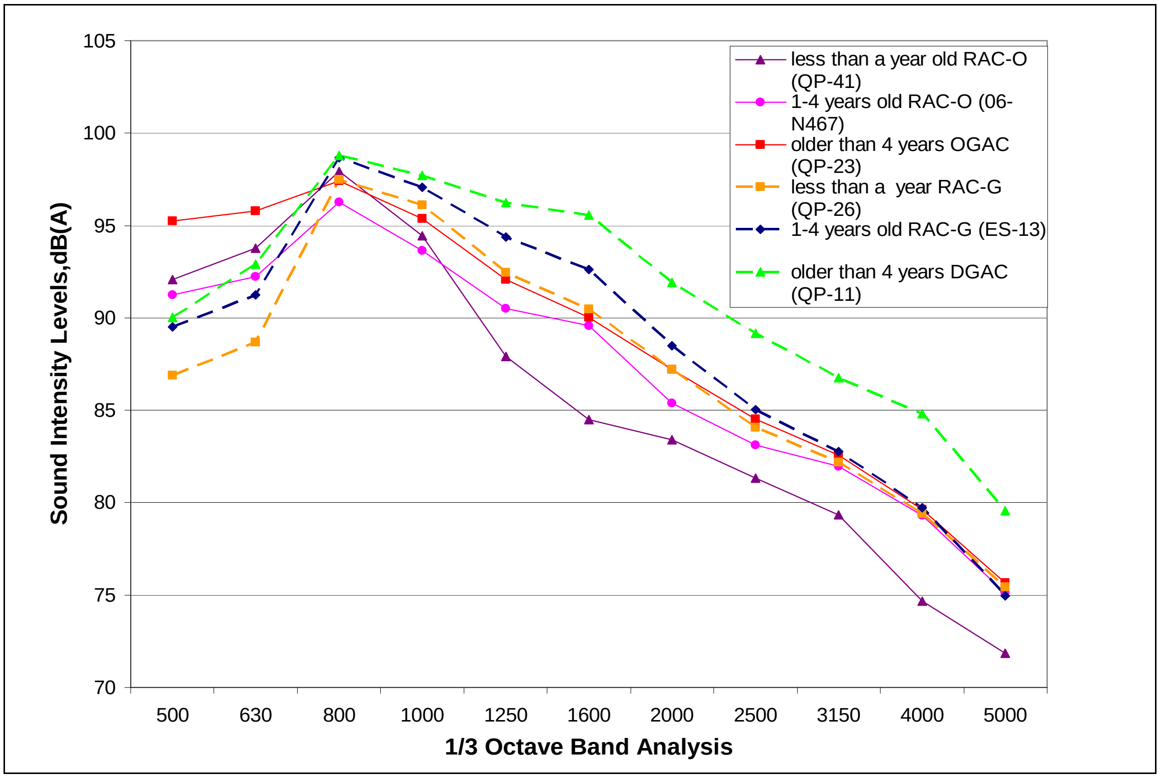

Figure 8: Example of one-third octave band sound intensity levels for different mix types at different ages.

3.4 Correlation of Absorption Values with Noise Levels

Tire/pavement noise generation and sound absorption are different phenomena, and as measured in this study, tire/pavement noise should not be affected by the sound absorption properties of the pavement surface. However, both are affected by the permeability of the pavement surface: tire/pavement noise primarily by reduction of the air pumping mechanism, and sound absorption by the passage of sound waves into the surface and the resulting attenuation and scattering of the sound energy.

In this study, the purpose of comparing tire/pavement noise (sound intensity) in the field and sound absorption in the laboratory was to determine if there were statistical correlations that would indicate whether sound absorption can be used to inexpensively screen mixes in the laboratory without having to build full-scale test sections and subject them to field measurements. It was found that the noise levels of dense- and gap-graded mixes decrease with increasing absorption. However, no correlation was found between the overall A-weighted sound intensity measured in the field and absorption measured in the laboratory for open-graded mixes. However, the extent of correlation between sound intensity (noise) measured in the field and laboratory absorption values was found to depend on frequency.

Noise levels around 500 Hz are governed by tire vibrations; therefore, absorption has no effect on the noise levels for any mix type. At frequencies above 630 Hz, absorption reduces the noise levels caused by air pumping for dense- and gap-graded mixes, and there are clear trends relating noise to absorption.

Tire vibrations may cause significant noise levels for open-graded mixes with high macrotexture values at lower frequencies (less than 1,000 Hz), and there is no trend between noise and absorption. The noise-reducing effect of absorption can be seen at 1,000 Hz for open-graded mixes, if macrotexture is also considered as shown in Figure 9. The noise-reducing effects of absorption can be clearly seen at frequencies above 1,000 Hz for open-graded mixes. Air-pumping noise governs noise generation at frequencies above 1,000 Hz, confirming the earlier findings of other researchers, as increasing absorption is correlated with the noise levels regardless of the macrotexture values. This trend is stronger for higher frequencies.

Again, it must be emphasized that the correlations between absorption and noise levels at higher frequencies is statistical and not causal because the mechanisms of absorption and tire/pavement noise generation are different. The strong statistical correlation at frequencies above 1,000 Hz is because the mechanisms of both absorption and noise are related to permeability of the pavement surface and connectivity of air-voids below the surface. This statistical correlation and understanding of the mechanisms indicates that absorption can be used as a surrogate in the laboratory for estimating field noise levels for different mixes.

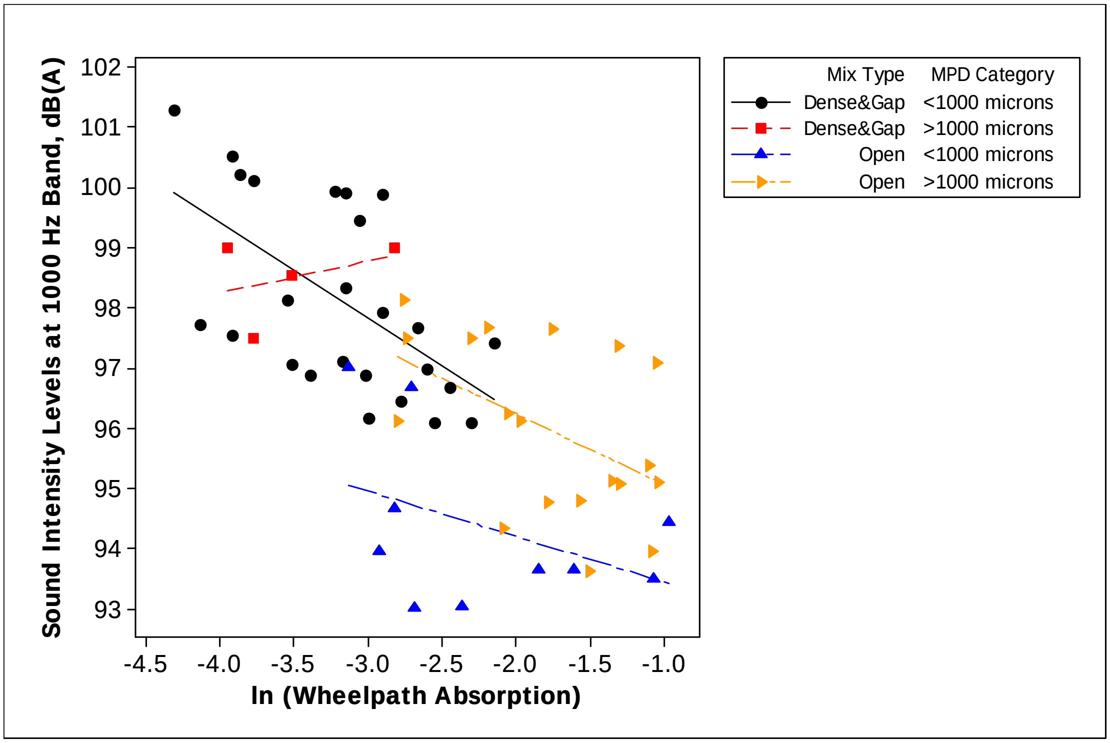

Figure 9: Sound intensity levels at 1,000 Hz band versus the absorption values for different mix types and different macrotexture values.

3.5 Performance of New Mixes

The bituminous wearing course (BWC) mix placed on the LA 138 sections exhibited lower permeability and friction, higher noise levels, and almost the same distress development as current Caltrans open-graded mixes in the LA 138 section study. Industry sources have questioned whether this BWC was representative of BWC designs elsewhere in the U.S. The answer to the question of noise levels on BWC mixes will be addressed in the third year of this study, which will include OBSI testing on additional BWC sections in California.

Based on the Fresno 33 (Firebaugh) sections, the RUMAC-GG and Type G-MB mixes did not perform as well as the RAC-G mix when placed in thin lifts (45 mm); the RUMAC-GG and Type G-MB mixes have higher noise levels and are more susceptible to bleeding. However, RUMAC-GG was more crack resistant when placed in thick layers (90 mm). Type D-MB (dense-graded aggregate with MB binder), which may be a candidate as an alternative to dense-graded mixes with conventional binders after further investigation, has performance characteristics very similar to those of DGAC mixes, and it may provide better crack resistance; however, it was more susceptible to bleeding.

The European gap-graded (EU-GG) mix placed on LA 19 has performance characteristics very similar to those of gap-graded mixes (RAC-G) used in California.

Performance of F-mixes, used only in a wet environment on the north coast, was not as good as the OGAC and RAC-O mixes in terms of noise, probably due to their large NMAS values and raveling.

3.6 Prediction of Lifetime for Different Asphalt Mix Types

The performance regression models developed as part of this study were evaluated for their effectiveness in estimating the performance variables and were then used to provide preliminary estimates the lifetimes of the different mixes with respect to the performance criteria: permeability, roughness (IRI), friction (BPN), and noise (OBSI).

It can be concluded that the permeability model can give reasonable estimates of the lifetime of open- and gap-graded mixes. The models for BPN and the one-year change in BPN do not provide good estimates of the lifetimes of the mixes in terms of BPN. This inability to provide good estimates is due to the missing variable, aggregate type, which is expected to affect the BPN values. The IRI model can give moderately reasonable estimates of the lifetime before the section no longer provides “acceptable” ride quality, here based on the FHWA criterion of 2.65 m/km (170 in/mi). The minimum lifetime predicted by the IRI model is nine years. However, some sections that are less than nine years old do not provide “acceptable” ride quality; therefore, the mixes may last less than the time estimated by the model. The reason for the difference between the actual and predicted IRI values is that the IRI of the overlay later in its life is highly affected by the IRI when originally built, which was not included in the analysis because it could not be measured. The OBSI model can give reasonable estimates of the lifetime of the open-graded mixes; however, it underestimates the lifetime of the RAC-G mixes. This underestimation occurs because the permeability model underestimates the permeability values of new RAC-G mixes and biases the OBSI model, which includes predicted permeability.

The best estimate of the time to failure of asphalt mixes in terms of permeability, friction (BPN), roughness, and noise reduction is given in Table 3. Since the regions with higher rainfall are associated with low temperatures, high rainfall and low temperatures are shown in the same cell. High rainfall is given as 800 mm and low rainfall is given as 200 mm in the models. Therefore, the actual lifetimes would be shorter than the predicted values for mixes that receive annual rainfall greater than 800 mm. Dense-graded mix performance was evaluated only for friction (BPN) and roughness (IRI); therefore, the DGAC (nonrubberized and non-open-graded mix) cells do not show any values for permeability and OBSI. Permeability is evaluated for RAC-G mixes since it is important for noise reduction. The equations used to predict the failure time were given along with the performance variables in Reference 1, the source report for this summary report.

Predicted lives greater than 9 years but less than 19 years are shown as ">9" in Table 3. Predicted lives greater than 19 years, where the extrapolation indicates very long lives, are shown as ">>19." This reporting approach was used because nearly all the sections in the data set used for the regressions are 9 years old or less.

It can be seen that OBSI controls the lifetime of the open- and gap-graded mixes. For open-graded mixes that are under high rainfall, the predicted lifetime is around seven years, and for those that are under low rainfall, the predicted lifetime is around eight years. Since open-graded mixes lose their noise-reducing properties before they lose their frictional properties and ride quality, the rubber inclusion does not provide any benefit according to the models. If the open-graded mixes are placed in low-rainfall and low-trafficked areas, the increase in MPD values would be less and the distress progression would be slower; however, under low rainfall, clogging may be greater, and the mixes would lose their permeability faster.

The OBSI model can give reasonable estimates of the lifetime of the open-graded mixes; however, it underestimates the lifetime of the RAC-G mixes. This underestimation occurs because the permeability model, which provides results to the OBSI model, underestimates the permeability values of new RAC-G mixes. Although the OBSI model predicted that the lifetime of RAC-G mixes is less than one year, the descriptive statistics of the field data showed that it usually takes about four years for RAC-G mixes to lose their noise-reducing properties compared to DGAC. The RAC-G mixes have MPD values close to those of DGAC mixes; therefore, they have the same noise levels as dense-graded mixes when they lose their permeability. Based on this reasoning it was concluded that the estimated lifetime of the RAC-G mixes is about four years, assuming they are intended as noise-reducing mixes.

Of the two performance variables used, roughness—not friction—is the one that controls the lifetime of dense-graded mixes that are under high rainfall. The predicted failure time for dense-graded mixes is nine years when they are under high rainfall. When they are under low rainfall, the failure time is 24 years for mixes that are under high truck traffic and 35 years for those that are under low truck traffic. These long predicted lifetimes are clearly extrapolations from the current data set, and are not realistic. It can be concluded that climate greatly affects the performance of all types of asphalt mixes. Note that all the sections in this study are less than nine years old and therefore predicted lifetimes beyond nine years are extrapolated and therefore suspect. Additional monitoring of these sections to failure will greatly improve the predictive capability of the regression models.

3.7 Other Conclusions

Conclusions presented herein are valid within the range of the air-void content, thicknesses, age, and gradation properties of the mixes used in this study and under California climate and traffic conditions. The OBSI measurements were conducted using an *Aquatred 3* tire and a passenger car. The conclusions may differ for trucks and vehicles with different tires because noise-generation mechanisms are highly dependent on the vehicle and tire type. Also, the OBSI method is a near-source measurement; therefore, it captures only the tire/pavement noise. Since the noise levels next to highways are also affected by noise propagation and noise absorption, the greater absorption values measured as part of this project may indicate that the open-graded mixes provide higher levels of noise reduction at the side of the highway than these results may show.

Comparison of pass-by measurements made by Volpe Center staff (unverified by UCPRC with regard to wind speeds and other factors) with OBSI measurements indicated that absorption may provide additional noise reduction next to highways since 75-mm OGAC showed higher noise reduction than dense-graded mixes when measured using the pass-by method. However, the pass-by measurements found no additional noise reduction for the 30-mm OGAC and RAC-O sections.

The effects of NMAS and thickness could not be fully evaluated. These variables have different specifications for different mix types. Open-graded mixes have NMAS values of 9.5 and 12.5 mm, and dense- and gap-graded mixes have NMAS values of 12.5 and 19 mm. F-mixes are the only open-graded mixes with an NMAS value of 19 mm. Open-graded mixes are placed in thin layers, while RAC-G and DGAC mixes are usually placed in a thicker lift. RAC-G mixes are usually placed at half the thickness of DGAC mixes as the rubber content allows for reduced thickness, providing reflection crack retardation equivalency. Therefore, NMAS and thickness effects were identified only within each mix type. Also, rubberized mixes were usually placed as overlays on pavements with more extensive cracking than those on which DGAC mixes are placed (6). Therefore, the effects of rubber on crack retardation could not be fully evaluated.

Table 3: Predicted Lifetime of Different Asphalt Mix Types with Respect to Performance Variables

Performance Variables	**High Traffic**								**Low Traffic**							
	High Rainfall/Low Temperature				**Low Rainfall/High Temperature**				**High Rainfall/Low Temperature**				**Low Rainfall/High Temperature**			
	Rubberized		**Non-rubberized**		**Rubberized**		**Non-rubberized**		**Rubberized**		**Non-rubberized**		**Rubberized**		**Non-rubberized**	
	Open Graded	**RAC-G**	**Open Graded**	**DGAC**	**Open Graded**	**RAC-G**	**Open Graded**	**DGAC**	**Open Graded**	**RAC-G**	**Open Graded**	**DGAC**	**Open Graded**	**RAC-G**	**Open Graded**	**DGAC**
Permeability (Eq. 8)	>9	–	>9	-	>9	–	>9	-	>9	–	>9	-	>9	–	>9	-
BPN (Eq. 13)	>>9	>>9	>>9	>>9	>>9	>>9	>9	>>9	>>9	>>9	>>9	>>9	>>9	>>9	>9	>>9
IRI (Eq.15)	>9	>9	9	9	>>9	>>9	>>9	>>9	>9	>9	9	9	>>9	>>9	>>9	>>9
OBSI (Eq. 18)	7	4*	7	-	8	4*	8	-	7	4*	7	-	8	4*	8	-
Minimum Lifetime	**7**	4*	**7**	**9**	**8**	4*	**8**	**>>9**	**7**	4*	**7**	**9**	**8**	4*	**8**	**>>9**

* Predicted by descriptive statistics assuming that RAC-G is intended as a noise-reducing overlay; OBSI model underpredicts noise performance and indicates less than one year of noise-reducing performance. See discussion in text.

Note: >9 indicates extrapolated life of 10 to 19 years; >>9 indicates extrapolated life greater than 19 years; equation numbers refer to equations in Source Report (1).

The effects of mix stiffness on noise levels were evaluated by comparing the noise levels of rubberized and nonrubberized mixes and by comparing shear moduli with noise levels for a few sections. A preliminary conclusion from this study is that stiffness does not play a major role in determining noise levels for mixes which were included in the limited data set.

4 RECOMMENDATIONS

Based on the evaluations made in this study, neither of the other asphalt mix types—DGAC and RAC-G—can provide an alternative to current Caltrans open-graded mixes in terms of noise reduction and safety. Durability of open-graded mixes with respect to surface distresses compared to DGAC and RAC-G depends on the climatic conditions and traffic.

The results indicate that the current recommendation for the best approach to noise reduction is to use thin layers of open-graded mixes with nominal maximum aggregate sizes of 12.5 or 9.5 mm. The smaller aggregate sizes will somewhat reduce air-void content and permeability; however, open-graded mixes with smaller aggregate sizes will likely have greater durability because of their lower air-void content and will likely cost less than open-graded mixes with larger aggregate sizes because they can be constructed as thinner lifts. The results indicated that the desired air-void content for open-graded mixes for noise reduction could be limited to a maximum of 15 percent since higher air-void content does not provide any additional noise reduction and reduces durability, according to the results obtained in this study.

There do not appear to be noise-reduction benefits from increasing the thickness of open-graded mixes for thicknesses less than 50 mm. However, the results gave some indication that thicknesses greater than 50 mm (2 inches) reduce noise. Placing open-graded mixes in thicker lifts would also help reduce the IRI value and increase cracking resistance for overlays of PCC. The results also gave some indication that thicker lifts may be less susceptible to clogging.

Open-graded mixes have longer lives in terms of noise and permeability, with lower levels of truck traffic and rainfall. High truck traffic increases clogging, and mixes under low rainfall are also more susceptible to clogging, although they are less likely to show raveling and polishing. When designing and placing open-graded mixes, the air-void content and thickness will need to be balanced with the permeability requirements needed to reduce hydroplaning for a given site.

Overall preliminary recommendations for open-graded mix design based on the results of this study are shown in Table 4. These recommendations are also the basis for recommendations for further work to improve the performance of open-graded mixes, discussed in the next section of this report.

Table 4: Preliminary Recommendation for Open-Graded Mix and Thickness Design to Achieve Performance Goals

	Performance Criteria (relevant section of report)				
Mix and Thickness Design Variables	**Noise**	**Permeability**	**Durability**[**]	**Ride Quality**	**Friction**
Air-Void Content	15 percent or greater	Maximize*	Minimize		Maximize
Nominal Max Aggregate Size	Minimize	12.5 mm instead of 9.5 mm			Maximize
Gradation	Greater fineness modulus (coarser gradation)	Greater fineness modulus (coarser gradation)			Greater fineness modulus (coarser gradation)
Binder Type			Rubberized	Rubberized	
Overlay Thickness	Greater than 50 mm may help				

[*] Permeability recommendations should be based on expected rainfall events for a particular project location. Development of these criteria are outside the scope of this project.

[**] Durability is defined as resistance to distress development. Few sections had significant distresses, and results were not statistically significant. Recommendations regarding durability are based on judgment as well as the results of this study.

5 RECOMMENDATIONS FOR FURTHER INVESTIGATION

In this study, pavement characteristics and noise were observed for two years. However, two years is a short time to observe any trends. Therefore, permeability, friction, IRI, and sound intensity measurements and condition surveys should be conducted on the given sections for at least two or three more years to develop better time histories and to see more sections reach failure. At this time, funding has been committed by Caltrans for two more years of measurement on the asphalt mix sections and updating of the models and performance predictions based on the four years of results. A similar study, funded for two years, will be performed on concrete surfaces.

Open-graded mixes have lower noise levels than dense- and gap-graded mixes at higher frequency levels, which may be a benefit that A-weighted measurements do not capture well in terms of annoyance rather than audibility. Since the human ear may be more sensitive at frequencies between 1,000 and 4,000 Hz, the open-graded mixes may be perceived as quieter than dense-graded mixes with the same overall noise levels. The noise levels should be correlated with the human perception of annoyance to better evaluate noise-mitigation strategies.

Since the reason for placing open-graded mixes is to reduce the noise levels next to highways, the way-side measurements should be better correlated with OBSI levels than was possible in this study to understand the actual noise reduction provided by open-graded mixes.

At 500 Hz, increasing air-void content was found to increase noise levels along with macrotexture; however, the noise-generation mechanism is unknown. The further effects of air-void content on noise levels at lower frequencies should be evaluated. In addition, a new parameter that correlates better with the sound intensity levels should be developed. This parameter can be a combination of MPD, RMS, and air-void content as well as a new measure of macrotexture.

The results gave some indication that open-graded mixes with coarser gradations (greater fineness modulus) may provide lower noise levels, particularly at higher frequencies of noise. In this study, only a few open-graded mixes had fine gradations. The effects of fineness modulus on the noise levels should be further evaluated, particularly for mixes with the same NMAS.

This study could not fully evaluate the effects of NMAS and thickness on pavement performance. Therefore, a laboratory study should be performed to consider the durability, sound absorption (correlated with high-frequency noise), and permeability for a full factorial experiment considering these variables. Some optimization of the mixes based on initial results should also be performed. Since the presence of polymer-modified binders could not be identified for the OGAC sections in this study because of a lack of reliable as-built records for many sections, polymer and conventional binders, as well as rubberized binders used by Caltrans, should also be included in the factorial. Macrotexture should also be measured, since the results indicate that absorption and macrotexture provide an indication of noise at 1,000 Hz.

The results of the laboratory study will provide a basis for designing a factorial for field-test sections to verify the laboratory results regarding the effects of thickness, NMAS, fineness modulus, and binder type on clogging, cracking, and noise levels. Permeability and noise measurements as well as condition surveys should be conducted on these test sections. The air-void content should also be measured using CT scans with a higher resolution than used in this study. A resolution around 15 microns (based on the results of this study) would be enough to see fine particles clogging the mix. The effects of pavement temperature on noise levels were evaluated measuring nine sections at three temperatures. No correlation was found between pavement temperatures and noise levels. A larger data set, with open-, gap-, and dense-graded mixes, should be obtained, and measurements should be conducted using a wider range of pavement temperatures. It would be useful to analyze the effects of pavement temperature on noise levels separately for each mix type

REFERENCES

1. Ongel, A, Harvey, J. T., Kohler, E., Lu, Q., and Steven, B.D. *Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types First and Second year Results.* UCPRC-RR-2007-03. University of California Pavement Research Center, Davis and Berkeley, CA, February 2008, 343 pp.
2. Ongel, A., Harvey, J., and Kohler, E. *State of the Practice in 2006 for Open-Graded Asphalt Mix Design.* UCPRC-TM-2008-07. Draft technical memorandum prepared for Caltrans by the University of California Pavement Research Center. December 2007.
3. Ongel, A., Kohler, E., and Nelson, J. *Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements.* UCPRC-RR-2007-13. Draft research report prepared for Caltrans by the University of California Pavement Research Center. July 2007.
4. Cooley, Jr., L. A., E. R. Brown, and S. Maghsoodloo. *Development of Critical Field Permeability and Pavement Density Values for Coarse-Graded Superpave Pavements.* NCAT Report No. 01-03. National Center for Asphalt Technology, Sept. 2001.
5. Industrial Computed Tomography.www.bioimaging.com, Industrial_Computed_Tomography.asp
6. Lee, C., Nokes, C., and Harvey, J. *Performance of Pavement Preservation Treatments (1988 to 2003).* UCPRC-TM-2007-05. Draft research report prepared for Caltrans by the University of California Pavement Research Center. November 2007.

ADDENDUM

Additional Analyses

It was noted earlier that an *Aquatred* tire was used for the OBSI measurements during the two years of study. In spring 2008 a study was developed for the UCPRC noise car to permit results from the *Aquatred* tire to be converted to equivalent Standard Research Test Tire (*SRTT)* tire values. These results are shown in Figure A1. The less aggressive *SRTT* tire indicates that RAC-G has noise levels only slightly less than those of OGAC, and RAC-O has lower noise levels than both. These results are somewhat different from the results with the *Aquatred* tire used previously.

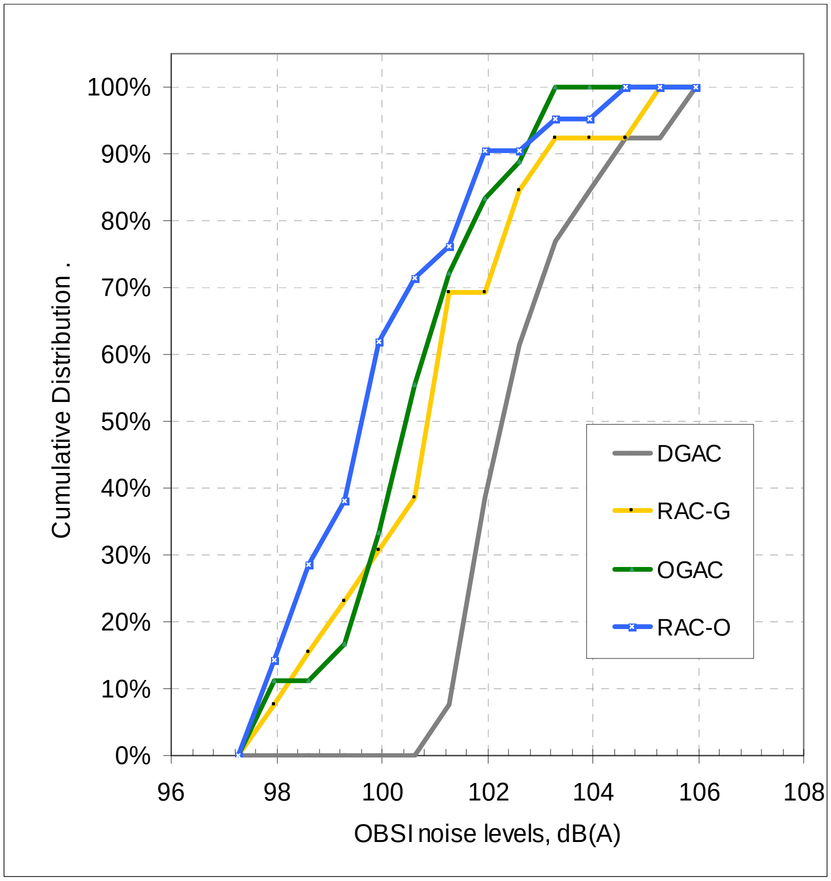

Figure A1: Cumulative distribution of second year OBSI (SRTT tire) for all four mix types.

The data in Figure A1 were obtained from analyses in which the mixes were organized by mix type and then sorted by noise level as seen in Figures A2. For an additional perspective the influence of age for each mix type is shown in Figure A3.

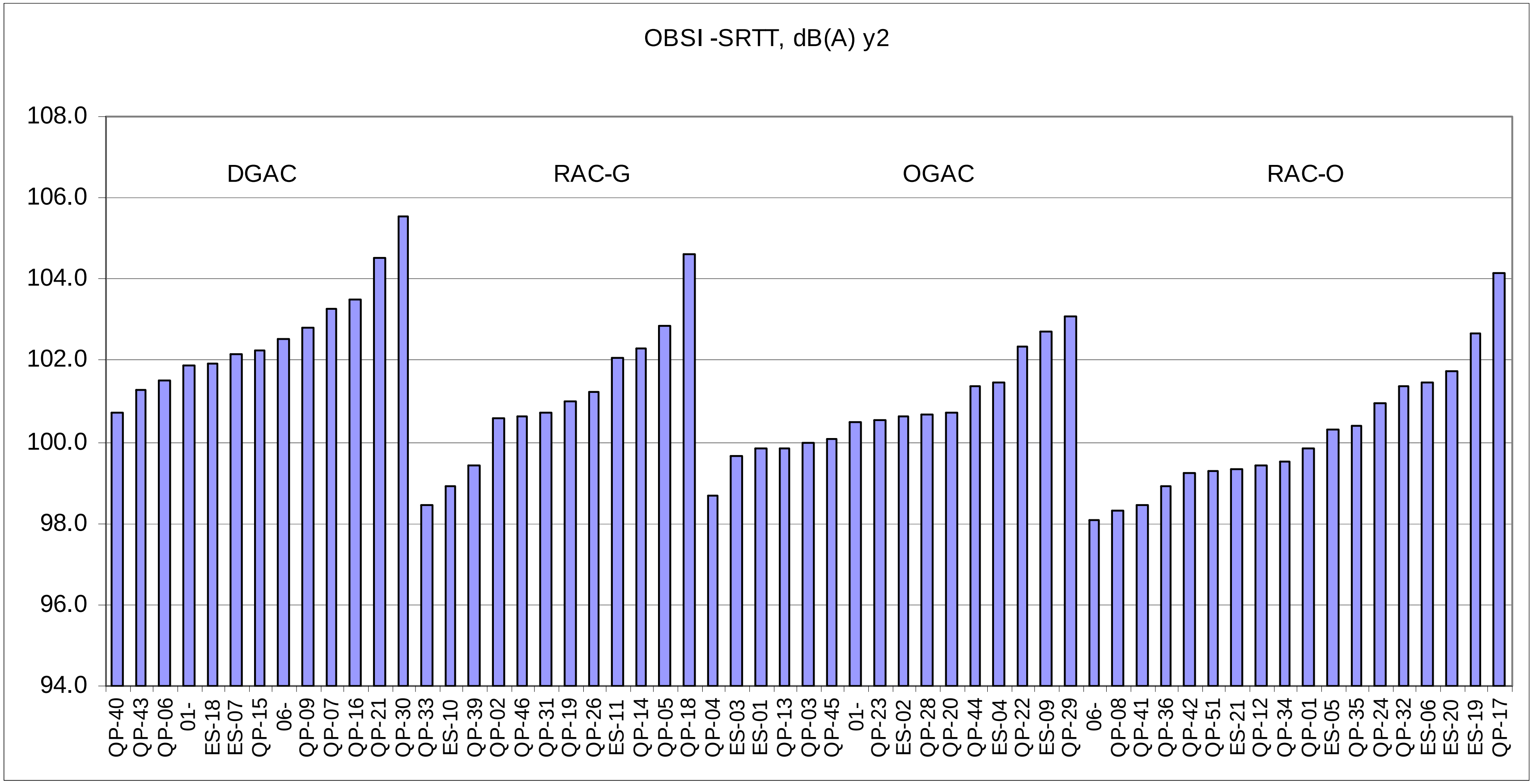

Figure A2. Second-year OBSI (SRTT tire) organized by material type and then sorted by increasing noise level.

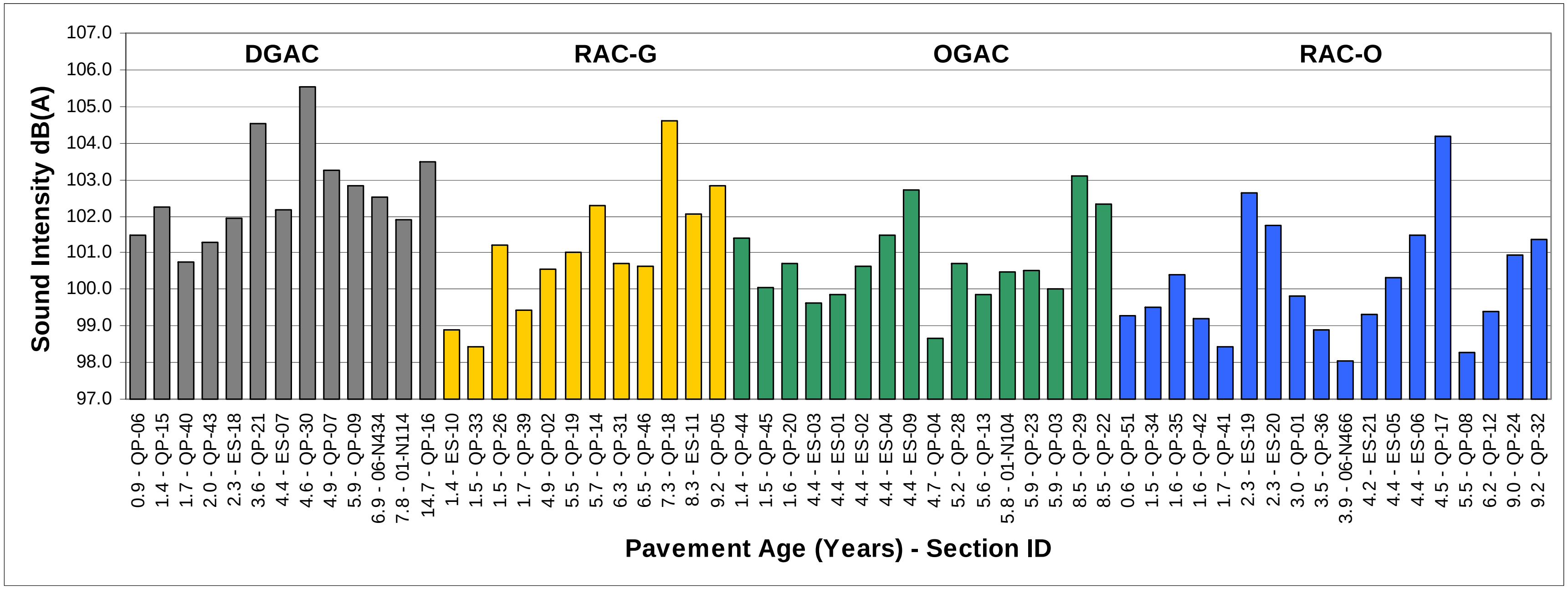

Figure A3: Second-year OBSI (SRTT tire) organized by material type and then sorted by increasing age (age in years since construction shown in front of section number on x-axis).