ASPHALT RUBBER – THE QUIET PAVEMENT?

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Abstract

In 2002, a group of Alberta transportation agencies, in cooperation with the Alberta Recycling Management Association, embarked on a trial project to evaluate Asphalt Rubber Concrete (ARC) pavement. ARC has been in use in the US since the mid 1980's and has proven to be an environmentally friendly alternative to conventional asphalt pavement. ARC has many reported benefits that distinguish it from conventional asphalt pavements. Among them are longer service life, reduced reflective cracking, reduced rutting, and reduced road noise. Although the primary goal of the trial project was to establish whether ARC was a viable alternative road surfacing material in Alberta's climate, reduced road noise has proven to be a significant side benefit.

In Alberta, several roadways have been paved with ARC since 2002 in both urban and rural areas. In conjunction with the ARC paving, road noise was measured at selected project locations both prior to and after paving with ARC and then on an annual basis through 2005. In this paper, the theory of noise propagation and methodology of measuring the road noise will be presented and, using the urban and rural area road noise data acquired over the last four years, a comparison between the road noise associated with ARC and previously existing conventional pavements will be discussed. The mechanism that results in lower road noise will be addressed as part of this discussion. In addition, the ramifications of quieter roads will be examined by addressing the cost of quieter ARC pavements compared to conventional pavements and the cost of other noise mitigation measures compared to ARC.

INTRODUCTION

Beginning in 2002 and carrying through 2006, several Alberta roads in both urban and rural settings were paved with Asphalt Rubber Concrete pavement (ARC). The ARC paving was conducted with the financial assistance of the Alberta Recycling Management Authority - Tire Recycling Division (ARMA) in conjunction with Alberta Transportation and Infrastructure, the City of Edmonton, the City of Calgary, the City of Lethbridge, and Strathcona County. EBA Engineering Consultants Ltd. (EBA) was retained by ARMA to provide technical advice and project management services.

Although the stated goal of the project was to establish that ARC was a viable alternative material that could be used in Alberta's harsh climate, a significant side benefit has been realized in the form of reduced road noise.

Through ARMA, EBA retained a specialist acoustical consultant, ACI Acoustical Consultants Inc. (ACI), to measure the road noise produced by the tire/pavement interaction on selected ARC and conventional asphalt concrete pavements. Measurements were taken in the first year of paving (2002), before and after construction, with subsequent follow-up measurements every year through 2005. As other roads were paved with ARC, a selected few were also subjected to testing for road noise with follow-up testing in subsequent years. Although several roads have been paved with ARC, this paper will focus on a select few for which road noise testing data is available. Those roads are identified below in Table 1.

TABLE 1 – ARC Road Noise Test Locations

Roadway	Owner	Roadway Type	Location	Posted Speed Limit (km/hr)	Length (lane-km)
Highway 630	Alberta Transportation	Rural 2-lane	25 km E of Edmonton	100	2.0
Highway 623	Alberta Transportation	Rural 2-lane	70 km SE of Edmonton	100	14.0
50 Street	City of Edmonton	2-lane Urban/Rural Arterial	Edmonton	60/80	10.4
Baseline Road (east)	Strathcona County	6-lane Urban Arterial	Sherwood Park	70	9.6
Baseline Road (west)	Strathcona County	6-lane Urban Arterial	Sherwood Park	70	8.6
Highway 16 EB #1	Alberta Transportation	Rural 4-lane	180 km E of Edmonton	110	8.4
Highway 16 EB #2	Alberta Transportation	Rural 4-lane	180 km E of Edmonton	110	2.0

A brief description of ARC, an explanation of noise theory and propagation and the testing methodology, and a comparison of the available road noise data and how it may be changing over time are presented. Finally, a comparison of the cost of ARC vs. other noise abatement measures and the cost of producing conventional pavements is also presented.

WHAT IS ARC AND HOW IS IT PRODUCED?

The asphalt rubber concrete pavement (ARC) produced in Alberta is based on similar material that has been produced in various jurisdictions in the US since the 1980s. The mix designs were based on a method-based specification used by the Arizona Department of Transportation (ADoT 413). This specification required the use of finely ground rubber crumb blended with asphalt cement and aggregate to produce the ARC mix. Typical conventional asphalt concrete pavement (ACP) mix designs in Alberta are based on end-product specifications.

The asphalt cements used on the various projects were 80-100A, 150-200A, and 200-300A penetration-grade asphalt cement. These are softer asphalt cements than are generally used in those US states that make extensive use of ARC. Alberta's cold winters preclude the use of harder asphalt cement because the low temperatures would result in extensive thermal cracking (much more so than we already see on Alberta roads).

The asphalt rubber binder produced in Alberta consisted of conventional straight run penetration grade asphalt cement blended with the rubber crumb at a high temperature. The binder contained approximately 19% rubber crumb by weight. The rubber crumb was of a specified gradation and bulk specific gravity with a maximum particle size of 2.00 mm. The rubber crumb used was obtained from an Alberta-based producer and consisted of ground light truck tires, which consist mostly of vulcanized rubber.

Typical conventional ACP mixes include a well graded aggregate with up to 8% fine (passing a 0.080 mm sieve) material. The aggregate required to produce the ARC mix was gap-graded with more coarse aggregate and very little fine material (less than 2.5%). Producing the aggregate for the ARC required blending several separate component aggregates.

Typical ACP mix designs contain 5% to 6% conventional asphalt cement by total weight of mix. ARC mix designs of the type placed in Alberta contain approximately 7.5% to 8.5% asphalt rubber binder by total weight of mix. The increased binder content and specially graded aggregate result in an increased cost per tonne for ARC that can be up 50% higher than that of conventional ACP mixes.

The blending of asphalt cement and rubber crumb requires special equipment. With conventional ACP, a temperature of 150 to 160 °C is generally sufficient to allow the proper mixing of asphalt cement and aggregate. Because ARC also includes rubber crumb, special considerations are required to blend the rubber crumb and asphalt cement. Specialized blending equipment was brought to Alberta from the US to facilitate the production of ARC.

To start the blending process, the asphalt cement is pumped into a special holding tank. This tank heats the asphalt cement to at least 190°C while one tonne bags of rubber crumb are loaded into an adjacent hopper. When the asphalt cement reaches the desired temperature, the rubber crumb is transported via auger into a mixing chamber adjacent to the holding tank. This mixing chamber employs a high-shear mixer to blend the hot asphalt cement and rubber crumb. When the mixture is sufficiently blended, it is pumped into a large two-chambered nurse tank.

The rubber crumb in ARC does not actually melt. In one chamber of the nurse tank, the mixture of asphalt cement and rubber crumb is heated (under constant agitation) to 205°C. At this temperature, the rubber crumb becomes gel-like and is surrounded and bonds with the asphalt cement. This process takes approximately 45 minutes. (This process repeats in the second chamber of the nurse tank to permit continuous production.)

The asphalt cement/rubber crumb blend is then tested to ensure that it has achieved the desired properties. The desired properties include the uniform dispersion of the rubber crumb in the asphalt cement and the achievement of a specified temperature and viscosity range. After the desired properties have been verified, the asphalt rubber binder is pumped into a conventional asphalt concrete production facility where it is mixed with the aggregate to produce ARC. The ARC mix is then loaded into trucks and placed on the road surface using conventional paving equipment.

ARC is placed at a higher temperature than conventional ACP and requires special compaction procedures. When paving is complete, the ARC surface has a rather coarse and porous appearance (similar to Superpave or Stone Mastic Asphalt [SMA] mixes) compared to conventional ACP. This coarse surface texture is an important aspect of why the use of ARC can result in reduced road noise.

ROAD NOISE – THEORY AND PROPAGATION

Throughout the world, noise generated by transportation systems is the number one noise complaint (1). According to the Organization for Economic Cooperation and Development (OECD), 50% of the people in member countries are routinely exposed to noise levels that exceed the disturbance threshold, and 15% of those are permanently subjected to unacceptable noise levels (2). The main source of these unacceptable noise levels is road traffic. Ongoing improvements to the mechanical design of exhaust systems and power trains of modern vehicles have reduced the noise generated by these components which renders the noise generated by the tire/pavement interaction the major source of road noise by all types of vehicles, even at moderate speeds.

Noise Theory

Sound is composed of two quantifiable elements: frequency and sound pressure level. Sound pressure level is expressed in decibels (dB) and frequency is expressed in Hertz (Hz, where 1 Hz = 1 oscillation per second). The sounds we hear can be described as a mixture of different levels of sound pressure at different frequencies. The human ear can hear frequencies ranging from 20 Hz to 16,000 Hz, although the upper range tends to decrease as we get older (to about 5,000 Hz) (3). The human ear is not very sensitive to low frequency sounds (up to about 400 Hz), is very sensitive to mid frequency sounds (about 400 Hz to 8000 Hz), and slightly less sensitive to high frequency sounds (above 8000 Hz). Because of the broad range of frequencies detectable to the human ear, the entire sound spectrum is often divided into several constant percentage frequency bandwidths, each known as a 1/3 octave band (4). The data presented herein has been broken down into these 1/3 octave bands.

Because we hear sounds from a subjective standpoint, some system of accounting for how we hear things differently was required. Modern sound measuring devices are equipped with an internationally standardized filter (labeled "A") that essentially simulates the sensitivity of the human ear to different sound frequencies. The result is that sounds are expressed in dB(A), which can be described as a dB corrected to account for human hearing (5). Because human hearing covers such a broad amplitude of sounds, it would be difficult and awkward to measure it on a linear basis. Therefore, sound levels are represented on a logarithmic scale. Thus a change in sound level of 10 dB(A) is generally perceived to be the equivalent of doubling (or halving) the noise level.

Because sound is represented on a logarithmic scale, multiple sound sources cannot be added arithmetically. The U.S. Federal Highway Administration (FHWA) has accepted the following equation for adding multiple sound sources to achieve an equivalent single sound level (6):

$$dB(A)_t = 10 * \log\{10^{dB(A)_1/10} + 10^{dB(A)_2/10} + ... + 10^{dB(A)_n/10}\} \cdots\cdots Equation\ 1$$

where: $dB(A)_t$ is the equivalent total sound level
$dB(A)_n$ is the sound level of the n^{th} individual source

From this equation, it can be shown that by doubling the number of equivalent sound sources (or doubling the number of vehicles in traffic flow in the case of road noise) the result is a net increase of about 3 dB(A). An increase of 3 dB(A) is generally just barely perceptible to the human ear (7).

Sound can be further defined for our purposes. Noise emanating from a road source tends to vary continuously. It has been observed that a fluctuating noise of a specified level is more annoying than a stable noise of the same constant level (8). As a consequence, there has been a trend to express sound levels in energy equivalent level for a specified period of time that is denoted L_{Aeq}. The L_{Aeq} metric weights the higher sounds levels more than the lower sound levels (due to the logarithmic nature) thus providing a better representation of human perception to noise levels.

In order to provide some reference point from which to gain perspective on the level of noise that we find annoying, OECD experts have determined that there are two critical threshold levels. Discomfort occurs at an approximate 24 hour L_{Aeq} level of 55 dB(A); and at a 24 hour L_{Aeq} level of 65 dB(A), noise begins to become a nuisance that most people consider unacceptable (9).

Noise Propagation (General)

Noise can be generated from a point source (e.g. a lawnmower) or from a series of several point sources (e.g. traffic flow on a busy road), which is classified as a quasi-line source. The sound level decreases with an increase in distance from the source. For a point source, the decrease is about 6 dB when the distance from the source is doubled.

For a line source, the decrease in sound level is different because the sound pressure waves are propagated all along the line and overlap at the point of measurement. The result is that for a line source, the decrease in sound level is about 3 dB when the distance from the source is doubled (10).

The magnitude of the sound level generated by a road traffic quasi-line source is dependent on three things: (1) the volume of traffic flow, (2) the speed of the traffic, and (3) the volume of trucks in the traffic flow. Heavier traffic volumes, higher speeds, and more trucks generally means increased road noise.

The noise level near a road depends not only on the magnitude of the noise generated by the traffic, but also on the type of terrain adjacent to the road. The Traffic Noise Model produced by the FHWA uses the following equation to determine the decrease in road noise as distance increases (11):

$$\Delta dB(A) = 10 * \log\{(\frac{d1}{d2})^{1+\alpha}\} \cdots\cdots \textit{Equation} \;\; 2$$

where: $\Delta dB(A)$=the decrease in sound level from the first point of interest to the second point of interest

α=attenuation coefficient which is 0.0 for hard ground or pavement and 0.5 for soft ground (vegetation, plowed fields, etc.)

d1= the distance from the sound source to the first point of interest

d2= the distance from the sound source to the second point of interest

Noise generated by traffic can be divided into two distinct sub-sources. The noise produced by engines/power trains, exhaust systems, and wind turbulence is generally in the lower frequency range, i.e. below about 500 Hz. The interaction between the tires and pavement produce higher frequency noise ranging from about 630 Hz to 4000 Hz. This is the range of frequencies to which the human ear is generally most sensitive. Consequently, a decrease in the noise produced by tires is more subjectively discernible for the typical human ear (12).

As noted, the noise produced by engines/power trains, etc. are generally of a lower frequency and, at lower speeds, tend to influence road noise more so than at higher speeds. At higher speeds, the tire/pavement noise tends to dominate. There has been some research conducted on where the transition from lower frequency dominated noise and higher frequency dominated noise occurs. Table 2 below illustrates some of the speeds at which the crossover from lower frequency dominated noise to higher frequency dominated noise occurs (13).

TABLE 2 – Road Noise Crossover Speeds

Vehicle Type	Cruising (constant speed)	Accelerating (increasing speed)
Cars made after 1996	15-25 km/hr	30-45 km/hr
Cars made 1985 – 1995	30-35 km/hr	40-50 km/hr
Heavy Trucks made after 1996	30-35 km/hr	45-50 km/hr
Heavy Trucks made 1985 – 1995	40-50 km/hr	50-55 km/hr

For speeds above 60 km/hr, it is clear that tire/road interaction noise becomes the dominant noise source for all vehicles.

Noise Propagation (Tires)

The interaction between vehicle tires and pavement produce the most dominant aspect of road noise, particularly at higher speeds. The noise produced by the tires can be broken down into two mechanisms: excitation and response (14).

Excitation consists of the rolling/deformation of the tire, the pavement texture or roughness, and discontinuities in the tire tread pattern. The rolling/deformation of the tire causes shear deformations in the tread rubber that leads to minute slipping of the tire on the road surface. This slippage causes the "scrubbing" noise we hear (particularly when turning). The pavement type can strongly influence the pavement surface roughness or texture and the magnitude of the scrubbing effect (15). The effects of rough surface texture and discontinuities in the tread pattern are obvious.

Response characteristics include tread element vibration, tread band vibration, sidewall vibration, air pumping, tube resonant radiation, and the "horn" amplification effect (16). The vibration effects generally cause noise in the lower frequencies (<1000 Hz) and are not as noticeable to the typical human ear. Air pumping occurs with the suction/expulsion of air from the hollows of the tread pattern. This effect is directed mostly rearward with air being compressed and pushed away at the front of the tread and expanding and being sucked in at the rear of the tread pattern (17). The "horn" effect is dependent on the amplification of sound waves off of the walls of the geometric shape (dihedron) formed by the contact area at the front and rear of the tread pattern and can affect the magnitude of the sound level by as much as 20 dB (18). A porous pavement type, such as ARC, can greatly affect the level of noise produced by absorbing sound and providing an escape for the expelled air (19).

NOISE SOURCES

In determining the relative effectiveness of different road surfaces, it is necessary to consider briefly the various components of overall vehicle noise.

Tire Noise

The noise source affected the most by the road surface condition is tire noise. This is noise created by the interaction of the tire with the road as it rolls along the surface and is typically comprised of mid to high frequency noise. Various factors such as frequency of rotation (due to vehicle speed), tread pattern and depth, vehicle weight, and number of tires contribute to the generated noise.

Engine Noise

Engine noise is typically low to mid frequency noise caused directly by internal combustion noises produced in the engine as well as mechanical noise produced by the various external devices such as belts/pulley's, alternators, air-conditioning pumps, etc. Most new light vehicles on the road have relatively quiet engine systems and employ more noise and vibration control methods than ever before.

The composition of the road surface can have an impact on the engine noise emanated to the environment. For most vehicles, most of the engine noise radiates from the underside of the vehicle and reflects off the road surface. Depending on the absorptive properties of the road surface, some of the sound can be absorbed and the total amount of reflected noise can be reduced.

Exhaust Noise

Similar to engine noise, exhaust noise is typically comprised of low to mid frequency noise. The source of the noise is the combustion process in the engine as well as any noise produced from the hot gasses flowing through the header and exhaust system and self-generated noise produced at the tail-pipe. As with engine noise, significant improvements have been made in the effectiveness of exhaust silencers, and most new vehicles produce insignificant levels of exhaust noise. Exhaust systems, which exit near the ground, are subject to the same reflection and absorption phenomenon as engine noise.

Turbulent Wind Noise

Noise generated by turbulent wind flow around a vehicle is another, always-present noise source. This noise is dependent on the shape and size of the vehicle as well as the speed of the vehicle. At speeds lower than 50-60 km/hr, this noise is typically insignificant compared to tire and engine noise, but at highway speeds (90-110 km/hr) this can become a significant contributing factor in the overall noise produced by the vehicle. This is a type of noise for which road surface absorption has negligible effect. However, for the purposes of studying the effect of ARC on road noise, turbulent wind noise can be neglected as it would be present in all testing situations and effectively cancels itself out of a comparative analysis.

ROAD NOISE TESTING METHODOLOGY

Starting in 2002, ACI was retained to measure and analyze the road noise associated with ARC and, in some cases, compare it to the road noise generated on conventional ACP pavements placed at the same time as the ARC. Where possible and/or practical, readings were taken both shortly before and shortly after paving with ARC so a comparison could be made between the road noise associated with the previously existing conventional pavement and the reduced noise associated with ARC.

After review of previous studies and international standards, a comprehensive method of long term monitoring and short term on-site observations was devised. Although not used directly, the International Organization for Standardization (ISO) standard 11819-1 *Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-By method* was used as a reference document for specific measurement parameters such as equipment, locations, weather, etc.

It is important to note that the test method described below does not specifically distinguish between the various vehicle noise sources and does not determine the relative effectiveness of the road surface in reducing each type of noise. *The study method determines the effect of the road surface on all of the noise sources simultaneously.*

Test Methodology

The test methodology consisted of two main types of data collection. The first was to have an environmental noise monitor measure the sound levels for a period of 26 hours (long-term monitoring) at 6 of the 7 project locations. The data was collected in the form of 1/3 octave frequency bands, as well as overall broadband Linear and A-weighted sound levels. Sound levels were recorded as 30-second $L_{Aeq's}$ for the entire monitoring period. It was important to not only measure the broadband (i.e. overall) sound levels, but to also determine the frequency content of the noise to obtain a more detailed analysis of the changes in the noise emanating from the road surface. The 2-hour overlap from one day to the next provided a time period in which the sound levels from one day could be compared to those of the next. This gave an indication of daily variances. Also, in conjunction with the 26-hour monitoring at most of the locations was a 26-hour digital audio recording. This was useful for identifying non-traffic related noise and gave an audio impression of the traffic noise quality.

As part of the long term monitoring, on-site observations were conducted for the first and last two hours of measurements (these being the same two hour periods on the consecutive days). While the sound measurement instrumentation was in operation, sound levels for specific vehicular movements were observed on the sound level meter's display and manually recorded. The sound levels recorded were the maximum sustainable sound level. Each of the specific events was recorded while the other events were not interfering with the results (i.e. other vehicles and outside noise influences were at sound levels of 10 dB below that of the specific event observed). In addition, to the best of the observer's ability, vehicles which were under acceleration or braking, and were producing abnormally high sound levels (i.e. modified engine or exhaust systems with elevated sound levels) were not used. It was intended to have vehicles traveling in a continuous fashion (consistent with using ISO 11819 as a guideline).

The measurements were conducted both *before* and *after* the paving of each particular road section (where possible and/or practical). The data was reviewed and compared to determine the changes (if any) from *before* to *after*. It should be noted that all of the measurements were conducted under what was deemed to be "typical" traffic conditions during summer or early fall. All measurements were conducted on a weekday with no abnormal activities such as festivals, nearby detours, etc. that would cause an inordinate amount of traffic using the road. The 2-hour overlap in the measurements was used to ensure that the traffic conditions were indeed "typical". Any follow-up measurements were conducted only once as a second (or third) *after* measurement and then compared to both the *before* and *after* measurements obtained previously.

The second data collection type involved shorter-term monitoring at only 1 of the 7 project locations (Highway 630). The data acquisition was conducted using a 15-second L_{Aeq} sampling period obtaining the broadband A-weighted and 1/3 octave band spectral sound levels. The sound level meter was manually started just prior to the pass-by of individual vehicles to obtain approximately 20 pass-bys at each of the ARC and ACP locations.

PROJECT LOCATIONS

The measurement methods outlined above were applied at the 6 different 26-hour (long-term) noise monitoring locations as well as 1 short term location. Each location has different traffic conditions and surrounding environment. Three locations are in urban areas while the remainders are in rural areas. The project locations are listed in Table 1 and are further described below.

PROJECT LOCATION #1 – Highway 630, 2005 WAADT=1430

Located in a rural area about 30 km east of Edmonton, this road has a posted speed limit of 100 km/hr. There are a few private homes located along the project section. This road was paved with ARC in 2002 with separate 40 mm and 80 mm overlay sections. Road noise from ARC and conventional ACP was measured at this location.

PROJECT LOCATION #2 – Highway 623, 2005 WAADT=730

Located in a rural area about 70 km southeast of Edmonton, this road has a posted speed limit of 100 km/hr. There are multiple private homes and one church located along the project section. This road was paved with ARC in 2003 with separate 40 mm and 80 mm overlay sections. Road noise from ARC and conventional ACP was measured at this location.

PROJECT LOCATION #3 – 50 Street

Located in a semi-rural area along 50 Street in southeast Edmonton between 13 Avenue and the City Limits, this road has posted speed limits of 60 km/hr and 80 km/hr placing it midway between a typical city road and a highway. The road traverses through a dense residential area before entering more open area with occasional residences, farmland, and forested areas. This road was paved in 2003 with 100 mm of ARC (50 mm mill and inlay followed by a 50 mm full width overlay).

PROJECT LOCATION #4 – Baseline Road (East Section)

Located in a dense residential and commercial area of Sherwood Park, AB, this road has a posted speed limit of 70 km/hr. This 6-lane arterial road was paved with 40 mm of ARC in 2003.

PROJECT LOCATION #5 – Baseline Road (West Section)

Also located in a dense residential and commercial area of Sherwood Park, AB, this road has a posted speed limit of 70 km/hr. This 6-lane arterial road was paved with 40 mm of ARC in 2004 and is adjacent to Location #4.

PROJECT LOCATION #6 – Highway 16 EB (West Section), 2005 WAADT=5020 to 6040

Located in a rural area about 180 km east of Edmonton, this road has a posted speed limit of 110 km/hr. There are a few private homes and some commercial development located along the project section. This section of road was paved with 70 mm of ARC in

2004. Road noise from ARC and conventional ACP was measured at this location.

PROJECT LOCATION #7 – Highway 16 EB (East Section), 2005 WAADT=5020 to 6040

Also located in a rural area about 180 km east of Edmonton, this road has a posted speed limit of 110 km/hr and is adjacent to Location #6. There are a few private homes and some commercial development located along the project section. This section of road was paved with 30 mm of Asphalt Rubber High Binder Friction Course (ARHBFC) over 40 mm of ARC in 2004. ARHBFC is an open graded mix with an elevated binder content (>10% by total weight of mix) that is intended to be used as a wearing course for high traffic volume roadways. It's surface texture is very similar to ARC, i.e. a rather coarse and porous appearance.

TEST RESULTS AND ANALYSIS

As noted previously, the frequencies to which the human ear is subjectively most sensitive range from 630 Hz to 4000 Hz. Figure 1 (Highway 630) shows the full historical spectral analysis covering all the audible frequencies ranging from 20 Hz to 12500 Hz. It can be seen that there is little or no noise reduction in the lower frequencies since they generally correspond to the sounds emitted by the engine/power train and wind turbulence that are not affected by the nature of the pavement surface. For the purposes of clarity, the remaining plots (Figures 2 through 8) will focus on the narrower spectral band to which the human ear is most sensitive. Following is a brief summary for each of the roads tested and for which reliable data is available. (There is data for two additional roads, but the data is somewhat suspect due to potential problems with the placement of the testing equipment.)

The 'dB' data below represents the average linear noise reduction in dB across the spectral band from 630 Hz to 4000 Hz. The 'dBA' (A-weighted) noise reduction data below is generally lower than the dB reduction because it represents all of the range of frequencies that we can hear, including those to which we are not very sensitive or tend to ignore as background noise. Tables 3 through 9 below provide a summary of the road noise testing results to date by comparing the 26-hour L_{eq} road noise from before paving to the 26-hour L_{eq} road noise after paving and in subsequent years.

Highway 630 (Figure 1 – Full Spectral Analysis and Figure 2 – Narrow Band Spectral Analysis)

The road noise at this location was tested shortly before and after paving with ARC in 2002 and once per year since then.

TABLE 3 – Highway 630 Road Noise Reduction Data

Test Year	Noise Reduction (dB)	Noise Reduction (dBA)
2002	6.9	5.7
2003	6.7	3.2
2004	4.9	3.1
2005	4.7	1.8

As can be seen, the dBA reduction in road noise tails off in successive years to a point at which it is just barely perceptible to the human ear. However, the linear dB noise reduction also decreased over time, but not to the same extent and may better represent the noise reduction at those frequencies to which the human ear is most sensitive. The average reduction in 2005 of 4.7 dB is readily perceptible to the human ear. The noise reduction value for 2005 is roughly the equivalent of being twice as far away from the sound source. By comparison, the conventional ACP placed at the same time as the ARC had a noise reduction of only 2.4 dB, which is just barely perceptible to the human ear (**Figure 3**).

Highway 623 (Figure 4)

The road noise was measured prior to and after paving in 2003 and again in 2004 and 2005.

TABLE 4 – Highway 623 Road Noise Reduction Data		
Test Year	**Noise Reduction (dB)**	**Noise Reduction (dBA)**
2003	6.4	4.7
2004	5.5	4.3
2005	5.0	4.1

As with Highway 630, the dBA noise reduction tails off after about one year, but appears to have stabilized somewhat and is significant enough that it can be detected by the human ear. The linear noise reduction value for 2005 of 5.0 dB is readily perceptible to the human ear. The noise reduction value for 2005 is roughly equivalent to being a little more than twice as far away from the sound source. By comparison, the conventional ACP placed at the same time as the ARC had a noise reduction of –0.2 dB, which is actually noisier than before paving (**Figure 5**).

50 Street, Edmonton (Figure 6)

The road noise was measured prior to and after paving in 2003 and again in 2004 and 2005.

TABLE 5 – 50 Street Road Noise Reduction Data		
Test Year	**Noise Reduction (dB)**	**Noise Reduction (dBA)**
2003	10.9	8.3
2004	6.8	4.8
2005	7.1	4.5

The initial noise reduction of 8.3 dBA was very significant and would be perceived as being approximately half as loud. The drop-off after about one year appears drastic, but the average A-weighted noise reduction for 2005 of 4.5 dBA is still significant and is roughly equivalent to being a little more than twice as far away from the sound source.

Baseline Road (East Section), Sherwood Park (Figure 7)

The road noise was measured prior to and after paving in 2003 and again in 2004 and 2005.

TABLE 6 – Baseline Road (East) Noise Reduction Data		
Test Year	**Noise Reduction (dB)**	**Noise Reduction (dBA)**
2003	8.0	6.3
2004	4.3	3.4
2005	3.5	2.7

The noise reduction quality (both linear and A-weighted) decreased drastically after about one year. The A-weighted noise reduction value for 2005 of 2.7 dBA, although still perceptible to the human ear, is not considered significant. However, for frequencies between 1000 and 2000 Hz, the A-weighted and linear noise reduction value remains greater than 5.0 dB.

Baseline Road (West Section), Sherwood Park (Figure 8)

The road noise was measured prior to and after paving in 2004 and again in 2005.

TABLE 7 - Baseline Road (West) Noise Reduction Data		
Test Year	**Noise Reduction (dB)**	**Noise Reduction (dBA)**
2004	3.9	3.7
2005	4.6	3.6

The linear noise reduction increased over the span of one year to 4.6 dB, which is easily perceived by the human ear. The noise reduction value is roughly equivalent to being twice as far away from the sound source. The A-weighted noise reduction appears to have been fairly stable as well.

Highway 16, ARC Section (Figure 9)

The road noise was measured prior to and after paving in 2004 and again in 2005.

TABLE 8 – Highway 16 (ARC Section) Road Noise Reduction Data		
Test Year	**Noise Reduction (dB)**	**Noise Reduction (dBA)**
2004	3.2	1.8
2005	3.6	2.1

As with the Baseline Road (West) Section noted above, the linear and A-weighted noise reduction value increased after one year. Both the linear and A-weighted noise reduction values are barely perceptible to the human ear and are not considered significant. By comparison, the conventional ACP placed at the same time as the ARC had a noise reduction of only 1.0 dB, which is imperceptible to the human ear (**Figure 10**).

Highway 16, ARHBFC Section (Figure 11)

As noted previously, the material placed on this section (ARHBFC) varies from ARC in that it has a significantly higher asphalt rubber binder content with some variation in the aggregate gradation requirements. The road noise was measured prior to and after paving in 2004 and again in 2005.

TABLE 9 - Highway 16 (ARHBFC Section) Road Noise Reduction Data		
Test Year	**Noise Reduction (dB)**	**Noise Reduction (dBA)**
2004	5.7	4.6
2005	6.1	5.0

The noise reduction value has again increased over the course of one year for both linear and A-weighted noise. The 2005 noise reduction value of 5.0 dBA is readily perceptible to the human ear and is roughly the equivalent of being a three times as far away from the sound source.

Analysis – What Makes ARC Quieter?

The primary assumed mechanism behind lower road noise on ARC paved surfaces is the porous surface texture of the finished product. As noted above, ARC has a very coarse and open appearing surface texture, similar to Superpave or SMA mixes. This porous texture appears to absorb sound energy radiated from the engine, exhaust, and tires. Indeed, research has shown that the sound absorption co-efficient (α) is much greater for a porous textured pavement like ARC than for a conventional dense graded ACP, particularly at frequencies between 630 Hz and 2500 Hz (20). The sound absorption effect also reduces the "horn" effect.

The sound absorption effect can be better understood if we assume that air pumping is the predominant cause of road/tire noise. Gaps in the tire tread allow some lateral air drainage that reduces air pumping. With a porous surface, vertical air drainage is also possible. This vertical air drainage into the pavement surface effectively prevents the occurrence of air pumping by the tire treads and results in reduced road noise (21).

The amount of time that ARC will remain a source of noise reduction is dependent on several factors. Perhaps the most important is clogging of the surface pores. The use of road salt and salt/sand mixtures for de-icing in winter can possibly result in the clogging of the ARC surface pores. One would expect a decrease in noise reduction when after clogging, the air pumping effect increases. Studies have shown that a decrease in noise reduction of about 2 dBA can result from clogging. Similarly, one would expect an increase in noise reduction if the pores were cleaned out (22). It is not yet clear if clogging has had a direct effect in Alberta.

The exact mechanisms and their quantifiable effect on reduced road noise have not yet been proven, although research is ongoing. Similarly, the length of time that ARC can effectively reduce road noise has also not been conclusively established.

COST – ARC vs. ACP and Other Noise Abatement Measures

ARC vs. ACP

The unit costs of asphalt rubber mixes are higher than those of conventional dense graded hot mix. Although project costs for the initial ARC project in 2002 are difficult to quantify in a meaningful way as a result of it being a trial, there are costs directly associated with the ARC gap graded mix that can be quantified independent of the nature of the project. These quantifiable costs include the cost of the rubber crumb (in the order of $250.00/tonne of rubber crumb) and the additional cost associated with an increase binder demand for the gap graded mix (1.4 to 1.7 times more for asphalt rubber than the conventional dense graded hot mix). This increase would equate to an increase of approximately $7.50/tonne of mix. Since the rubber crumb cost in 2002 was approximately equal to the 2002 asphalt binder costs, the net increase in binder cost is considered to be approximately $7.50/tonne. In 2005 the raw binder cost had escalated to approximately $275.00/tonne while the rubber crumb has escalated to $440.00/tonne. This would result in a calculated net increase in binder cost of approximately $9.25/tonne of mix. It is recognized this value varies depending on assumed asphalt contents for conventional mixes.

Other costs, which were somewhat more difficult to quantify in the absence of significant experience, are the cost of producing the gap graded aggregate and the costs associated with the asphalt rubber blending equipment.

Based on experience with other gap graded mixes (e.g. SMA), it has been estimated that there was a $10.00/tonne premium for the aggregates required for a gap graded mix in 2002 that has increased to approximately $25.00/tonne in 2005 for ARC mix in the City of Edmonton. Based on experience with Superpave mixes in Alberta, Alberta Transportation has estimated a $1.00/tonne premium for these mixes throughout the province. This premium includes a cost premium for the aggregate and a cost reduction for the reduced asphalt demand of typical Superpave mixtures. Based on this experience, Alberta Transportation expects that the aggregate premium is on the order of $2.50/tonne of aggregate for ARC mix on Alberta highways.

The additional costs for asphalt rubber blending equipment that was used in the initial trial project in 2002 and in the first year of more sustained production in 2003 are not considered representative of work that would be carried out on a normal production basis. In both 2002 and 2003, a U.S. based contractor was brought to Alberta to do the blending of the rubber crumb and the asphalt cement. Based on the cost of renting the equipment and its operational costs, the extra production cost for ARC was approximately $10.00/tonne in 2002 and 2003. In 2004 a local contractor purchased the blending equipment and has since been contracted to do the blending of the rubber crumb and the asphalt cement. The resulting reduction in mobilization and operational costs has reduced the extra production cost to approximately $2.75 to $3.00/tonne in 2004 and 2005.

Paving contractors have also built in some unquantifiable extra per tonne costs for absorbing some risk in working with a new material.

The following table describes the cost comparison for asphalt rubber to a conventional dense graded hot mix asphalt employed on rehabilitation projects in the City of Edmonton both on a per tonne basis and on a lane-km basis.

Table 10 - Rubber Asphalt vs. Conventional Asphalt (City of Edmonton Data)				
Year	Asphalt Rubber ($/tonne)	Asphalt Rubber ($/lane-km)	Conventional Asphalt ($/tonne)	Conventional Asphalt ($/lane-km)
2002*	$83	$59,500	$70	$33,400
2003*	$79	$37,600	$67	$31.900
2004*	$90	$43,000	$71	$33.600
2005**	$108	$51,200	$90	$42,900

*Note: Per Tonne Price of Asphalt Rubber does not include the costs for the rubber crumb of approximately $7.50/tonne of ARC mix.

**Note: Per Tonne Price of Asphalt Rubber does not include the costs for the rubber crumb of approximately $9.25/tonne of ARC mix.

As can be seen from the above table, asphalt rubber mixes generally cost about $20.00 to $30.00/tonne more than conventional mixes, although this may vary with job size. Mobilization and set up of the asphalt rubber binder production equipment costs as much for small jobs as for big ones. Large projects may thus allow some reduction in unit costs because mobilization costs can be spread over a greater ARC tonnage.

ARC vs. Other Noise Abatement Measures

In urban areas, road noise is often a serious (and sometimes contentious) issue that has to be addressed by road owners. Noise abatement is most often accomplished by constructing noise walls (of concrete, steel, or wood) or earthen berms. Making use of heavy vegetation can also reduce noise, but requires active maintenance and takes a large area of land to be effective. However, as will be shown below, the cost of noise walls is quite high and earthen berms are also costly and require substantial land area in order to be effective.

In order for a noise abatement measure to be considered effective, it should reduce the ambient noise level by 10 to 15 dB. In order for this to happen, the measure has to be high enough and long enough to block a view of the road. A reduction of 5 dB can be achieved by having a barrier tall enough to break the line of sight from the road to the receiver and an additional 1.5 dB reduction can be achieved for each additional meter of height (23). For a 3.0 m tall wall, that amounts to a noise reduction of about 6.5 dB, for a 4.0 m wall, about 8 dB, and so on. In order to achieve a 10 dB reduction in noise, a wall or berm would have to be about 5.0 meters tall. Some authorities require a minimum noise reduction of 6 dBA before a noise barrier will even be considered (before costs and other factors are considered) (24). So for the purposes of comparison, a typical noise barrier can be considered to be about 4.0 meters tall.

It is plain that the cost of a noise barrier depends on many factors including height, length, material type, maintenance, etc. In order to compare the cost of noise barriers to ARC as noise abatement measures, the cost of constructing some noise barriers in the City of Edmonton between 1979 and 2001 are presented in Table 11. The costs of older projects have been adjusted to 2005 dollars using the Consumer Price Index.

TABLE 11 - NOISE WALL INSTALLATION COST HISTORY

Year	Location	Construction Cost	Length m	Cost/meter	2005 Adjusted Cost/meter (using CPI)	Material
1979	Mayfield Road 107-111 Avenue	$449,000	1,500	$300	$804	steel
1984	Grain Terminal	$156,000	814	$191	$338	concrete
1985	79 Avenue 159-178 Street	$517,000	3,691	$139	$236	concrete
1986	Whitemud Drive 111-122 Street	$1,078,000	3,586	$300	$489	concrete
1986	Capilano Drive 112-118 Avenue	$277,000	877	$315	$513	concrete
1987	Whitemud Drive 106-111 Street	$87,412	605	$144	$225	concrete
1987	Whitemud Drive (SS) 106-111 Street	$176,000	600	$293	$457	concrete
1987	Whitemud Drive 149-159 Street	$560,000	1,780	$314	$490	concrete
1987	Capilano Drive 101-103 Avenue	$180,000	695	$259	$404	concrete
1987	79 Avenue 149-159 Street	$473,000	1,408	$335	$523	concrete
1987	Capilano Drive 101-104 Avenue	$211,000	693	$251	$392	concrete
1987	& Terwillegar Drive @ 40 Avenue		145			concrete
1989	178 Street 93-100 Avenue	$317,000	1,073	$295	$422	concrete
1989	Groat Road 107-111 Avenue	$615,000	1,200	$512	$732	acoustic steel panels
2001	97 Street 139 to 153 Avenue	$1,390,000	1,178	$1,180	$1,298	concrete
				Average Cost/meter (2005 dollars):	**$523**	

As can be seen, the average cost of constructing a noise wall in Edmonton is $523,000 per kilometer. ARC can achieve a detectable (although lower) reduction in road noise for the much cheaper cost of about $205,000 per kilometre (based on 2005 per lane km costs and a typical 4 lane roadway). What remains unknown is how long the ARC will provide a noticeably quieter driving surface.

SUMMARY

ARC was placed on Alberta roads and is being evaluated to establish whether it is a viable surfacing alternative to conventional pavements. The reduction in road noise has proven to be a potentially significant side benefit. Based on the limited testing conducted to date, it is apparent that ARC is generally a quieter pavement surface, at least after placement and for a few years after, that can be used on urban and rural roadways. What remains unclear is how long the ARC will maintain a lower road noise level. The data shows that there is generally a perceptible drop-off in noise reduction levels after about one year of service, and then the road noise level appears to stabilize. With the exception of two roads, the noise reduction level remains perceptible to the human ear and is generally equivalent to being roughly two to three times as far away from the sound source.

It has been demonstrated that ARC could possibly be considered an alternate noise abatement measure. For a typical 4.0 m tall noise wall (or berm), a road surfaced with ARC would provide a perceptible reduction in road noise for about half the cost. However, because there are uncertainties about how long the noise reduction will last and how significant an effect it has, there may be some reluctance to consider ARC as a common noise reducing surfacing alternative due to it's higher costs compared to conventional ACP.

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Figure 1 - Highway 630 Broad Spectral Analysis (2002 to 2005)

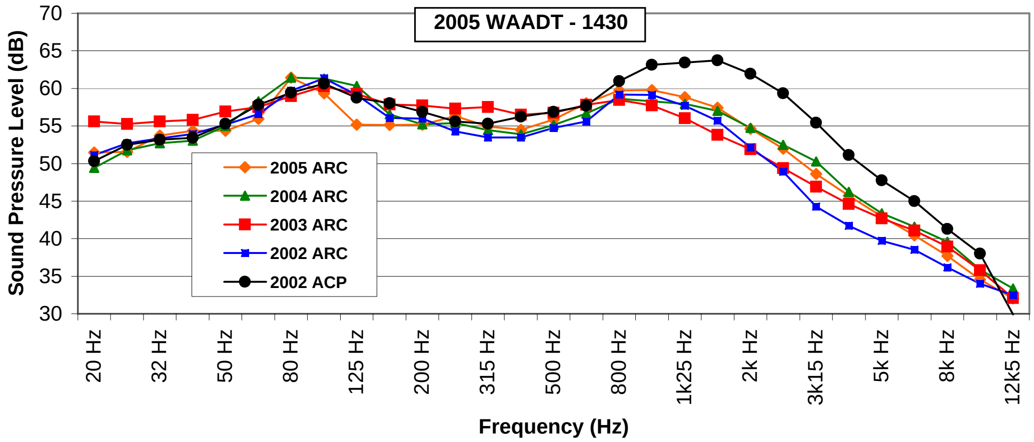


Figure 2 - Highway 630 ARC Spectral Analysis (2002 to 2005)

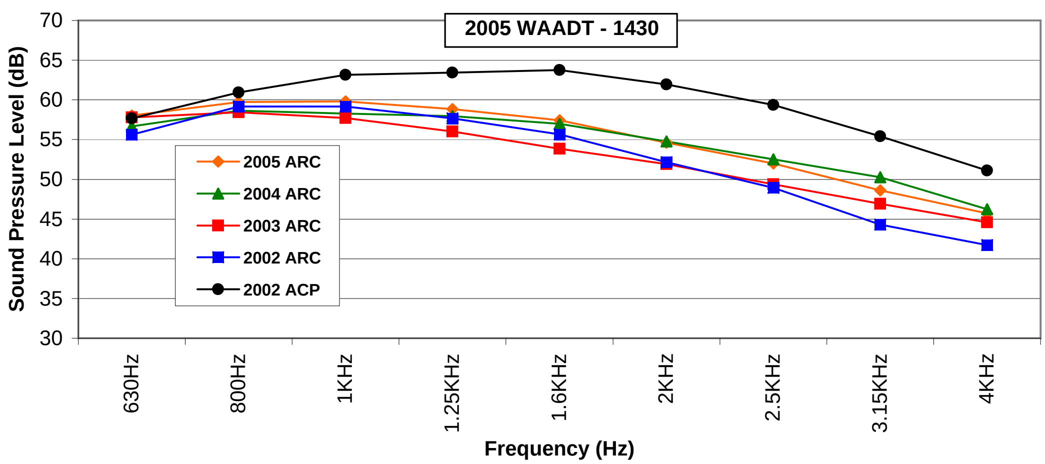


Figure 3 - Highway 630 ACP Spectral Analysis

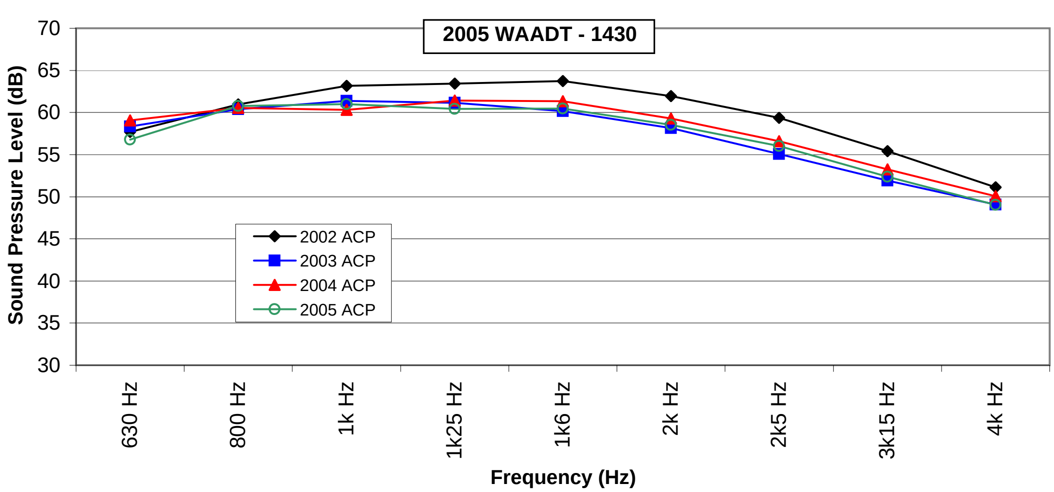


Figure 4 - Highway 623 ARC Spectral Analysis (2003 to 2005)

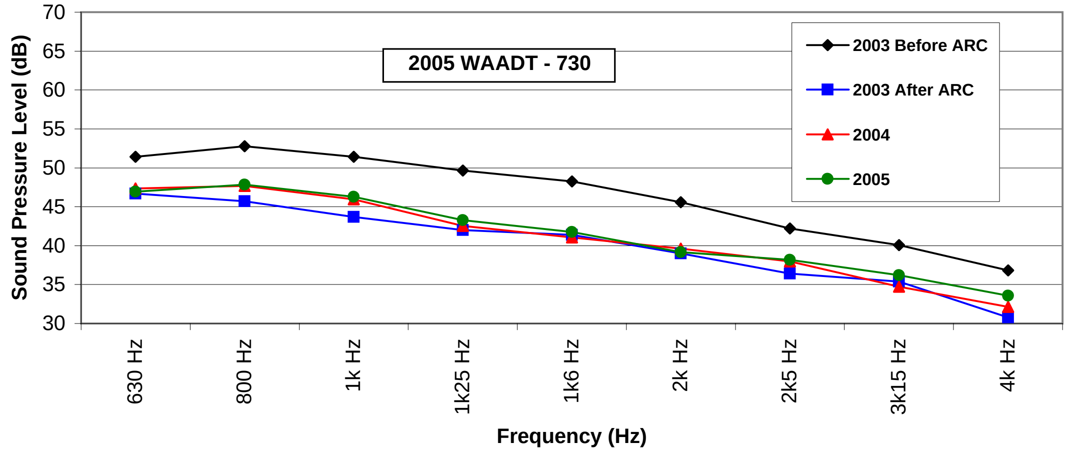


Figure 5 - Highway 623 ACP Spectral Analysis

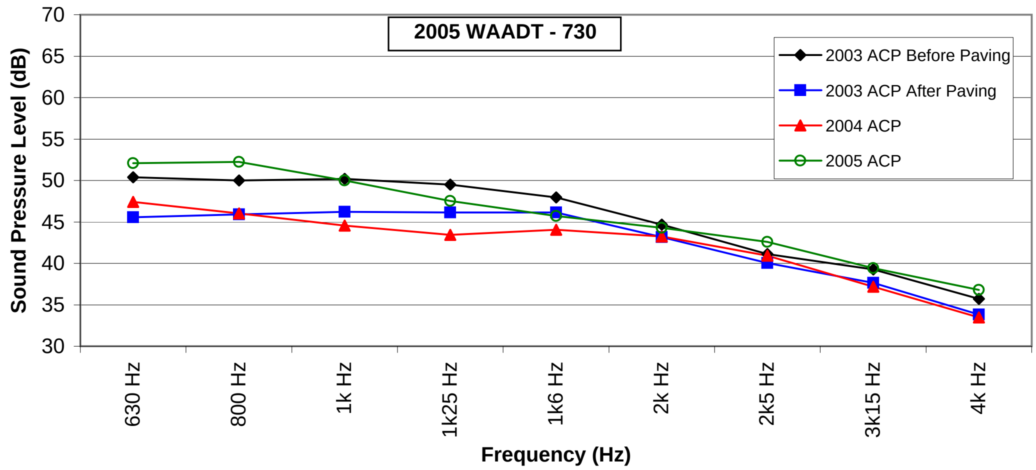
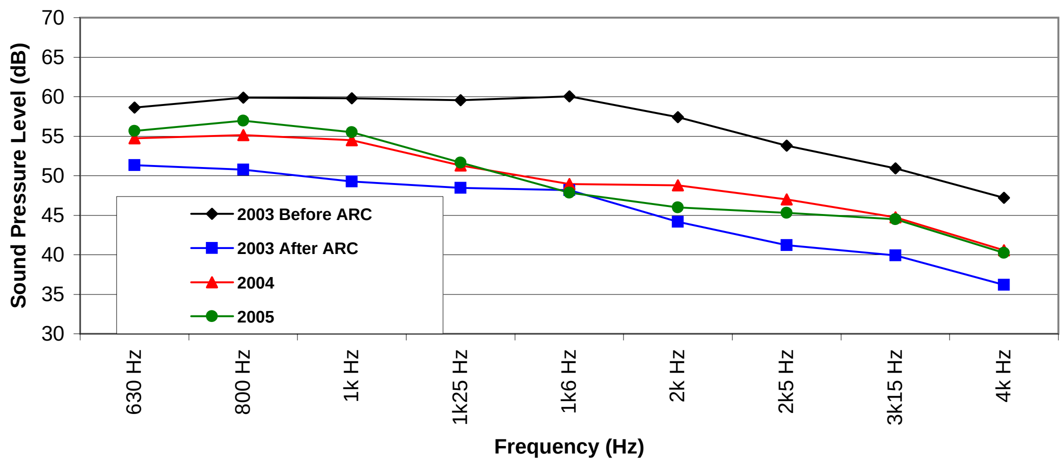


Figure 6 - 50 Street ARC Spectral Analysis (2003 to 2005)



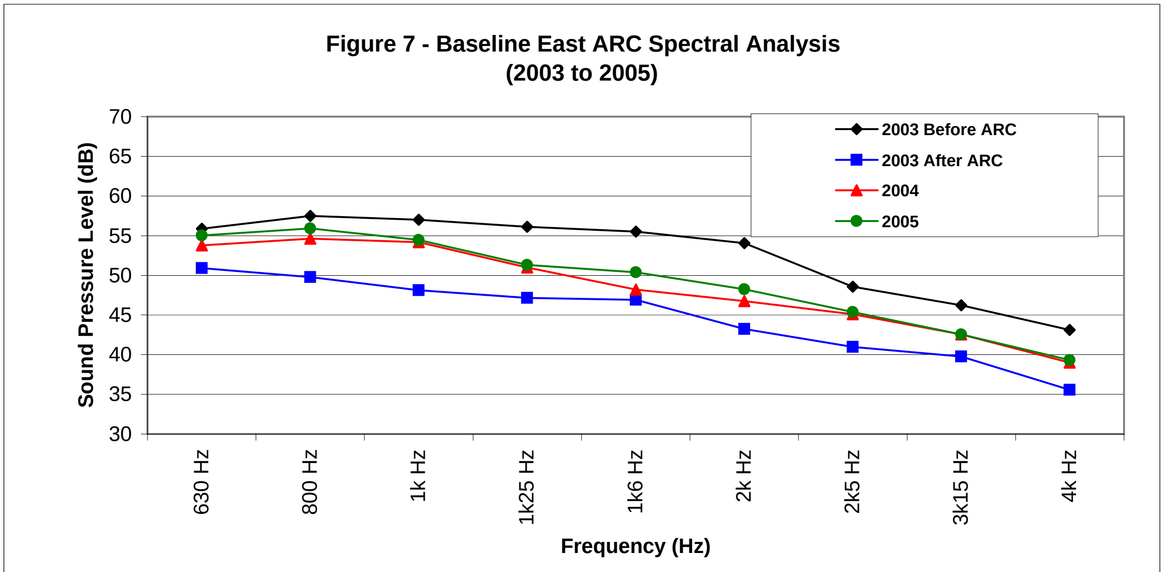


Figure 7 - Baseline East ARC Spectral Analysis
(2003 to 2005)
2003 Before ARC
2003 After ARC
2004
2005
Sound Pressure Level (dB)
70
65
60
55
50
45
40
35
30
630 Hz
800 Hz
1k Hz
1k25 Hz
1k6 Hz
2k Hz
2k5 Hz
3k15 Hz
4k Hz
Frequency (Hz)

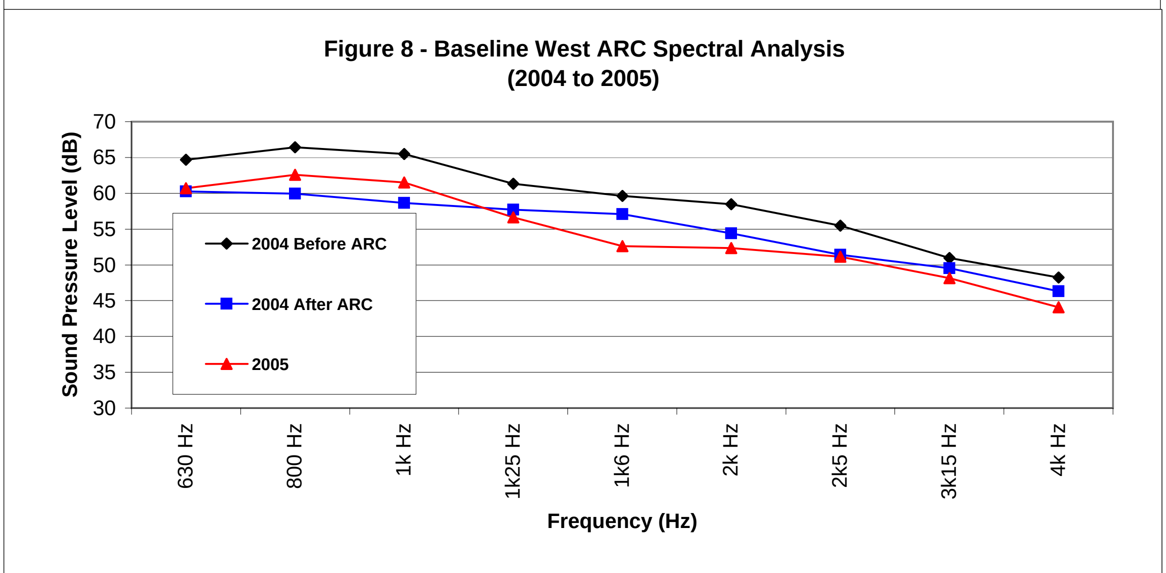


Figure 8 - Baseline West ARC Spectral Analysis
(2004 to 2005)
2004 Before ARC
2004 After ARC
2005
Sound Pressure Level (dB)
70
65
60
55
50
45
40
35
30
630 Hz
800 Hz
1k Hz
1k25 Hz
1k6 Hz
2k Hz
2k5 Hz
3k15 Hz
4k Hz
Frequency (Hz)

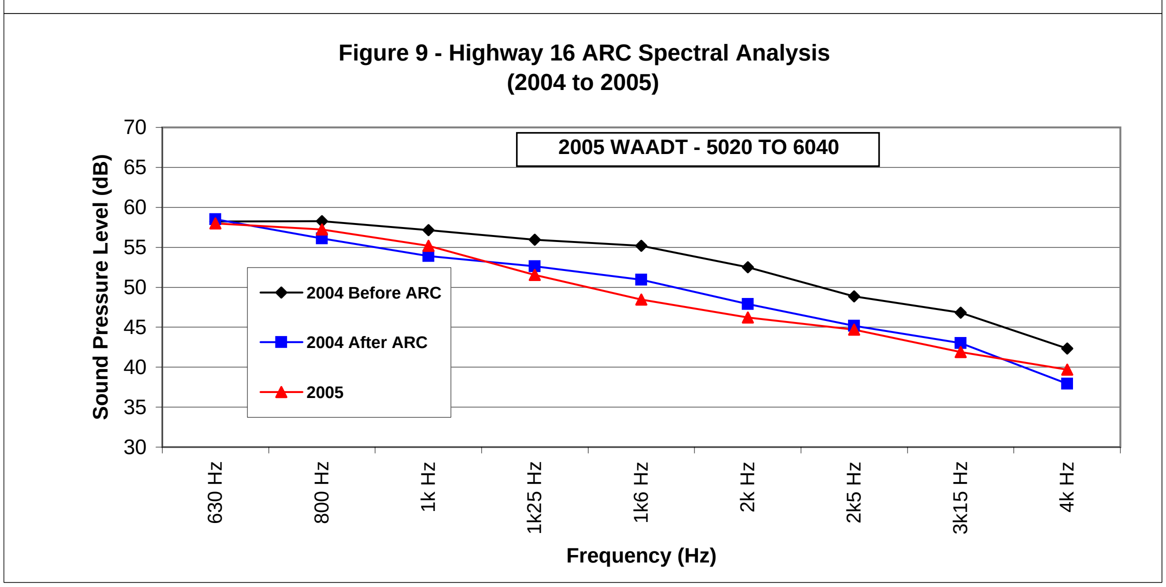


Figure 9 - Highway 16 ARC Spectral Analysis
(2004 to 2005)
2005 WAADT - 5020 TO 6040
2004 Before ARC
2004 After ARC
2005
Sound Pressure Level (dB)
70
65
60
55
50
45
40
35
30
630 Hz
800 Hz
1k Hz
1k25 Hz
1k6 Hz
2k Hz
2k5 Hz
3k15 Hz
4k Hz
Frequency (Hz)

Figure 10 - Highway 16 ACP Spectral Analysis

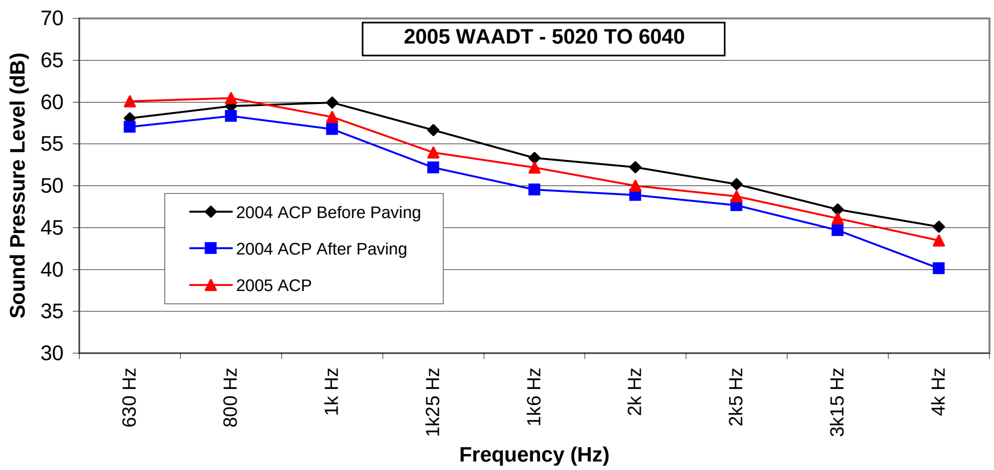


Figure 11 - Highway 16 ARHBFC Spectral Analysis (2004 to 2005)