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Feasibility of the Use of Two Spent blast Materials as Aggregate in Hot Mix Asphalt in Louisiana Post-Katrina

A Dissertation

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Engineering and Applied Science

By

Amer Kholoqui Khanfar
B.Sc Palestine Polytechnic University 2001
M.S. University of New Orleans 2004

December, 2007

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Amer Khanfar

Table of Contents

List of Figures

List of Tables

Abstract

Using spent abrasive blast material (ABM) in hot mix asphalt to replace part of the fine aggregates used in the production of conventional hot mix asphalt has several environmental benefits. First, onsite storage of spent ABMs negatively impact neighboring properties because the fine materials are a source of airborne debris and dust. Use of tarps as curtains only reduces this hazard. Secondly, storage piles of this waste are situated near canals, waterways and the Mississippi River. Future storms may carry these waste products into the neighboring waterways. Most importantly, these wastes are ultimately disposed of in non-hazardous landfills. Reuse of this waste has benefits that are even important in southeast Louisiana, where massive amounts of hurricane debris and construction-related wastes require vast landfill space for disposal. This thesis is concerned with recycling the spent abrasive materials that are generated at two shipyards in New Orleans, Bollinger Shipyards Inc (Bollinger), and Northrop-Grumman Avondale (Avondale), as opposed to storage onsite at shipyard facilities with subsequent disposal in non-hazardous landfills. The reported production rate of spent ABM from the two shipyards is in the range of 400-600 tons/month. A feasibility study, including physical, mechanical and environmental tests, was performed to evaluate if the waste can be used as part of a modified hot mix asphalt. Two methods, the Marshall Method and Super-Pave Method, were used for evaluating the performance of the modified mix. Consequently, a large number of samples based on these methods have been made and tested. One of the major findings of this study is that the recycling and reuse option is a more desirable waste management option. Waste minimization credit may be given to the shipyard generator of the spent ABM. Preliminary results indicate that this reuse option seems to be both effective and conservative.

An additional part of this research is concerned with the impact of Hurricane Katrina on asphalt pavement life due to submergence in flood water. Two sets of samples were conditioned using water for two different salinity, durations, and heights to evaluate the strength of conditioned specimen by comparing the tension strength of conditioned specimens to that of unconditioned control specimens. Test results are given for specimens made of a conventional mix, a mix modified with 8% of spent coal slag, and a mix modified with 10 % of silica sand varying two variables:

- Salinity.
- Storm surge.

CHAPTER ONE INTRODUCTION

1.1 Introduction

The recycling of waste into hot mix asphaltic concrete is not a new concept. A wide variety of materials have successfully been substituted for some portion of the normal ingredients without adverse effects on the asphalt quality. The greatest example of waste used as aggregate in asphalt is the reuse of old asphalt from previous pavement. Old asphalt paving is scraped up from a roadway surface and crushed, then substituted for a portion of the virgin aggregates in hot mix asphaltic concrete. A more recent reuse of waste in hot mix asphalt is the recycling of spent abrasive blast materials as a substitution for a part of the normal virgin aggregate materials. As long as the metals concentrations in the spent ABM are not excessive, the concentrations in the asphaltic concrete will be very low. Any metals present will be physically and chemically bound within the hot mix asphalt mixture. However the recycling of spent ABM into hot mix asphalt must be qualified on a case-by-case basis.

Typically, asphaltic concrete is 4%-10% bitumen mix with graded aggregate. The aggregate is a mixture of specific proportions of particles ranging in size from fine sand to medium-diameter gravel (1/2” – 1”). Depending on the mix design and strength and durability requirements, the fine particles may comprise 35-45% of the asphaltic concrete. Total aggregate portion in a mix may be as high as 90-95% by weight of the paving mixture. This makes the quality (size, gradation, cleanliness, toughness, shape, surface texture, absorptive capacity and affinity for asphalt), cost and availability of aggregate a critical factor in pavement performance. Although the bitumen makes up the smallest percentage in the mixture, it is by far the most costly ingredient, so a good aggregate should not be too absorptive.

When using spent ABM's as a substitute for normal aggregate, the aggregate must comply with both performance and environmental standards. ABM containing solvents should not be used. ABM with high metals concentrations may pose health risks to asphalt plant personnel due to dust inhalation and to the general public due to metals leaching. The presence of sulfate or metallic iron should be avoided; upon oxidation, detrimental swelling will occur. High silt or very fine particles are undesirable, as the portion allowed in a hot mix is limited and they contribute to poor wetting capabilities in the bitumen matrix. Finally and most importantly, aggregate particle shape is very important for good vehicular traction and pavement durability; angular particles give the best hot mix asphaltic concrete performance. Round particles should be avoided.

The recycling of spent ABM in asphaltic concrete can be an effective and inexpensive way to manage waste material. This type of recycling has a track record in other states such as California, Maine, North Carolina and Ohio. Each project must be qualified on a case-by-case basis. Each spent ABM has different physical and chemical characteristics, the mixes provided by an asphalt producer are highly dependent on aggregate cost and availability in the specific locality, and environmental regulations vary from state to state.

1.2 Objectives of the research

The primary objective of this research is to assess and demonstrate the feasibility of recycling two different spent abrasive materials (Black Beauty and silica sand) as aggregate in hot mix asphalt in Louisiana.

In order to achieve this objective, these materials must be characterized as fine aggregate for use in hot mix asphalt. This requires many tests to be conducted to determine the physical properties of the virgin spent ABM. Next the modified asphalt mix must be tested using methods used typically in asphalt pavement design. These include Marshall and Superpave methods. Using these specifications performance of the modified hot mix asphalt can be compared to minimum measures required.

A second objective of this research is to ascertain the impact of prolonged flooding on conventional and modified hot mix asphalt by simulating Hurricane Katrina flooding. The performance of modified mixes should be close to that of a conventional mix.

1.3 Research outline and organization

This dissertation documents the feasibility of using two different spent ABM (Black Beauty and silica sand) in hot mix asphalt, characterizes the new aggregate ABM, evaluates the new mixture performance, mechanical and physical behavior under the new aggregate internal structure, and evaluates the life strength of submerged specimens. This dissertation is organized into five chapters and one appendix (Appendix A).

Chapter one is an introduction and presents background information on hot mix asphalt. Chapter two defines the materials used and their sources. It has detailed information about the reuses of the ABM, and advantages and limitations of using spent blast materials. Chapter three describes the physical and mechanical behavior and properties of the aggregate ABM. It contains all tests and procedures used to characterize these new aggregate. Chapter four presents detailed information about the modified hot mix asphalt with a different percent of the virgin asphalt cements (AC), and the optimum AC is founded for both materials the Black Beauty and the silica sand. Chapter five concludes the results and future research. Appendix A contains hot mix asphalt tests tables for Superpave results.

1.4 Scope

A procedure for determining the feasibility of recycling spent abrasive blast materials as part of hot mix asphalt has been developed. Two spent blast materials were chosen from two local shipyards in New Orleans. The first phase in this research is a feasibility study of using a spent coal slag (Black Beauty) that is generated in North-Grumman shipyard as a result of the production process.

The second phase in this research is a feasibility study including physical and chemical analysis, for characterizing spent silica sand material used by Bollinger Shipyard in the New Orleans area.

The final phase is novel. After Hurricane Katrina there has been a marked deterioration of New Orleans asphaltic pavement. A new test procedure has been developed and implemented to determine the degradation of asphalt specimens conditioned by submergence in water of varying depth, duration and salinity. Comparison of the tensile strength of control specimens and that of conditioned specimen is made. Mixes used in this final phase of testing include a conventional mix typically used in the New Orleans area, a modified spent coal slag mix, and a modified spent silica sand mix. Mixes recycling spent ABM’s should not show a marked difference in degradation when compared to that of the conventional mix.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Many types of ABM are used to remove paint, coatings, and/or corrosion from industrial structures. When the blast material no longer functions as required, it is typically classified as a waste and is disposed of in a landfill. Promising waste minimization alternatives are available for managing spent ABM such as recycling the spent material as part of asphaltic pavement.

Thus recycling of the spent abrasive blast material such as coal slag or silica sand into hot mix asphalt is not an essentially new concept. A wide variety of materials have been successfully substituted for some portion of the normally used aggregate without undesirable effects on product quality.

Recycling spent ABM has the potential to significantly reduce waste generation while saving money. This research is to demonstrate the feasibility of substituting two different spent abrasive materials as aggregate in hot mix asphalt in Louisiana. The reported production rate of spent ABM from two shipyards in New Orleans (Bollinger and Avondale) is in the range of 400-600 tons/m.

Coal slag is a fused ferro-alumino-silicate formed when molten slag from a coal combustion boiler is quenched in water. The water quench cools the slag quickly, resulting in an amorphous, non-crystalline particulate. Thermal shock from the rapid cooling fractures the slag into rough, angular particles. ABM can be produced from the slag particles simply by segregating different particle-size grades using screens (Austin, 1995). Higher quality ABM can be made by performing an initial crushing and screening followed by magnetic separation to remove metal particles. Avondale uses a coal slag ABM marketed under the name Black Beauty.

Silica sand (industrial sand) is high-purity quartz (SiO_2) sand deposited by natural processes. Depending on its chemical and physical characteristics, silica sand is used as glass sand, foundry sand, abrasives, fillers, and hydraulic fracturing sand (also termed "frac" sand by the petroleum industry). Bollinger uses silica sand as ABM.

2.2 Hot Mix Asphalt Recycling Technology

The ABM-to-asphalt recycling technology involves substituting the ABM for a portion of the fine-size aggregate in asphalt concrete. As long as the metal concentrations in the spent ABM are not excessively high, the metal concentrations in the asphalt concrete product should be very low, and any metals present must be physically and chemically immobilized in the asphalt binder (Ahmed, 1993). Typically, asphalt concrete consists of approximately 4-5 percent bitumen and 94-96 percent graded aggregate by weight. The graded aggregate includes particles varying from fine sand to 12- to 25-mm (1/2- to 1-in.) gravel. Depending on the mix design and the ultimate strength requirements of the product, the fine-size particle fraction may comprise 25 to 35 percent of the asphalt concrete. Using the quality control Lab at Barriere Construction Co, a maximum ABM concentration of (7-10) percent by weight of the final asphalt concrete is being used. In other words, spent ABM equals (7-10) percent of the asphalt concrete and approximately two-tenth to three-tenth of the normal fine fraction component of the asphalt concrete. Higher ABM contents are possible; theoretically, the entire fine fraction of the mix design could be composed of ABM. At higher ABM concentrations, however, a greater potential exists for adverse impact on product quality and/or elevated metals concentrations in the product. ABM recycling is applicable to both cold- and hot-mix asphalt processes. The ABM being recycled into hot-mix asphalt in this research is for an asphalt pavement used in normal commercial paving applications. It replaces part of the typically used fine aggregate, such pump sand or fine sand, yielding high-strength asphalt concrete for heavily used highways.

2.3 Abrasive Blast Material Reuses

A wide variety of ABM spent blast materials have successfully been substituted for some portion of the normal ingredients without adverse effect on the asphalt quality.

ABM is potentially usable as a raw of different construction materials other than asphalt.

2.3.1 Use of Spent Abrasive as a Raw Material in Ceramic Manufacture.

Spent ABM and similar waste streams consisting predominantly of silica and/or alumina with low levels of metal contaminants can be processed thermally to form glass or ceramic products or be used as raw materials in ceramic manufacture. The glass or ceramic matrix can effectively immobilize many metal impurities. The metal contaminants may even impart desirable properties such as coloration or increased hardness to the product.

2.3.2 Use of Spent Abrasive as a Construction Material.

Depending on its chemical and physical characteristics, spent ABM is potentially usable as a raw material in the production of a number of different construction materials other than asphalt concrete. In California, the U.S. Navy has been studying the recycling of spent copper slag ABM in the manufacture of Portland cement. This recycling option takes advantage of the relatively high iron content of copper slag ABM.

2.3.3 Use of Spent ABM in Hot Mix Asphalt

Numerous waste materials resulting from manufacturing operations have been the subject of recycling studies. Several states in recent years have either mandated the use of some waste materials or examined the feasibility of reusage. The hot mix asphalt (HMA) industry has been pressured in recent year to incorporate a variety of waste materials in HMA pavement. This has raised the following legitimate concerns:

1- Engineering properties (such as strength and durability, impact on its production and its future recyclability).
2- Environmental issues (such as emission, fumes, handling, and leaching).

Despite these concerns, some wastes have been successfully used in Hot Mix Asphalt.

2.3.3.1 Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) can be used as a recycling aggregate in asphalt paving mixtures in one of two ways. The most common method (conventional recycled hot mix) involves a process in which RAP is combined with virgin aggregate and new asphalt cement in a central mixing plant to produce new hot mix paving mixtures. A second method (hot in-place recycling) involves a process in which asphalt pavement surface distress is corrected by softening the existing surface with heat, mechanically removing the pavement surface, mixing it with a recycling or rejuvenating agent, possibly adding virgin asphalt and/or aggregate, and replacing it on the pavement without removing the recycled material from the pavement site (Brown, 1992).

2.3.3.2 Use of Glass Cullet as an Aggregate in Asphalt

Asphalt containing glass cullet as an aggregate is called “glassphalt,” and has been widely tried as a means to dispose of surplus waste glass since the 1960’s. Glassphalt is basically the same as conventional hot-mix asphalt, except that 5% to 40% of the rock and/or sand aggregate are replaced by crushed glass. The cost-effectiveness of substituting glass for conventional aggregate is highly dependent on the location, the quality and cost of local aggregates, and any credits available for using recycled materials in beneficial re-use applications (Monroe, 1990).

2.3.3.3 Use of Rubber as Modifier or Fine Aggregate in Hot Mix

Scrap tire rubber can be incorporated into asphalt paving mixes using two different methods referred to as the wet process and the dry process. In the wet process, crumb rubber acts as an asphalt cement modifier, while in the dry process, granulated or ground rubber and/or crumb rubber is used as a portion of the fine aggregate. In both cases, crumb rubber is sometimes referred to as crumb rubber modifier (CRM) because its use modifies the properties of the resultant hot mix asphalt concrete product (Heitzam, 1992).

2.4 ABM (Black Beauty and Silica Sand) Used in this Study

Two kinds of spent ABM were used in this research to be substituted as part of the fine aggregate in the hot mix asphalt. The spent ABM came from two different generators and locations. The two spent ABM used in this study are produced in large quantities by local shipyards in Louisiana.

Spent coal slag is the ABM waste generated by Avondale shipyards, one of the industrial partners in this research. The amount produced by Avondale ranges between 150-300 tons a month. Silica sand waste is produced and generated by Bollinger shipyards, another industrial partner in this research. The amount Bollinger produces ranges between 100-150 tons per month.

2.4.1 Environmental Issues

Physical and chemical characteristics influence the recyclability of slag ABM. The regulatory status is the single most important factor because waste management practices controlled by the Resource Conservation and Recovery Act (RCRA) or state hazardous waste regulations reduce the flexibility in selecting and implementing recycling options. Physical properties such as particle size and shape and chemical properties such as total composition also affect the acceptance of spent ABM in commercial applications. ABM produced from slag may contain elevated background levels of regulated metals. ABM from coal slag will typically contain nickel and vanadium and a variety of other metals depending on the coal that was used as the source of the slag. Copper slag from primary smelters contains elevated copper and barium levels and lower but significant levels of cobalt, trivalent chromium, and nickel. Copper slag from secondary smelters may contain significant levels of lead and arsenic. Nickel slag typically contains elevated concentrations of nickel, copper, and trivalent chromium and lower levels of cobalt and vanadium. Arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver are used to determine leachable metal toxicity by the U.S. Environmental Protection Agency (U.S. EPA) under RCRA. Some states, for example California, consider additional metals and total content as well as leachability in their definition of hazardous waste. It is unlikely but possible that unused ABM will be classified as a hazardous material by virtue of its background soluble or total metal content. A high background metals content in the virgin ABM means that the addition of a relatively small amount of metals-containing dust during blasting may cause the spent ABM to be classified as hazardous.

2.4.2 ABM Production and Compatibility of Recycling

Most ABMs are produced in at least three different particle size grades. In general, the coarser grades are more compatible with recycling as aggregate for Portland cement concrete or asphaltic concrete because they mix better. Rounded particles are more suitable for use in Portland cement, whereas sharp, angular particles are better for use in asphaltic concrete.

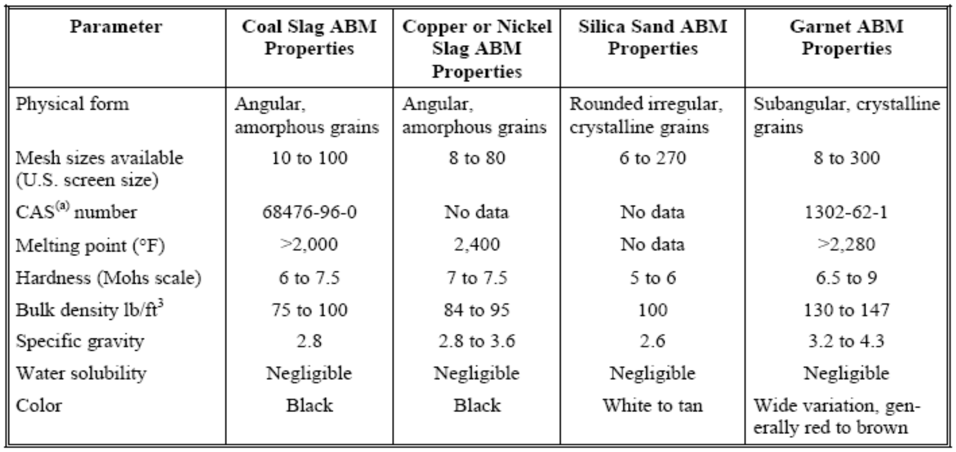
The chemical composition can affect the performance of spent ABM. The dark colors of slag ABM may limit acceptance in products with an appearance function where the slag materials replace lighter colored natural minerals. High chloride concentrations are undesirable in many applications. Sulfate concentrations or high alkali reactivity would make the ABM unsuitable for use as aggregate in Portland cement.

Natural minerals such as silica sand, garnet, or staurolite are also used for ABM. Silica sand ABM is typically composed of mostly quartz with some garnet and feldspar and traces of lithic fragments such as hornblende. The fine silica particles produced by blasting with sand create a significant health concern, so use of sand as ABM is declining. Garnet is a general name for a family of complex silicate minerals having similar physical properties and crystal form. The general formula for garnet is A3B2(SiO4)3, where A can be calcium, magnesium, ferrous iron, or manganese and B can be aluminum, ferric iron, chromium, or (in rare cases) titanium. The most common garnet minerals for use as ABM are $Mg_3Al_2(SiO_4)_3$ (pyrope), $Fe_3Al_2(SiO_4)_3$ (almandite), and Ca3Fe2(SiO4)3 (andradite). Almandite andalmandite-pyrope solid solutions make the best abrasive grains. Andradite is softer and breaks down more easily. Staurolite is $(Fe^{2+},Mg,Zn)_2Al_9(Si,Al)_4O_{23}(OH)_{2.}$

Mineral ABM may be naturally occurring sand or may be manufactured by crushing and size grading using screens. Sand for abrasive blasting is produced by 48 companies operating 84 mines (Austin, 1995).Ten firms produce garnet ABM with a total volume and sales in 1992 of 25,000 tons (22,700 metric tons) and $7,800,000, respectively (Paumanok, 1992). DuPont, marketing Starblast, is the only supplier of staurolite ABM. Unofficial sources estimate the 1992 volume and sales for Starblast at 55,000 tons (50,000 metric tons) and $7,700,000, respectively (Paumanok, 1992). Similar to slag ABM, mineral ABM is available in different particle sizes, with the coarse grades more amenable to recycling into asphalt. However, unlike slag ABM, abrasives made from natural minerals contain low background metals concentrations. The matrix of mineral ABM is unlikely to contribute to total or leachable hazardous metals which can make recycling easier.

2.5 Physical Characteristics of Abrasive Blasting Media

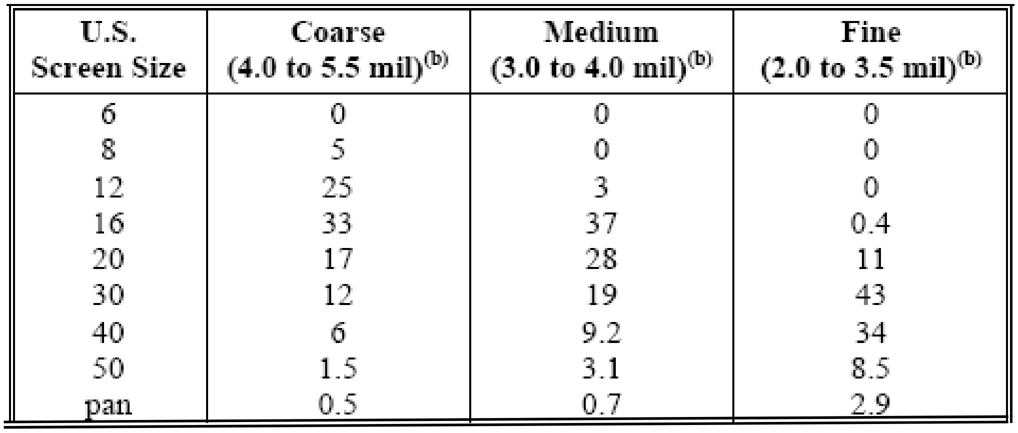
As discussed above, the physical properties of ABM influence the selection of recycling options. Some key properties of unused slag and mineral ABM are shown in Table 2.1



Parameter	Coal Slag ABM Properties	Copper or Nickel Slag ABM Properties	Silica Sand ABM Properties	Garnet ABM Properties
Physical form	Angular, amorphous grains	Angular, amorphous grains	Rounded irregular, crystalline grains	Subangular, crystalline grains
Mesh sizes available (U.S. screen size)	10 to 100	8 to 80	6 to 270	8 to 300
CAS$^{(a)}$ number	68476-96-0	No data	No data	1302-62-1
Melting point (°F)	>2,000	2,400	No data	>2,280
Hardness (Mohs scale)	6 to 7.5	7 to 7.5	5 to 6	6.5 to 9
Bulk density lb/ft^3	75 to 100	84 to 95	100	130 to 147
Specific gravity	2.8	2.8 to 3.6	2.6	3.2 to 4.3
Water solubility	Negligible	Negligible	Negligible	Negligible
Color	Black	Black	White to tan	Wide variation, generally red to brown

Table 2.1: Physical Properties of Unused Abrasive Blasting Media

ABM is available in grades, based on particle size, ranging from extra coarse to very fine. The size grading available varies with the grit maker but some example particle size ranges for grades of expendable ABM are indicated in Table 2.2. The correspondence of screen size to screen opening is shown in Table 2.2 along with the Unified Soil Classification size ranges for sand, silt, and clay to provide a basis for comparing the size of ABM with typical soil materials (see Table 2.5).



U.S. Screen Size	Coarse (4.0 to 5.5 mil)$^{(b)}$	Medium (3.0 to 4.0 mil)$^{(b)}$	Fine (2.0 to 3.5 mil)$^{(b)}$
6	0	0	0
8	5	0	0
12	25	3	0
16	33	37	0.4
20	17	28	11
30	12	19	43
40	6	9.2	34
50	1.5	3.1	8.5
pan	0.5	0.7	2.9

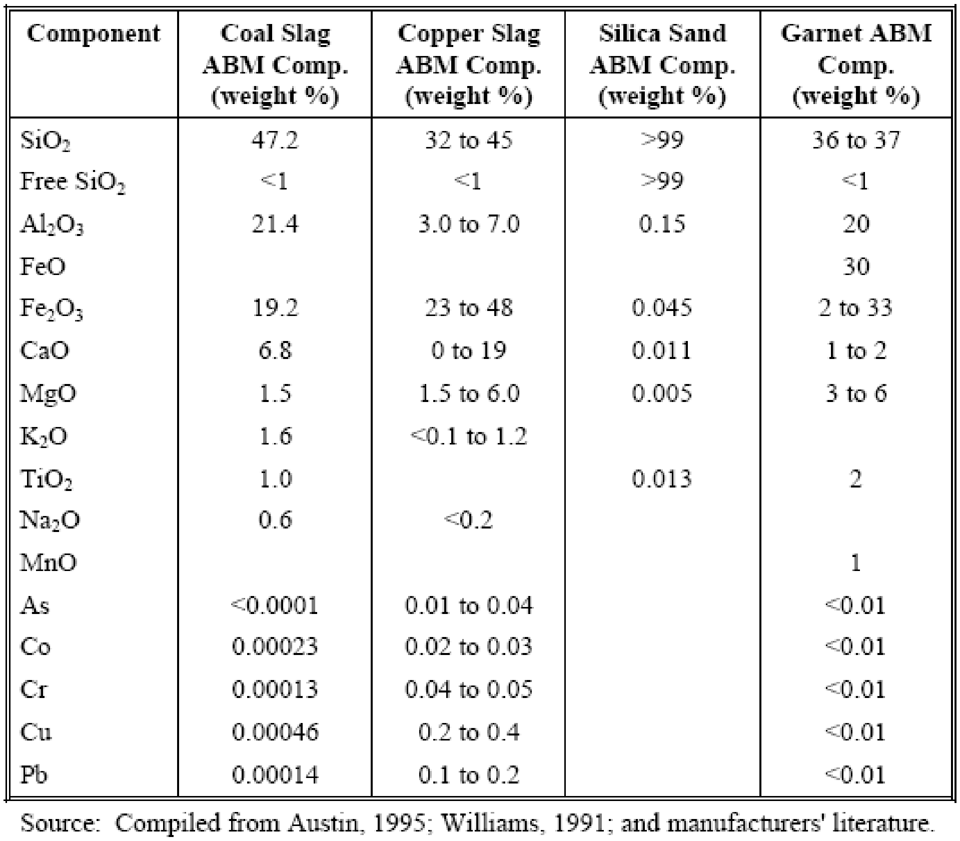
Table 2.2: US standard sieves (Screen Size)

2.6 Chemical Characteristics of Abrasive Blasting Media

This section summarizes some recent data about the total composition and leachable metals content of unused and spent ABM. Slag media may contain elevated levels of regulated metals. Pigments in paint chips removed by ABM increase the leachable metal content of spent ABM. Some common pigments containing RCRA hazardous metals include red lead, white lead, chromium yellow, chromium orange, molybdate orange, zinc yellow, chromium green, and chromium oxide green (U.S. EPA, 1990b, EPA/530-SW-90-059Y). Spent ABM in shipyards can contain paint chips with copper- or tributyltin-based antifouling paints or lead-based primers.

2.6.1 Chemical Characteristics of Unused Media

The approximate chemical composition of some example slag and mineral ABM materials in unused condition is shown in Table 2.3. Most coal slag ABM contains only small quantities of RCRA-regulated metals, and the vitrified form provides a leach-resistant matrix, so hazardous metal leachability should be low. For example, all Toxicity Characteristic Leaching Procedure (TCLP) leachable metal concentrations from Black Beauty ABM, as shown in Table 2.4, are far below the regulatory level for a toxic leachable characteristic. Metallurgical slag typically will have higher residual metal content but is still unlikely to have a RCRA leachable toxicity characteristic in the unused condition. The natural mineral ABM materials should have low trace metal content (see Table 2.4).



Component	Coal Slag ABM Comp. (weight %)	Copper Slag ABM Comp. (weight %)	Silica Sand ABM Comp. (weight %)	Garnet ABM Comp. (weight %)
SiO_2	47.2	32 to 45	>99	36 to 37
Free SiO_2	<1	<1	>99	<1
Al_2O_3	21.4	3.0 to 7.0	0.15	20
FeO				30
Fe_2O_3	19.2	23 to 48	0.045	2 to 33
CaO	6.8	0 to 19	0.011	1 to 2
MgO	1.5	1.5 to 6.0	0.005	3 to 6
K_2O	1.6	<0.1 to 1.2		
TiO_2	1.0		0.013	2
Na_2O	0.6	<0.2		
MnO				1
As	<0.0001	0.01 to 0.04		<0.01
Co	0.00023	0.02 to 0.03		<0.01
Cr	0.00013	0.04 to 0.05		<0.01
Cu	0.00046	0.2 to 0.4		<0.01
Pb	0.00014	0.1 to 0.2		<0.01

Source: Compiled from Austin, 1995; Williams, 1991; and manufacturers' literature.

Table 2.3: Chemical Composition of Unused Abrasive Blasting Media

Contaminant	Coal Slag Leachability[a] (mg/L)	Garnet Leachability (mg/L)	Regulatory Limit (mg/L)
Ag	BDL to 0.151	<0.05	5.0
As	BDL to 0.048	<0.1	5.0
Ba	BDL to 0.482	<0.1	100.0
Cd	BDL to 0.007	<0.02	1.0
Cr	BDL	<0.05	5.0
Hg	BDL to 0.041	<0.001	0.2
Pb	BDL to 0.605	<0.5	5.0
Se	BDL to 0.048	<0.1	1.0

Table 2.4: TCLP Analysis of Unused Black Beauty ABM

U.S. Screen Size	Opening Size (mm)	Opening Size (inches)	Unified Soil Classification
4	4.75	0.187	Coarse sand
6	3.35	0.132	
8	2.36	0.0937	
10	2.00	0.0787	
12	1.7	0.0661	Medium sand
14	1.4	0.0555	
16	1.18	0.0469	
18	1.00	0.0394	
20	0.850	0.0331	
30	0.600	0.0234	
40	0.425	0.0165	
50	0.300	0.0117	
60	0.250	0.0098	
70	0.212	0.0083	Fine sand
80	0.180	0.0070	
100	0.150	0.0059	
120	0.125	0.0049	
140	0.106	0.0041	
200	0.075	0.0029	
230	0.063	0.0025	Clay or silt[a]
270	0.053	0.0021	
325	0.045	0.0017	

Table 2.5: Unified Soil Classification

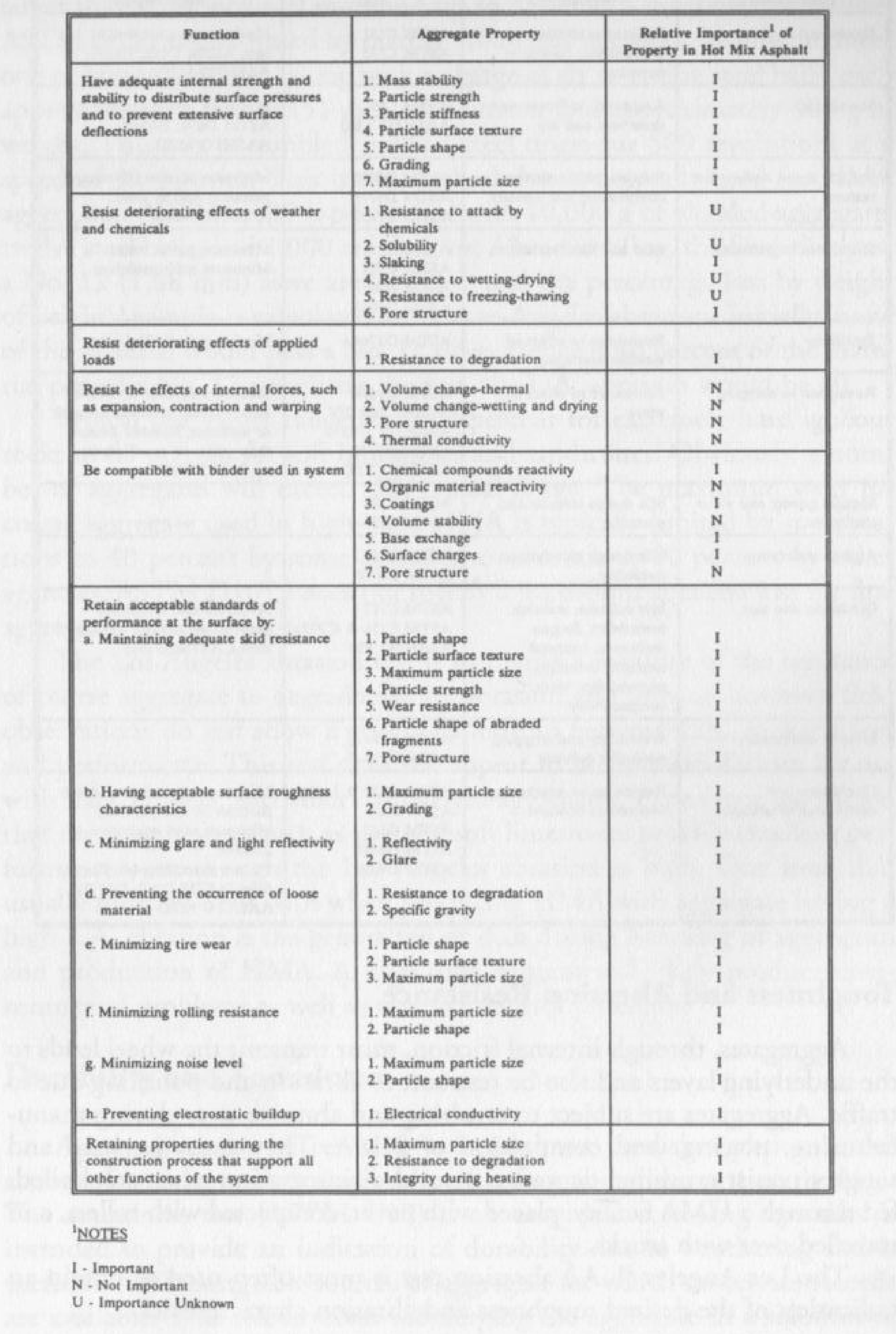
2.7 Physical and Mechanical Properties of Aggregates

Aggregates used for HMA are usually classified by size as coarse aggregates, fine aggregates, or mineral fillers. ASTM defines coarse aggregate as particles retained on a No.4 (1.75 mm) sieve, fine aggregate as that passing a No.4 sieve, and mineral filler as material with at least 70% passing the No.200 (75 µm).

Aggregate for HMA are generally required to be hard, tough, strong, durable (sound), properly graded, to consist of cubical particles with low porosity, and to have clean, rough, hydrophobic surface. Table 2.6 summarizes the various properties that an aggregate must possess in order to fulfill its function and the relative importance of aggregate in HMA.

Specification of coarse aggregates, fine aggregates, and mineral fillers, are given in ASTM D692, D1073, and D242, respectively. The suitability of aggregates for use in HMA is determined by evaluating the following material characterization:

- Size and gradation
- Cleanliness/deleterious materials
- Toughness/hardness
- Durability/soundness
- Surface texture
- Particle shape
- Absorption



Function	Aggregate Property	Relative Importance[1] of Property in Hot Mix Asphalt
Have adequate internal strength and stability to distribute surface pressures and to prevent extensive surface deflections	1. Mass stability 2. Particle strength 3. Particle stiffness 4. Particle surface texture 5. Particle shape 6. Grading 7. Maximum particle size	I I I I I I I
Resist deteriorating effects of weather and chemicals	1. Resistance to attack by chemicals 2. Solubility 3. Slaking 4. Resistance to wetting-drying 5. Resistance to freezing-thawing 6. Pore structure	U U I U U I
Resist deteriorating effects of applied loads	1. Resistance to degradation	I
Resist the effects of internal forces, such as expansion, contraction and warping	1. Volume change-thermal 2. Volume change-wetting and drying 3. Pore structure 4. Thermal conductivity	N N N N
Be compatible with binder used in system	1. Chemical compounds reactivity 2. Organic material reactivity 3. Coatings 4. Volume stability 5. Base exchange 6. Surface charges 7. Pore structure	I N I N I I N
Retain acceptable standards of performance at the surface by: a. Maintaining adequate skid resistance	1. Particle shape 2. Particle surface texture 3. Maximum particle size 4. Particle strength 5. Wear resistance 6. Particle shape of abraded fragments 7. Pore structure	I I I I I I I
b. Having acceptable surface roughness characteristics	1. Maximum particle size 2. Grading	I I
c. Minimizing glare and light reflectivity	1. Reflectivity 2. Glare	I I
d. Preventing the occurrence of loose material	1. Resistance to degradation 2. Specific gravity	I I
e. Minimizing tire wear	1. Particle shape 2. Particle surface texture 3. Maximum particle size	I I I
f. Minimizing rolling resistance	1. Maximum particle size 2. Particle shape	I I
g. Minimizing noise level	1. Maximum particle size 2. Particle shape	I I
h. Preventing electrostatic buildup	1. Electrical conductivity	I
Retaining properties during the construction process that support all other functions of the system	1. Maximum particle size 2. Resistance to degradation 3. Integrity during heating	I I I

[1] NOTES

I - Important
N - Not Important
U - Importance Unknown

Table 2.6: Aggregates Properties to Meet Function System (Robert, 1996).

2.8 Performance Tests for HMA

Performance tests are used to relate laboratory mix design to actual field performance. The Hveem (stabilometer) and Marshall (stability and flow) mix design methods use only one or two basic performance tests. Superpave is intended to use a better and more fundamental performance test. However, performance testing is the one area of Superpave yet to be implemented. The performance tests discussed in this section are used by various researchers and organizations to supplement existing Hveem and Marshall tests and as a substitute for the Superpave performance test until it is finalized.

As with asphalt binder characterization, the challenge in HMA performance testing is to develop physical tests that can satisfactorily characterize key HMA performance parameters and how these parameters change throughout the life of a pavement. These key parameters are:

- **Deformation resistance (rutting)** is a key performance parameter that can depend largely on HMA mix design. Therefore, most performance test efforts are concentrated on deformation resistance prediction.

- **Fatigue life** is a key performance parameter that depends more on structural design and subgrade support than mix design. Those HMA properties that can influence cracking are largely tested for in Superpave asphalt binder physical tests. Therefore, there is generally less attention paid to developing fatigue life performance tests.

- **Tensile strength** can be related to HMA cracking - especially at low temperatures. Those HMA properties that can influence low temperature cracking are largely tested for in Superpave asphalt binder physical tests. Therefore, there is generally less attention paid to developing tensile strength performance tests.

- **Stiffness** of HMA's stress-strain relationship, as characterized by elastic or resilient modulus, is an important characteristic. Although the elastic modulus of various HMA mix types is rather well-defined, tests can determine how elastic and resilient modulus varies with temperature. Also, many deformation resistance tests can also determine elastic or resilient modulus.
- **Moisture susceptibility** is the final key parameter. Certain combinations of aggregate and asphalt binder can be susceptible to moisture damage. Several deformation resistance and tensile strength tests can be used to evaluate the moisture susceptibility of a HMA mixture.

2.9 Methods of HMA Design

This section details an overview of the mixture design methods that have been or being used by the asphalt industry. Generally, most of the mix design methods rely on experience and performance of mixes of known composition. Almost all mixture design methods include specimen fabrication and compaction in the mix design process to determine the mixture composition and volumetric properties.

2.9.1 Hubbard-Field Method

A test method for determining the optimum asphalt content of sheet asphalt surfaces and sand asphalt bases was devised by Hubbard and field tested in the middle 1920s. The test consisted of determining the maximum load developed as a specimen 2 inches (50.8

mm) in diameter by 1 inch (25.4mm) high was forced through a 1.75-in (44.4 mm) diameter standard orifice. The load was reported as the stability value. Stability numbers corresponding to various asphalt content were plotted and the optimum binder content determined. This was probably the first attempt to quantify empirical mix stability values at various asphalt contents. The method was widely accepted and survived in some states for a long time. The test was modified in the mid 1950s to test six-inch (150 mm) diameter specimens to accommodate mixes containing coarse aggregate up to ¾ inch (19 mm) maximum size. However, the modified version was used for a very short time because the Marshall Test had started to gain popularity during the period.

2.9.2 Hveem Mix Design Method

Hveem a resident engineer in California, Francis Hveem began to work with “oil mixes” during the late 1920s. Oil mixes, which were a combination of fairly good quality gravel and slow-curing liquid asphalts, were being used in California to obtain an intermediate type surfacing for moderate traffic conditions.

When mechanical pavers were introduced in 1937, it became possible to place mixes with heavier grades of asphalt cements. Hveein noticed that there was a relationship between the gradation of the mineral aggregate and the amount of oil required to maintain a consistent color and appearance of the mix. He subsequently found a method for calculating surface area of aggregate gradations developed by a Canadian engineer, L.N. Edwards. Refinements in the method occurred as Hveem realized that the film thickness on a particle decreased as the diameter of the particle decreased. The kerosene equivalent test was developed to take into account differences in oil requirements as the absorption and surface roughness of aggregates varied.

Hveem realized that having the proper oil content did not guarantee good performance relative to rutting. Therefore, another test was needed to evaluate the stability, or the ability to resist the shear forces applied by wheel loads. This led to the development of the Hveem stabilometer. A specimen of a 4-inch (101.6 mm) diameter and 2½inch (63.5 mm) height is subjected to a vertical load on the circular surface and the amount of vertical load that is transmitted horizontally is measured. The circumferential perimeter of the specimen is restrained by a neoprene diaphragm and is surrounded by an oil reservoir to simulate field loading conditions. Empirical stability numbers are obtained at various asphalt contents. Specimens are prepared with a kneading compactor, which is a hydraulic device that applies pressure to the specimen through a hydraulically operated tamper foot. The foot is raised after a specified pressure is sustained by the specimen, the base rotates 1/6 of a revolution, the tamper foot automatically lowered, and the specified pressure is applied again around the perimeter of the specimen. The area of the tamper foot is one-fourth the cross sectional area of the specimen.

A second mechanical test device called a cohesiometer was developed along with the Hveem stahitometer. It was designed to measure the cohesive strength across the diameter of a compacted specimen on which the stability test had already been conducted. The specimen is placed in the cohesiometer, the specimen is secured, and the load is applied by lead shots flowing from a reservoir into a bucket at the end of the moment (details are given in ASTM D1560). Load is applied until the specimen fails, and at that time the shot supply is automatically shut off. The total applied force is determined and the cohesion calculated by a formula. This test was aimed at measuring a tensile property of the oil mixes that could be related to a minimum level to preclude raveling of surface mixes under tractive forces. This test proved to be of little value in characterizing HMA surfacing. HMA surfacing was made with asphalt cement and always had cohesion values large enough to prevent raveling. Therefore, when oil mixes were replaced by HMA surfacing after World War II, the cohesiometer test served no real purpose and it gradually fell out of favor.

2.9.3 HMA - Marshall Method

The basic concepts of the Marshall mix design method were originally developed by Bruce Marshall of the Mississippi Highway Department around 1939 and then refined by the U.S. Army. Currently, the Marshall Method is used in some capacity by about 38 states. The Marshall Method seeks to select the asphalt binder content at a desired density that satisfies minimum stability and range of flow values (White, 1985).

During World War II, the U.S. Army Corps of Engineers (USCOE) began evaluating various HMA mix design methods for use in airfield pavement design. Motivation for this search came from the ever-increasing wheel loads and tire pressures produced by larger and larger military aircraft. Early work at the U.S. Army Waterways Experiment Station (WES) in 1943 had the objective of developing a modified Marshall Test.

WES took the original Marshall Stability Test and added a deformation measurement (using a flow meter) that was reasoned to assist in detecting excessively high asphalt contents. This appended test was eventually recommended for adoption by the U.S. Army because:

- It was designed to stress the entire sample rather than just a portion of it.
- It facilitated rapid testing with minimal effort.
- It was compact, light and portable.

- It produced densities reasonably close to field densities.

WES continued to refine the Marshall method through the 1950s with various tests on materials, traffic loading and weather variables. Today the Marshall method, despite its shortcomings, is probably the most widely used mix design method in the world. It has probably become so widely used because of two reasons. It was adopted and used by the U.S. military all over the world during and after WWII and it is simple, compact and inexpensive.

2.9.4 Superpave Mix Design Method

The Superpave Mixture Design and Analysis System were developed in the early 1990's under the Strategic Highway Research Program (SHRP). Originally, the Superpave design method for Hot-Mix Asphalt (HMA) mixtures consisted of three proposed phases:

- Materials selection,
- Aggregate blending, and
- Volumetric analysis on specimens compacted using the Superpave Gyratory Compactor (SGC).

It was intended to have a fourth step which would provide a method to analyze the mixture properties and to determine performance potential. However this fourth step is not yet available for adoption. Most highway agencies in the United States have now adopted the volumetric mixture design method, but there is no strength test to compliment the Superpave volumetric mixture design method. The traditional Marshall and Hveem mixture design methods have associated strength tests.

Even though the Marshall and Hveem stability tests are empirical, they do provide some measure of the mix quality because of the strength tests. There is much work going on to develop a strength test for Superpave, but one has not been finalized for adoption at the time. Considering that approximately 2 million tons of HMA is placed in the U.S. during a typical construction day, contractors and state agencies must have some means as soon as practical to better evaluate performance potential of HMA. Unfortunately, it is likely be several years before one is recommended nationally.

Research from WesTrack, NCHRP 9-7 (Field Procedures and Equipment to Implement SHRP Asphalt Specifications), and other experimental construction projects have shown that the Superpave volumetric mixture design method alone is not sufficient to ensure reliable mixture performance over a wide range of materials, traffic and climatic conditions. The HMA industry needs a simple performance test to help ensure that a quality product is produced. Controlling volumetric properties alone is not sufficient to ensure good performance.

The volumetric analysis in a Superpave mix design uses a traffic loading designated as the Equivalent Single Axle Loading (ESAL), which relates the damage to a pavement by a single equivalent 18-kip axle load. This term is correlated empirically to the traffic volume that the in-place pavement would be expected to experience at the end of the design life. The completed mix is evaluated in the lab by compaction in a gyratory compactor, specifically designed for the Superpave method. Using the calculated ESAL's, the number of gyrations the mix is subjected to is determined and this number is designated as N_{design} . Thus, the loading component the pavement will experience is simulated by compacting the mix specimen at a pre-set pressure of 600 KPa and a determined number of gyrations.

2.10 Asphalt Binder Evaluation

The Marshall test does not have a common generic asphalt binder selection and evaluation procedure. Each specifying entity uses their own method with modifications to determine the appropriate binder and, if any, modifiers. Binder evaluation can be based on local experience, previous performance or a set procedure. Perhaps the most common set procedure now in use is based on the Superpave PG binder system (see Figure 2.1). Before this system there was no nationally recognized standard for binder evaluation and selection. Once the binder is selected, several preliminary tests are run to determine the asphalt binder's temperature-viscosity relationship.

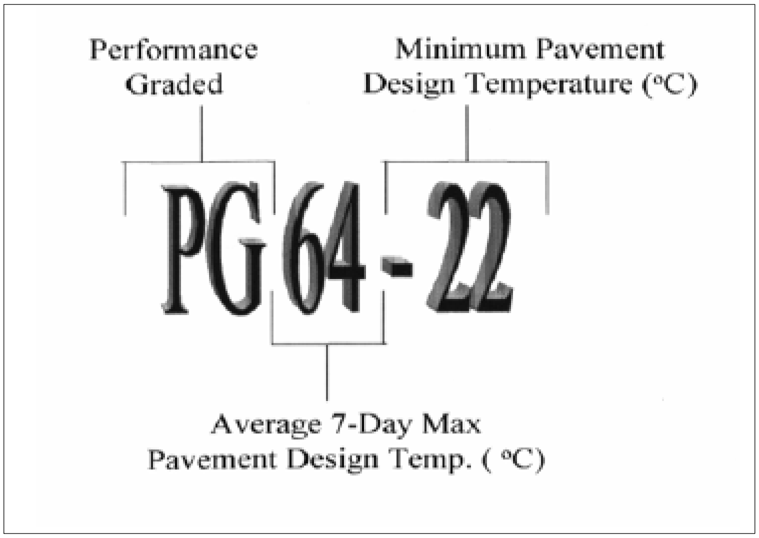


Fig 2.1: Performance graded binder System

CHAPTER 3 MODIFIED HMA TESTING

3.1 Introduction

This chapter details the tests procedures used to characterize ABM as an accepted material for use in hot mix asphalt. These are tests used in a quality control lab.

A number of tests have been conducted and their acceptability is decided based on the test results and the specifications as shown in Figure 3.1. This ensures the desirable level of performance of the chosen material in terms of its permeability, volume stability, strength, hardness, toughness, fatigue, durability, shape, viscosity, specific gravity, purity, safety, and temperature susceptibility. The work plan used included consultation with Louisiana Department of Environmental Quality (LADEQ) and Louisiana Department of Transportation and Development (LADOTD) personnel, creation and use of a sampling plan for acquisition of the spent ABM material from each shipyard, physical testing of virgin conventional materials as well as spent ABM materials, design of trial mixes for both regular Marshall and Superpave hot mixes, optimization of mix design, and environmental/chemical testing of the optimum mixes.

The second part of this study is concerned with simulation of asphalt pavement in New Orleans metropolitan area (Post-Katrina test). Katrina-affected pavements not only were subjected to long term submersion by storm surge, but also increased heavy truck traffic as part of debris removal after the flooding subsided. Therefore, new test procedures were developed by the researchers, with advice from experts in the industry and the Louisiana Transportation Research Center (LTRC) to determine the affects of salinity, submergence duration, and height on the HMA specimens. This testing attempts to simulate the impact of Katrina flooding in HMA pavements.

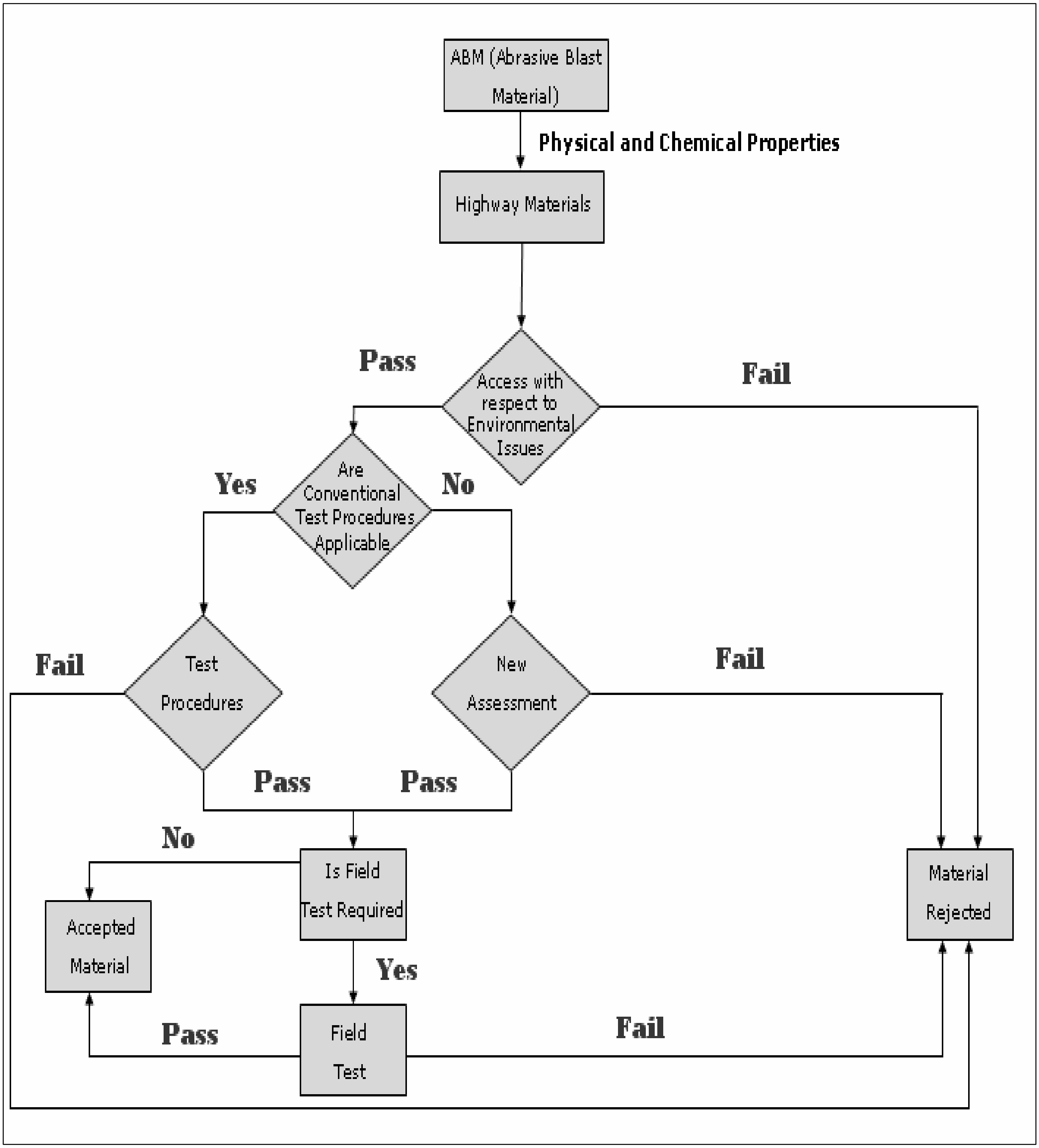


Fig 3.1: Recommended Design Methodology for substituting ABM in HMA

3.2 Laboratory Performance tests and procedures

A number of tests have been conducted in the laboratory in order to classify the spent ABM (Black Beauty coal slag, and silica sand) to determine their acceptability as fine aggregate in hot mix asphalt. Performance tests are used to relate laboratory mix design to actual field performance. The performance tests discussed in this section are used by various researchers and organizations to supplement existing Marshall Tests and as a substitute for the Superpave performance test until it is finalized (McGennis, 1995).

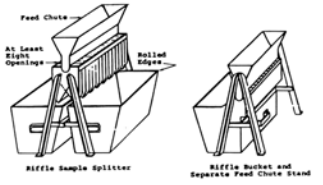
3.2.1 Sampling of Aggregate

Prior to conducting any tests on aggregates, samples must be taken from the source using proper sampling techniques (ASTM D75). The sample may be randomly selected or may be selected to representative depending on the purpose of samples. Usually for mix design, representative samples are taken, and for quality control, random samples are taken.

Samples of aggregate are normally taken from stockpiles, belt, hot bins, or sometimes from loaded trucks. Once a sample has been taken, it must be reduced to the proper size prior to testing. For aggregates this can be done by using either the quartering method or using a sample splitter (ASTM C702).

Random samples were taken from Bollinger and Avondale stockpiles for quality control purposes. ASTM C702 was the method used to create specimens of the required size and shape for subsequent testing.

Cont Figure 3.2



(a) Large Riffle Samplers for Coarse Aggregate

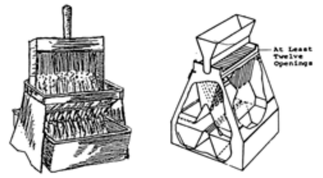


Fig 3.2: Shown the mechanical splitter

3.2.2 Specific Gravity and Absorption.

Specific gravity is the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. Water, at a temperature of 73.4°F (23°C), has a specific gravity of one.

Specific gravity is important for several reasons. Some deleterious particles are lighter than the "good" aggregates. Tracking specific gravity can sometimes indicate a change of material or possible contamination. Differences in specific gravity can be used to separate the bad particles from the good using a heavy media liquid.

Specific gravity is critical information used in HMA. It is used in calculating air voids, voids in mineral aggregate (VMA), and voids filled by asphalt (VFA). All are critical to a well-performing and durable asphalt mix. Water absorption can also be an indicator of asphalt absorption. A highly absorptive aggregate could lead to a low durability asphalt mix. It also negatively impacts the cost of the HMA.

3.2.3 Liquid Limit and PI.

The plastic limit (PL) is the moisture content at an arbitrary limit between the plastic and semisolid state. It is reached when the fine aggregate is no longer pliable and crumbles under pressure. Between the liquid and plastic limits is the plastic range. The numerical difference in moisture content between the two limits is called the plasticity index (PI). The equation is

$$PI = LL - PL.$$

Where: LL: Liquid Limit, and

PL: Plastic Limit.

It defines the range of moisture content within which the fine aggregate is in a plastic state.

3.2.4 Durability and Soundness

Aggregates must be resistant to breakdown and disintegration from weathering (wetting/drying and freezing/thawing) or they may break apart and cause premature pavement distress. Durability and soundness are terms typically given to an aggregate's weathering resistance characteristic. Aggregates used in HMA are dried in the production process and therefore should contain almost no water. Thus, for aggregate used in HMA, freezing/thawing should not be a significant problem.

The most common soundness test involves repeatedly submerging an aggregate sample in a saturated solution of sodium or magnesium sulfate. This process causes salt crystals to form in the aggregate pores, which simulate ice crystal formation (see Figures 3.3 and 3.4). The basic procedure is as follows (from AASHTO T 104):

- Oven dry the sample and separate it into specific sieve sizes.
- Immerse the sample in a saturated solution of sodium or magnesium sulfate and let it remain at a constant temperature for 18 hours.
- Remove the sample from the solution and dry to a constant weight at 110 ± 5^{o}C (230 ± 9^{o}F).

- Repeat this cycle five times.
- Wash the sample to remove the salt; then dry.
- Determine the loss in weight for each specific sieve size and compute a weighted average percent loss for the entire sample.

The maximum loss values typically range from 10 – 20 percent for every five cycles.

Figure 3.3 : Aggregates Before a Soundness Test

Figure 3.4: Aggregates After a Soundness Test

In this research study, the standard soundness tests used are AASHTO T 104 and ASTM C 88 (Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate), and AASHTO T 103 (Soundness of Aggregates by Freezing and Thawing).

3.2.5 Sieve Analysis of Fine Aggregate

The particle size distribution, or gradation, of an aggregate is one of the most influential aggregate characteristics in determining how it will perform as a pavement material. In HMA, gradation helps determine almost every important property including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage (Roberts et al., 1996). Because of this, gradation is a primary concern in HMA design and thus most agencies specify allowable aggregate gradations.

Gradation of aggregates can be graphically represented by a gradation curve for which the ordinate is the total percent by weight passing a given size on an arithmetic scale, which the abscissa is the particle size plotted to a logarithmic scale.

Sieve No.	**Opening (mm)**
2 inches	50.8
1 ½ inches	38
1 inch	25.4
3/4 inch	19
1/2 inch	12.5
3/8 inch	9.5
No. 4	4.75
No. 8	2.36
No. 16	1.18
No. 30	0.6
No. 50	0.3
No. 100	0.15
No. 200	0.075

Table 3.1: US Standard Sieve Sizes

The gradation of a particular aggregate is most often determined by a sieve analysis (see Figure 3.5). In a sieve analysis, a sample of dry aggregate of known weight is separated through a series of sieves with progressively smaller openings. Once separated, the weight of particles retained on each sieve is measured and compared to the total sample weight. Particle size distribution is then expressed as a percent retained by weight on each sieve size. Results are usually expressed in tabular or graphical format. Gradation graph is traditionally of HMA employ the standard 0.45 power gradation graph (see fig 3.6).

Fig 3.5: Standard US sieves

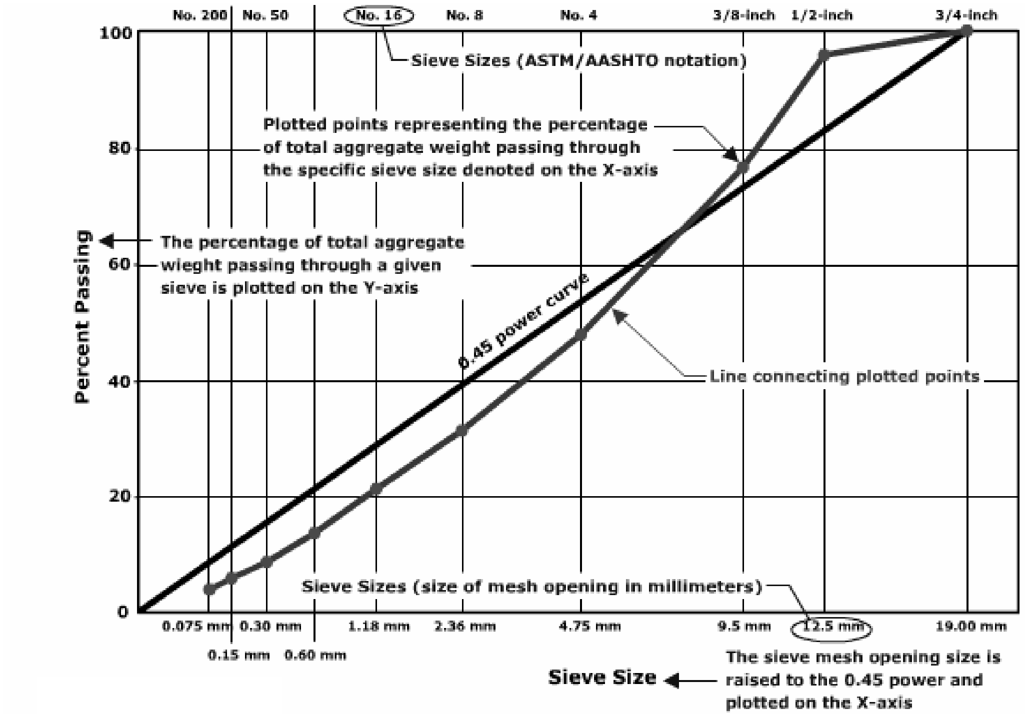


Fig 3.6: Example Sieve Analysis Plot on a 0.45 Power Graph

Its desired characteristics, loading, environmental, material, structural and mix property inputs. Therefore, gradation requirements for specific HMA mixes are discussed in their respective pavement type sections. This section presents some basic guidelines applicable to common dense-graded mixes.

It might be reasonable to believe that the best gradation is one that produces the maximum density. This would involve a particle arrangement where smaller particles are packed between the larger particles, which reduces the void space between particles (White 1995). This creates more particle-to-particle contact, which in HMA would increase stability and reduce water infiltration. However, some minimum amount of void space is necessary to:

- Provide adequate volume for the binder (asphalt binder) to occupy.
- Promote rapid drainage and resistance to frost action for base and sub-base courses.

Therefore, although it may not be the "best" aggregate gradation, a maximum density gradation does provide a common reference. A widely used equation to describe a maximum density gradation was developed by Fuller and Thompson in 1907. Their basic equation is:

$$P = \left(\frac{d}{D} \right)^{n}$$

where: P = % finer than the sieve,

d = aggregate size being considered,

D = maximum aggregate size to be used, and

n = Parameter which adjusts curve for fineness or coarseness (for maximum particle density, n ≈ 0.5 according to Fuller and Thompson).

3.2.6 The 0.45 Power Maximum Density Curve

In the early 1960s, the FHWA introduced the standard gradation graph used in the HMA industry today. This graph uses n = 0.45 and is convenient for determining the maximum density line and adjusting gradation. This graph is slightly different than other gradation graphs because it uses the sieve size raised to the n^{th} power (usually 0.45) as the x-axis units. Thus, n = 0.45 appears as a straight diagonal line (see Figure 3.7). The maximum density line appears as a straight line from zero to the maximum aggregate size for the mixture being considered (the exact location of this line is somewhat debatable, but the locations shown in Figure 3.6 are generally accepted).

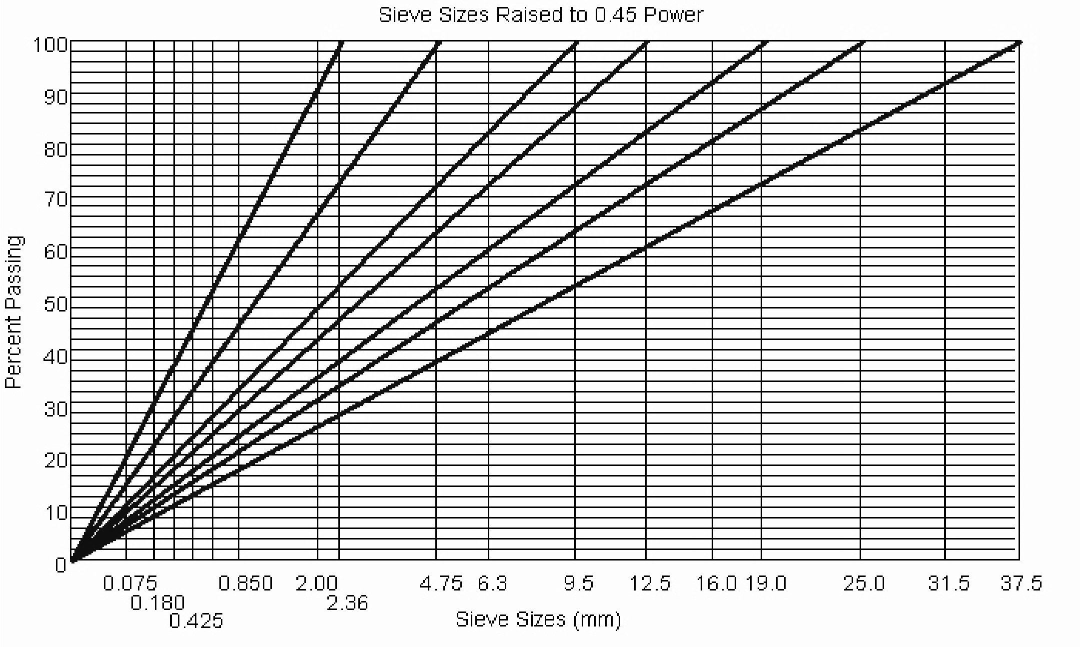


Figure 3.7: Maximum Density Curves for 0.45 Power Gradation Graph

(each curve is for a different maximum aggregate size)

To illustrate how the maximum density curves in Figure 3.7 are determined, Table 3.2 shows the associated calculations for a maximum aggregate size of 19.0 mm.

Particle Size (mm)	**% Passing**
19.0	$P = \left(\frac{19.0}{19.0}\right)^{0.45} = 1.000 \ (100.0\%)$
12.5	$P = \left(\frac{12.5}{19.0}\right)^{0.45} = 0.833 \ (83.3\%)$
9.5	$P = \left(\frac{9.5}{19.0}\right)^{0.45} = 0.732 \ (73.2\%)$
2.00	$P = \left(\frac{2.00}{19.0}\right)^{0.45} = 0.363 \ (36.3\%)$
0.300	$P = \left(\frac{0.300}{19.0}\right)^{0.45} = 0.154 \ (15.4\%)$
0.075	$P = \left(\frac{0.075}{19.0}\right)^{0.45} = 0.082 \ (8.2\%)$

Table 3.2: Calculations for a 0.45 Power Gradation Curve using 19.0-mm (0.75-inch) Maximum Aggregate Size

Several common terms are used to classify gradation. These are not precise technical terms but rather terms that refer to gradations that share common characteristics (refer to Figure 3.7). "Dense" or "well-graded" refers to a gradation that is near the FHWA's 0.45 power curve for maximum density. The most common HMA mix design in the U.S. tends to use dense graded aggregate. Typical gradations are near the 0.45 power curve but not right on it. Generally, a true maximum density gradation (exactly on the 0.45 power curve) would result in unacceptably low VMA.

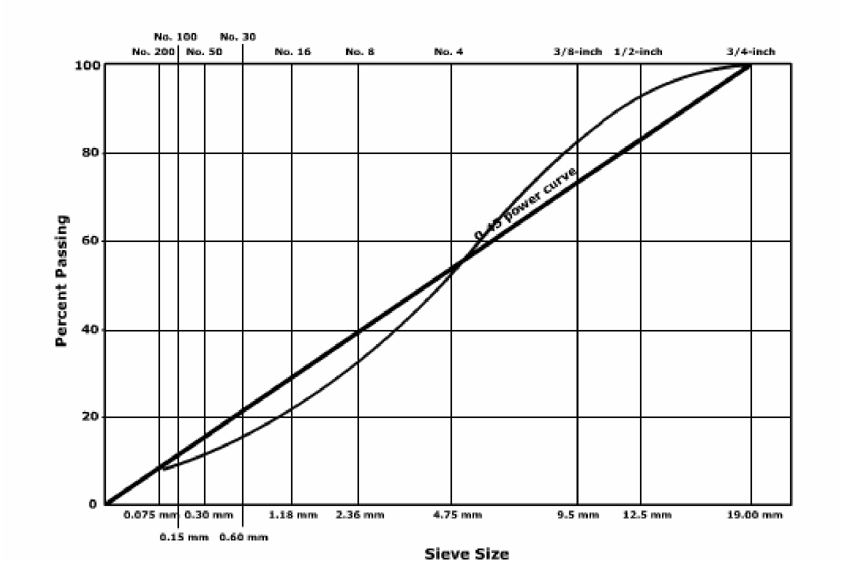


Fig 3.8: Dense or well graded gradation

Gap graded refers to a gradation that contains only a small percentage of aggregate particles in the mid-size range. The curve is flat in the mid-size range. HMA gap graded mixes can be prone to segregation during placement.

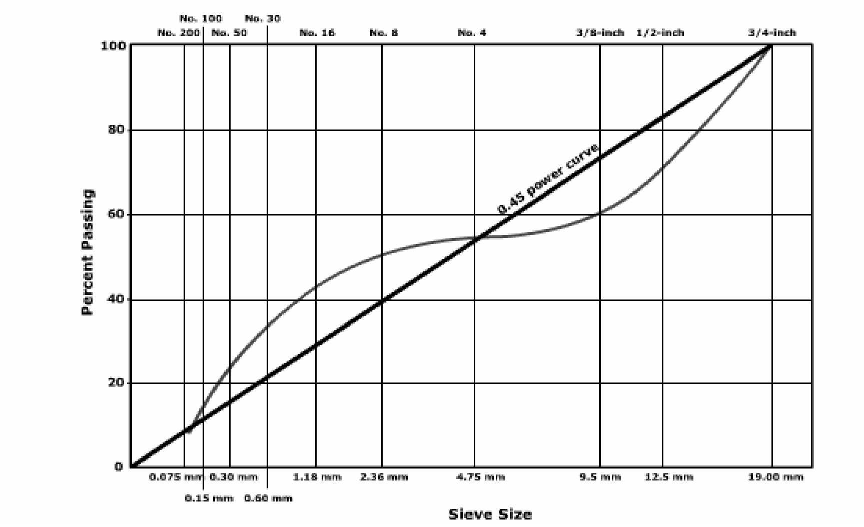


Fig 3.9: Gap graded gradation

Open graded refers to a gradation that contains only a small percentage of aggregate particles in the small range. This results in more air voids because there are not enough small particles to fill in the voids between the larger particles. The curve is near vertical in the mid-size range and flat and near-zero in the small-size range.

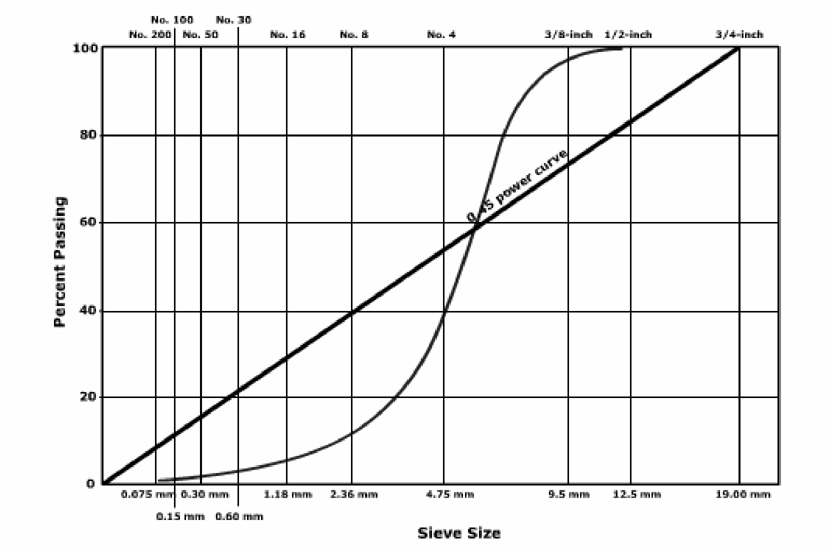


Fig 3.10: Open graded gradation

Uniformly graded refers to a gradation that contains most of the particles in a very narrow size range. In essence, all the particles are the same size. The curve is steep and only occupies the narrow size range specified.

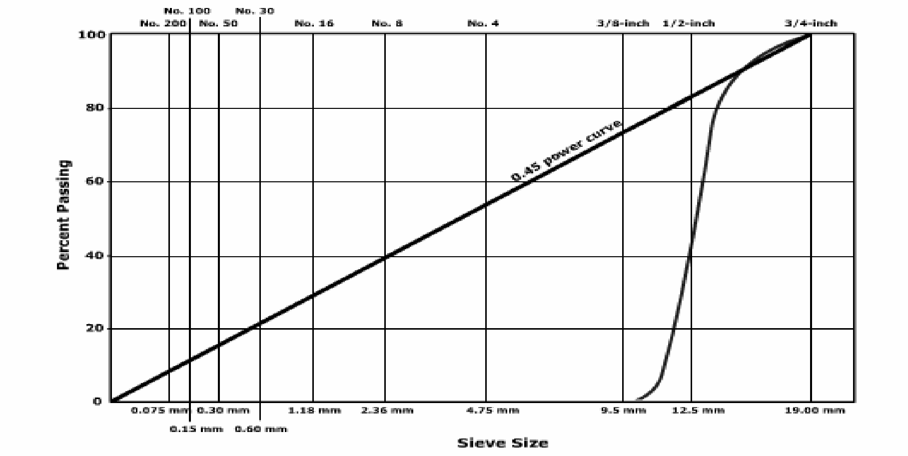


Fig 3.11: Uniformly graded gradation

There is a restricted zone which was eliminated by late 2002. The restricted zone refers to a particular area of the FHWA’s 0.45 power gradation graph associated with Superpave mix designs. It was originally observed that mixes closely following the 0.45 power maximum density line in the finer gradations sometimes had unacceptably low VMA. Therefore, in an attempt to minimize this problem, Superpave included a restricted zone through which a typical gradation should not pass as a recommended guideline. However, since the restricted zone's original inception, NCHRP Report 464: The Restricted Zone in the Superpave Aggregate Gradation Specification has concluded that gradations that violated the restricted zone performed similarly to or better than the mixes having gradations passing outside the restricted zone; therefore, the restricted zone requirement is redundant for mixes meeting all Superpave volumetric parameters. It has been recommended to delete references to the restricted zone as either a requirement or a guideline from the AASHTO specification (AASHTO MP 2) and practice (AASHTO PP 28) for Superpave volumetric mix design. (Kandhal and Cooley, 2002).

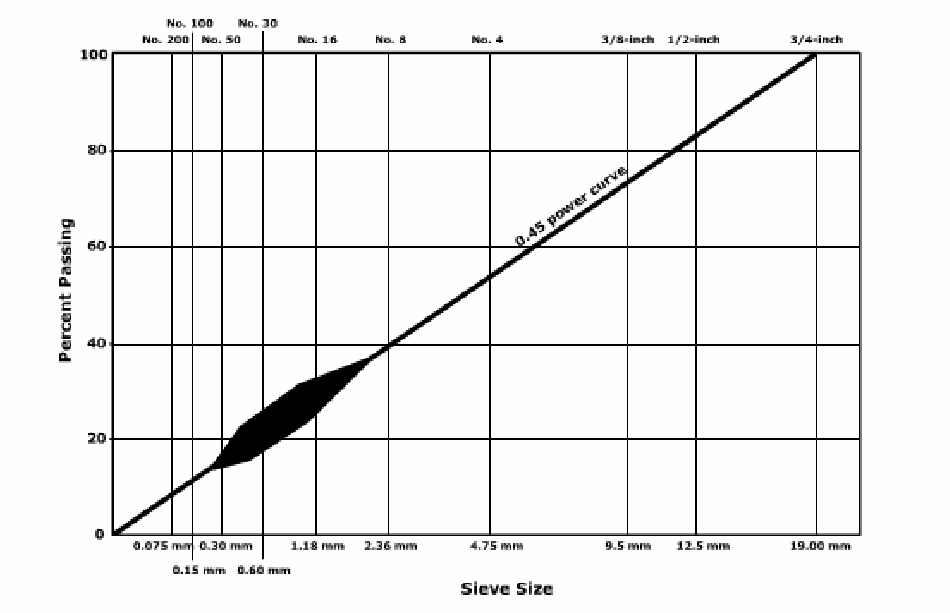


Fig 3.12: Restricted Zone in 0.45 power chart

3.2.7 Aggregate Particle Structure

A typical aggregate particle consists of some amount of solid material along with a certain amount of air voids. These air voids within the aggregate particle (see Figure 3.13) can become filled with water, binder or both (see Figure 3.13). It takes a finite amount of time for water/binder to penetrate these pores, so specific gravity test procedures generally contain a 15 to 19-hour (for AASHTO procedures) or a 24-hour (for ASTM procedures) soak period for the purpose of allowing penetration into these pores.

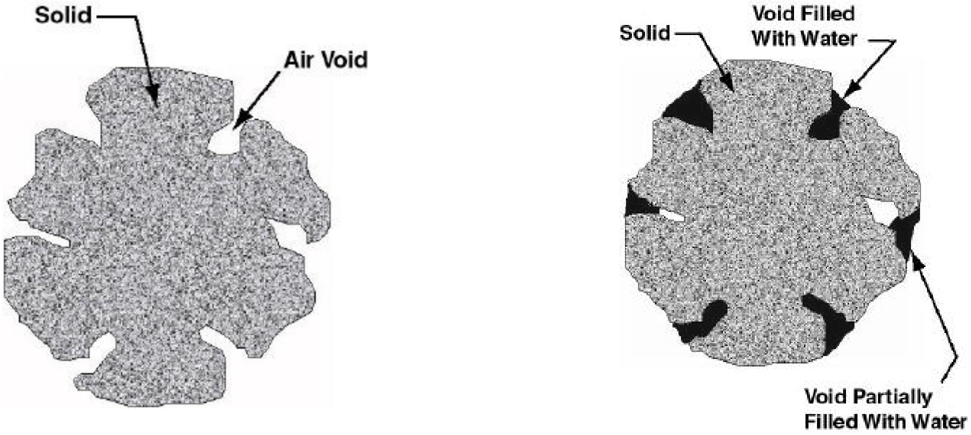


Fig 3.13: Dry and Wet aggregate (Robert, 1996)

Depending upon how aggregate voids are dealt with, calculated aggregate specific gravities can vary. If they are excluded entirely, then the specific gravity is that of the solid portion of the aggregate only, while if they are included entirely then the specific gravity essentially becomes a weighted average of the specific gravity of the solid aggregate and whatever is in its voids.

3.2.8 Particle Index

The particle index test provides a combined shape-texture characterization. This test requires that an aggregate sample be divided up into specific size fraction. Each size fraction is placed into a container in three layers (McLeod et al, 1981). This is done twice; the first time, each layer is compacted with 10 blows of a tamping rod, and the second time, each layer is compacted with 50 blows of a tamping rod. The particle index is computed from the following equation:

$$I_a = 1.25(V_{10}) - 0.25(V_{50}) - 32.0$$

where: I_a = particle index

V_{10} = voids in aggregate compacted at 10 drops per layer

V_{50} = voids in aggregate compacted at 50 drops per layer

The overall sample particle index is computed as a weighted average of the individual size fraction particles indexes based on the size fraction weights. Aggregates composed of rounded, smooth particles may have a low particle index of around 6 or 7, while aggregates composed of angular, rough particles may have a high particle index of between 15 and 20 or more. The standard particle index test is ASTM D 3398 (Index of Aggregate Particle Shape and Texture).

3.2.9 Percent Fractured Face (Coarse Aggregate Angularity)

For coarse aggregate, a sample retained on the 4.75 mm (No. 4) sieve is collected and the number of particles with fractured faces is compared to the number of particles without fractured faces. A fractured face is defined as an "angular, rough or broken surface of an aggregate particle created by crushing, by other artificial means, or by nature" (ASTM, 2000). In order for a face to be considered fractured it must constitute at least 25 percent of the maximum cross-sectional area of the rock particle. The standard percent fractured face test is ASTM D 5821 (Determining the Percentage of Fractured Particles in Coarse Aggregate).

3.2.10 Fine aggregate Angularity

Superpave uses a test to determine the un-compacted voids content in fine aggregates, which gives some indication of fine aggregate particle shape and surface texture. The test involves filling a 100 mL cylinder with fine aggregate (see Figure 3.14), defined as that aggregate passing the 2.36 mm (No. 8 - LaDOTD) sieve, by pouring it from a funnel at a fixed height. After filling, the amount of aggregate in the cylinder is measured and a void content is calculated. The assumption is that this void content is related to the aggregate angularity and surface texture (e.g., more smooth rounded particles will result in a lower void content). The key disadvantage to this test is that inclusion of flat and elongated particles, which are known to cause mix problems, will cause the fine aggregate angularity test results to appear more favorable. Finally, surface texture may have a larger effect on mix performance than fine aggregate angularity values.

The standard fine aggregate angularity test is AASHTO T 304 (Un-compacted Void Content of Fine Aggregate). This test was used to evaluate the angularity of both materials and test results and analysis is presented in Chapter 4, Section 4.3.3 of this document.

Fig 3.14: Fine Aggregate Angularity Test

Flat and elongated particles can cause HMA problems because they tend to reorient and break under compaction. Therefore, they are typically restricted to some maximum percentage. An elongated particle is most often defined as one that exceeds a 5:1 length-to-width ratio. Testing is done on a representative sample using a caliper device and a two-step process. First, the longest dimension is measured on one end of the caliper (see Figure 3.15). Then, based on the position of the pivot point (numbered holes shown in Figure 3.15), the other end of the caliper (see Figure 3.15) is automatically sized to the predetermined length-to-width ratio (in Figures 3.15 and 3.16, it is set at 2:1). If the aggregate is able to pass between the bar and caliper, it fails the test.

The standard flat or elongated particle test is ASTM D 4791 (Flat or Elongated Particles in Coarse Aggregate).

Fig 3.15: Testing Caliper Measuring the Elongated Dimension

Figure 3.16: Testing Caliper Measuring the Flat Dimension

3.2.11 Sand Equivalency

The sand equivalent test (DOTD TR 120) is used to determine the relevant proportions of plastic fines and dusts in fine aggregates (Black Beauty and silica sand). In this test, 85 ml of aggregate passing a No.4 (4.76 mm) sieve is agitated in a water-filled transport cylinder (1.25 inches or 32 mm inside diameter, 17 inches or 432 mm high, and graduated from the bottom up to 15 inches or 381 mm by tenths) which is filled with a mixture of water and a flocculating agent (a combination of calcium chloride, glycerin and formaldehyde). After agitation and 20 minutes of settling, the sand separates from the flocculated clay, and the heights of clay and sand in the cylinder are measured. The sand equivalent is the ratio of the height of sand to the height of clay times 100. Cleaner aggregate will have a higher sand equivalent value. Specifications for aggregates in HMA often specify a minimum sand equivalent in the range of 25 to 35.

$$\text{Sand Equivalent} = 100\left(\frac{\text{Height of Sand}}{\text{Height of Clay}}\right)$$

Figure 3.17: Sand Equivalency test tubes with Black Beauty and Silica Sand

Figure 3.18: Mechanical Shaker used for Sand Equivalency Test

The test results for the sand equivalent test for both materials (Black Beauty and Silica Sand) are presented in Chapter 4 in Section 4.3.2 of this document.

3.3 Asphalt Mixture Design

Mixture design were performed on all aggregates structures using Marshall Design Method and followed by Superpave methods to evaluate volumetric parameters for the modified hot mix. The Marshall Design Method is used to measure the stability (the maximum load carried by a compacted specimen tested at 140^o F (60^o C) at a loading rate of 2 inches/minutes (50.8 mm/minutes), and the flow (the vertical deformation of the sample measured from start of loading to the point at which the stability starts to decrease) of the modified hot mix asphalt specimen. Using the density analysis (VMA) and the results of stability and flow of a set of five specimens, the optimum AC% by weight can be found graphically. Table 3.3 shows the mixture design criteria for surface and base pavements parameters.

Marshall Method Mix Criteria	Traffic					
	Light		Medium		Heavy	
	Minimum	Maximum	Minimum	maximum	Minimum	Maximum
Compaction No. Of Blows/side	35		50		75	
Stability, Ib (N)	750 (3333)	------------	1200 (5333)	------------	1800 (8000)	-----------
Flow 0.01 inches (0.25mm).	8	18	8	16	8	14
Air Voids (%)	3	5	3	5	3	5
VMA (Voids in mineral aggregates)	Graphically shown in Table 3.4- next page					

Table 3.3: Marshall Mixture design criteria for surface and base parameters

Nominal Maximum Particle sizes		Minimum VMA (percent)
(mm)	US	
63	2.5 inch	11
50	2.0 inch	11.5
37.5	1.5 inch	12
25.0	1.0 inch	13
19.0	0.75 inch	14
12.5	0.5 inch	15
9.5	0.375 inch	16
4.75	No. 4 Sieve	18
2.36	No. 8 Sieve	21
1.18	No. 16 Sieve	23.5

Table 3.4: Typical Marshall Minimum VMA (from Asphalt Institute, 1979)

3.3.1 Preparation of Test Specimens

Once each aggregate is determined acceptable for use in HMA using results from Sand Equivalency, Gradation, Soundness, Particle Shape, and Specific Gravity test, laboratory test specimens must be formed for use in different mechanical tests. A weight up sheets for each blend was design and prepared (see Table 3.5) for different sets of specimens. Each set had a different Asphalt Content (AC) ranged between 4-5 percent by weight of the total specimen weight. Using the Marshall design method that is approximately 1200g/specimen (see Table 3.5). All specimens were batched until all the aggregate was coated using a mechanical mixer as shown in Figure 3.19. The entire batching process was done after a 24-hour oven dry of the materials mixed in one pan as shown in Figure 3.20. A 0.01 percent by weight dust was added to each pan containing the mix of materials for one specimen in order to simulate the field conditions.

Fig 3.19: Mechanical Mixer and Mixing Bucket

Fig 3.20: The oven used to heat up the mix

The coated aggregates from the mixing bucket were poured into a Marshall mold. A Marshall Specimen has a 4-inch diameter and a 2.5″ height see (Figure 3.22). Then the mixture was tamped with a spatula 15 times around the perimeter and 10 times over the interior. Each sample is then heated to the anticipated compaction temperature and compacted with a Marshall hammer, a device that applies pressure to a sample through a tamper foot (see Figure 3.21). Some hammers are automatic and some are hand operated. The hammer used for this research was Automatic. Key parameters of the compactor are:

- Sample size = 4-inch diameter cylinder (2.5 inches) in height (corrections can be made for different sample heights).
- Tamper foot: flat and circular with a diameter of 98.4 mm (3.875 inches) corresponding to an area of 7 (11.8 in^2).
- Compaction pressure: specified as a (18 inches) free fall drop distance of a hammer assembly with a 4536 g (10 lb.) sliding weight.
- Number of blows: typically 35, 50 or 75 on each side depending upon anticipated traffic loading (See Table 3.3).
- Simulation method: the tamper foot strikes the sample on the top and covers almost the entire sample top area. After a specified number of blows, the sample is turned over and the procedure repeated.

Fig 3.21: Marshall Compactor

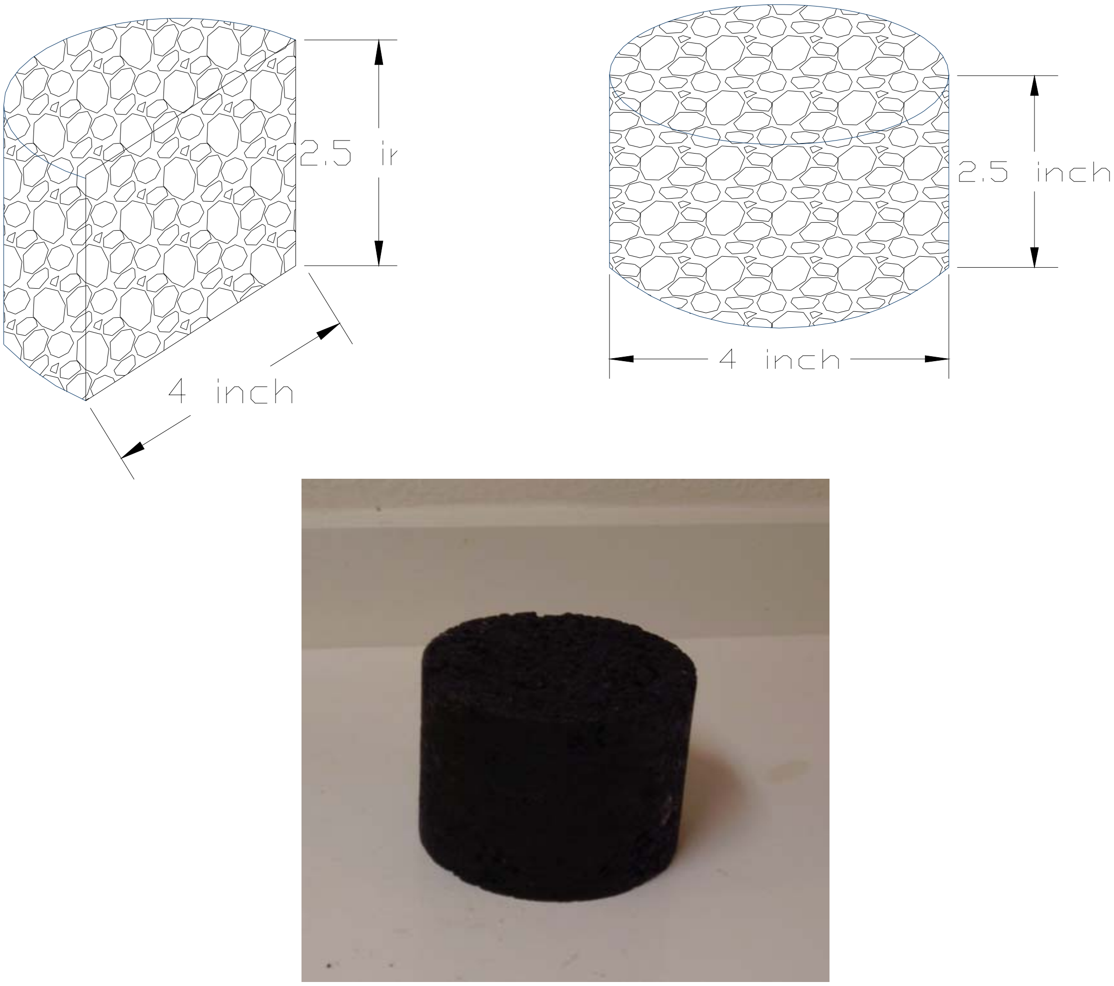


Fig 3.22: Marshal Specimen (4-in diameter and 2.5-inch height)

Aggregates Batch Weights/ Gram

AC: 4 % **Blend #: 2** **By: Amer Khanfar**

Material	% Ret	% of total Batch	Accumulative Weight	
Pump Sand				
1 ½ ”-1”	0.0	0.0	0.0	0.0
1”-3/4”	0.0	0.0	0.0	0.0
3/4”-1/2”	0.0	0.0	0.0	0.0
1/2”-3/8 ”	0.0	0.0	0.0	0.0
3/8-#4	0.0	0.0	0.0	0.0
#4-#8	0.0	0.0	0.0	0.0
Minus #8	100	0.087	108.8	108.8
		Total	108.8	
Black Beauty				
1 ½ ”-1”	0.0	0.0	0.0	108.8
1”-3/4”	0.0	0.0	0.0	108.8
3/4”-1/2”	0.0	0.0	0.0	108.8
1/2”-3/8 ”	0.0	0.0	0.0	108.8
3/8-#4	0.0	0.0	0.0	108.8
#4-#8	0.0	0.0001	0.1	108.9
Minus #8	100	0.1349	168.7	277.5
		Total	168.8	
# 911 sand stone				
1 ½ ”-1”	0.0	0.00	0.0	277.5
1”-3/4”	0.0	0.00	0.0	277.5
3/4”-1/2”	0.0	0.00	0.0	277.5
1/2”-3/8 ”	0.0	0.00	0.0	277.5
3/8-#4	15	0.0248	31	308.5
#4-#8	21	0.0341	42.6	351.1
Minus #8	64	0.1051	131.4	482.5
		Total	205	
# 7 lime stone				
1 ½ ”-1”	0.0	0.00	0.0	482.5
1”-3/4”	0.0	0.00	0.0	482.5
3/4”-1/2”	7	0.0205	25.6	508.1
1/2”-3/8 ”	35	0.1017	127.2	635.3
3/8-#4	48	0.1396	174.5	809.8
#4-#8	5	0.0147	18.4	828.2
Minus #8	4	0.0124	15.5	843.8
		Total	361.3	

Cont. Table 3.5:

# 67 lime stone				
1 ½ ”-1”	0.0	0.00	0.0	843.8
1”-3/4”	9	0.0260	32.5	876.3
3/4”-1/2”	43	0.1231	153.9	1030.2
1/2”-3/8 ”	21	0.0601	75.1	1105.3
3/8-#4	21	0.0610	76.2	1181.5
#4-#8	3	0.0095	11.9	1193.4
Minus #8	3	.0092	11.6	1205.0
		Total	361.3	
Moisture 5.5 %				
	Virgin AC – 4 % Total = 46.3 g AC Total Specimen Wt= 1251.3 g			

Table 3.5: One example of one HMA blend used in this study

3.3.2 Density and Void analysis

Basic HMA weight-volume relationships are important to understand for both mix design and construction purposes. Fundamentally, mix design is meant to determine the volume of asphalt binder and aggregates necessary to produce a mixture with the desired properties (Roberts et al., 1996). However, since weight measurements are typically much easier, they are typically taken then converted to volume by using specific gravities. The following is a brief discussion of the more important volume properties of HMA.

In general, weight and volume terms are abbreviated as G_{xy},

where: x: b = binder
s = stone (i.e., aggregate)
m = mixture

y: b = bulk
e = effective
a = apparent
m = maximum

For example, G_{mm} = gravity, mixture, maximum = the maximum gravity of the mixture. Other common abbreviations are:

V_T	=	Total volume of the compacted specimen	W_T	=	Total weight of the compacted specimen
V_a	=	Volume of air voids	W_D	=	Dry weight
V_b	=	Volume of asphalt binder	W_{SSD}	=	Saturated surface dry (SSD) weight
V_{be}	=	Volume of effective asphalt binder	W_{sub}	=	Weight submerged in water
V_{ba}	=	Volume of absorbed asphalt binder	W_b	=	Weight of the asphalt binder
V_{agg}	=	Volume of aggregate	W_{be}	=	Weight of effective asphalt binder
V_{eff}	=	Effective volume of aggregate = (V_T - V_{AC})	W_{ba}	=	Weight of absorbed asphalt binder
			W_{agg}	=	Weight of aggregate
G_{sa}	=	Apparent specific gravity of the aggregate			
G_b	=	Asphalt binder specific gravity	P_b	=	Asphalt content by weight of mix (percent)
G_{sb}	=	Bulk specific gravity of the aggregate	P_s	=	Aggregate content by weight of mix (percent)
G_{se}	=	Effective specific gravity of the aggregate	P_a	=	Percent air voids
G_{mb}	=	Bulk specific gravity of the compacted mixture			
G_{mm}	=	Maximum theoretical specific gravity of the mixture	γ_W	=	Unit weight of water

Table 3.6: common hot mix asphalt design abbreviations

Specific Gravities

The Bulk Specific Gravity of the Compacted Asphalt Mixture (G_{mb}) is the ratio of the mass in air of a unit volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the mass in air (of equal density) of an equal volume of gas-free distilled water at a stated temperature. This value is used to determine weight per unit volume of the compacted mixture. It is very important to measure G_{mb} as accurately as possible. Since it is used to convert weight measurements to volumes, any small errors in G_{mb} will be reflected in significant volume errors, which may go undetected.

The standard bulk specific gravity test is AASHTO T 166 (Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens). The following equation is used in determining the G_{mb}.

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}}$$

The theoretical Maximum Specific Gravity of Bituminous Paving Mixtures (G_{mm}) is the ratio of the mass of a given volume of voidless (Va = 0) HMA at a stated temperature (usually 25° C) to a mass of an equal volume of gas-free distilled water at the same temperature. It is also called the Rice Specific Gravity after James Rice who developed the test procedure. Multiplying G_{mm} by the unit weight of water gives Theoretical Maximum Density (TMD).The standard TMD test is AASHTO T 209 (Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures). The following equations can be used in determining Gmm:

$$G_{mm} = \frac{W_{agg} + W_b}{V_{eff} + V_b} \qquad G_{mm} = \frac{1}{\frac{1 - P_b}{G_{se}} + \frac{P_b}{G_b}}$$

The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture is the air voids (Va). The amount of air voids in a mixture is extremely important and closely related to stability and durability. For typical dense-graded mixes with 12.5 mm (0.5 inch) nominal maximum aggregate sizes air voids below about 3 percent result in an unstable mixture. An air voids above about 8 percent result in a water-permeable mixture. The following equations can be used in determining Va:

$$Va = \frac{V_v}{V_T} \times 100 \qquad Va = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100$$

The Voids in the Mineral Aggregate (VMA) is the volume of inter-granular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of the total volume of the specimen. When the VMA is too low, there is not enough room in the mixture to add sufficient asphalt binder to adequately coat the individual aggregate particles. Also, mixes with a low VMA are more sensitive to small changes in asphalt binder content. Excessive VMA will cause unacceptably low mixture stability (Roberts et al., 1996). Generally, a minimum VMA is specified and a maximum VMA may or may not be specified. The following equations can be used in determining VMA:

$$VMA = \frac{V_v + V_{be}}{V_T} \times 100 \qquad VMA = 100 - \left(\frac{G_{mb} Ps}{G_{sb}}\right)$$

$$VMA = \left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right) \times 100$$

Voids Filled with Asphalt (VFA) is the portion of the voids in the mineral aggregate that contain asphalt binder. This represents the volume of the effective asphalt content. It can also be described as the percent of the volume of the VMA that is filled with asphalt cement. VFA is inversely related to air voids: as air voids decrease, the VFA increases. The following equations can be used in determining VFA:

$$\mathrm{VFA} = \frac{V_{be}}{V_{be} + V_v} \times 100 \qquad \mathrm{VFA} = \frac{\mathrm{VMA - Va}}{\mathrm{VMA}} \qquad \mathrm{VFA} = \mathrm{VMA} - \mathrm{Pa}$$

The effective Asphalt Content (P_{be}) is the total asphalt binder content of the HMA less the portion of asphalt binder that is lost by absorption into the aggregate.

The volume of Absorbed Asphalt (V_{ba}) is the volume of asphalt binder in the HMA that has been absorbed into the pore structure of the aggregate. It is the volume of the asphalt binder in the HMA that is not accounted for by the effective asphalt content. The following equations are used in determining V_{ba}:

$$V_{ba} = \left(\frac{W_{ba}}{W_{agg}} \right) \times 100$$

$$V_{ba} = \left(\frac{G_{sa} - G_{sb}}{G_{sb} G_{se}} \right) G_b \times 100$$

Fig 3.23: Hot bath container and electronic scale

3.3.3 Stability and Flow analysis

The Marshall test provides the performance prediction measure for the Marshall Mix design method. The stability portion of the test measures the maximum load supported by the test specimen at a loading rate of 2 inches/minute. Basically, the load is increased until it reaches a maximum. Then, when the load just begins to decrease, the loading is stopped and the maximum load is recorded.

During the loading, an attached dial gauge measures the specimen's plastic flow as a result of the loading (see Figure 3.24). The flow value is recorded in 0.25 mm (0.01 inch) increments at the same time the maximum load is recorded.

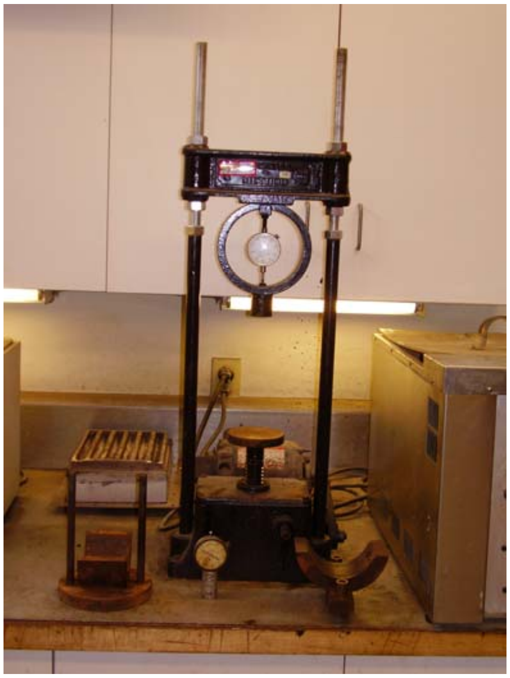


Figure 3.24: Marshall Testing Equipment

3.3.4 Selection of Optimum Asphalt Binder Content

The optimum asphalt binder content is finally selected based on the combined results of Marshall Test density analysis and void analysis. Optimum asphalt binder content can be arrived at in the following procedure:

1. Plot the following graphs:

- Asphalt binder content vs. density. Density will generally increase with increasing asphalt content, reach a maximum, and then decrease. Peak density usually occurs at higher asphalt binder content than peak stability.
- Asphalt binder content vs. Marshall Stability. This should follow one of two trends:
    - Stability increases with increasing asphalt binder content, reaches a peak, then decreases.

  - Stability decreases with increasing asphalt binder content and does not show a peak. This curve is common for some recycled HMA mixtures. …

- Asphalt binder content vs. flow.

- Asphalt binder content vs. air voids. Percent air voids should decrease with increasing asphalt binder content.

- Asphalt binder content vs. VMA. Percent VMA should decrease with increasing asphalt binder content, reach a minimum, then increase.

- Asphalt binder content vs. VFA. Percent VFA increases with increasing asphalt binder content.

1. Determine the asphalt binder content that corresponds to the specifications median air void content (typically this is 4 percent). This is the optimum asphalt binder content.
2. Determine properties at this optimum asphalt binder content by referring to the plots. Compare each of these values against specification values, and if all are within specification, then the preceding optimum asphalt binder content is satisfactory. Otherwise, if any of these properties is outside the specification range, the mixture should be redesigned.

Finally, the optimum AC content is selected based on results of Marshall Stability and flow, density analysis and void analysis (see Figure 3.25). All test results for ABM are presented in Chapter 4, Section 4.4.

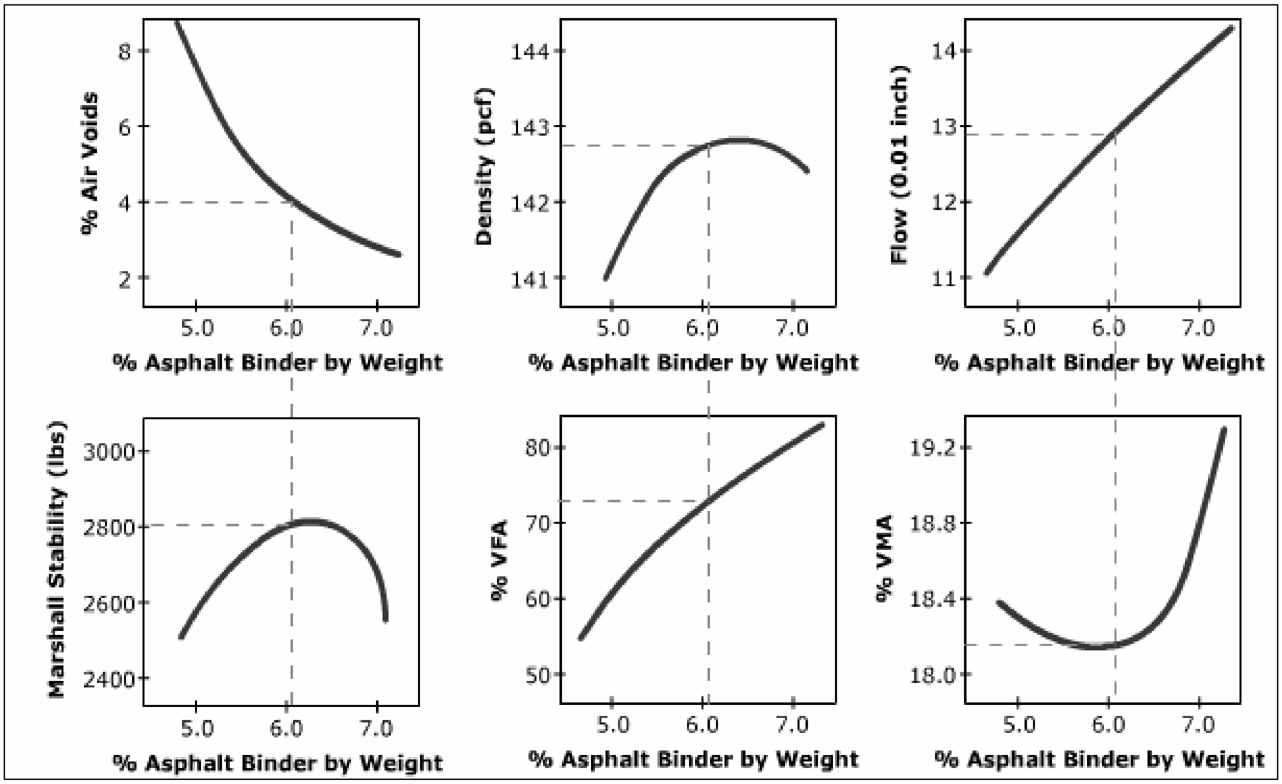


Figure 3.25: Optimum Asphalt Design by Marshall

3.4 Superpave Design for HMA with ABM

A modified HMA mix was designed by using the most updated, but uncomplete, version for Superpave HMA. This test was performed to ensure that the volumetric properties (VMA and VFA) for the modified HMA are in the ranges of LADOTD Superpave specification.

In this section, the methodology used to evaluate the new HMA with ABM will be briefly described. The Superpave method, like other mix design methods, creates several trial aggregate-asphalt binder blends, each with different asphalt binder content. Then, by evaluating each trial blend's performance, optimum asphalt binder content can be selected. In order for this concept to work, the trial blends must contain a range of asphalt contents both above and below the optimum asphalt content. Therefore, the first step in sample preparation is to estimate optimum asphalt content. Trial blend asphalt contents are then determined from this estimate (see Table 3.11).

The Superpave gyratory compactor (Figure 3.26) was developed to improve mix design's ability to simulate actual field compaction particle orientation with laboratory equipment (McGennis, 1998).

Each sample was heated to the anticipated mixing temperature, aged for a short time (up to 4 hours) and compacted with the gyratory compactor, a device that applies pressure to a sample through a hydraulically or mechanically operated load. Mixing and compaction temperatures are chosen according to asphalt binder properties so that compaction occurs at the same viscosity level for different mixes. Key parameters of the gyratory compactor are:

- Sample size: (6-inch) diameter cylinder approximately (4.5 inches) in height (corrections can be made for different sample heights).
- Load: Flat and circular with a diameter of 149.5 mm (5.89 inches) corresponding to an area of 175.5 cm^2 (27.24 in^2)
- Compaction pressure : Typically 600 kPa (87 psi)
- Number of blows: varies (75, 100, 120)
- Simulation method = the load is applied to the sample top and covers almost the entire sample top area. The sample is inclined at 1.25° and rotates at 30 revolutions per minute as the load is continuously applied. This helps achieve a sample particle orientation that is somewhat like that achieved in the field after roller compaction.

Fig 3.26: The Superpave gyratory compactor

The Superpave gyratory compactor establishes three different gyration numbers:

1. $N_{initial}$ is the number of gyrations used as a measure of mixture compactability during construction. Mixes that compact too quickly (air voids at $N_{initial}$ are too low) may be tender during construction and unstable when subjected to traffic. Often, this is a good indication of aggregate quality. HMA with excess natural sand will frequently fail the $N_{initial}$ requirement. A mixture designed for greater than or equal to 3 million ESALs with 4 percent air voids at N_{design} should have at least 11 percent air voids at $N_{initial}$.

2. N_{design} is the design number of gyrations required to produce a sample with the same density as that expected in the field after the indicated amount of traffic. A mix with 4 percent air voids at N_{design} is desired in mix design.

3. N_{max} is the number of gyrations required to produce a laboratory density that should never be exceeded in the field. If the air voids at N_{max} are too low, then the field mixture may compact too much under traffic resulting in excessively low air voids and potential rutting. The air void content at N_{max} should never be below 2 percent air voids.

Typically, samples are compacted to N_{design} to establish the optimum asphalt binder content and then additional samples are compacted to N_{max} as a check. Previously, samples were compacted to N_{max} and then $N_{initial}$ and N_{design} were back calculated. Table 3.7 lists the specified number of gyrations for $N_{initial}$, N_{design} and N_{max} while Table 3.8 shows the required densities as a percentage of theoretical maximum density (TMD) for $N_{initial}$, N_{design} and N_{max}. Note that traffic loading numbers are based on the anticipated traffic level on the design lane over a 20-year period regardless of actual roadway design life (AASHTO, 2001).

20-yr Traffic Loading (in millions of ESALs)	Number of Gyrations		
	$N_{initial}$	N_{design}	N_{max}
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 10*	8 (7)	100 (75)	160 (115)
10 to < 30	8	100	160
^{3} 30	9	125	205

* When the estimated 20-year design traffic loading is between 3 and < 10 million ESALs, the agency may, at its discretion, specify $N_{initial} = 7$, $N_{design} = 75$ and $N_{max} = 115$.

Table 3.7: Number of Gyrations for $N_{initial}$, N_{design} and N_{max} (from AASHTO, 2001)

20-yr Traffic Loading (in millions of ESALs)	**Required Density (as a percentage of TMD)**		
	$N_{initial}$	**N_{design}**	**N_{max}**
< 0.3	≤ 91.5	96.0	≤ 98.0
0.3 to < 3	≤ 90.5		
3 to < 10	≤ 89.0		
10 to < 30			
³ 30			

Table 3.8: Required densities for $N_{initial}$, N_{design} and N_{max} (from AASHTO, 2001)

3.5 Density and Voids Analysis

All mix design methods use density and voids to determine basic HMA physical characteristics. Two different measures of densities are typically taken:

- Bulk specific gravity (G_{mb}) - often called "bulk density"
- Theoretical maximum density (TMD, G_{mm})

These densities are then used to calculate the volumetric parameters of the HMA. Measured void expressions are usually:

- Air voids (V_a), sometimes called voids in the total mix (VTM)
- Voids in the mineral aggregate (VMA)
- Voids filled with asphalt (VFA)

Generally, these values must meet local or State criteria.

VMA and VFA must meet the values specified in Table 3.8. Note that traffic loading numbers are based on the anticipated traffic level on the design lane over a 20-year period regardless of actual roadway design life (AASHTO, 2000b).

20-yr Traffic Loading (in millions of ESALs)	Minimum VMA (percent)					VFA Range (percent)
	9.5 mm (0.375 inch)	12.5 mm (0.5 inch)	19.0 mm (0.75 inch)	25.0 mm (1 inch)	37.5 mm (1.5 inch)	
< 0.3	15.0	14.0	13.0	12.0	11.0	70 - 80
0.3 to < 3						65 - 78
3 to < 10						65 - 75
10 to < 30						
^{3} 30						

Table 3.9: Minimum VMA and VFA requirements range (from AASHTO, 2001)

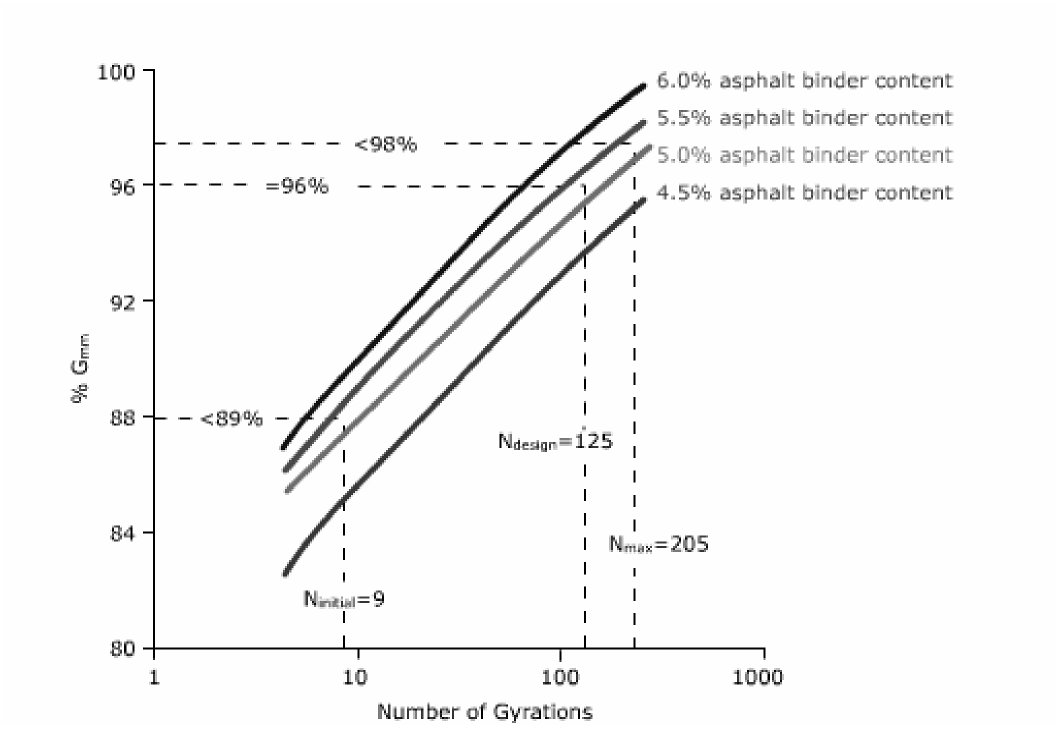
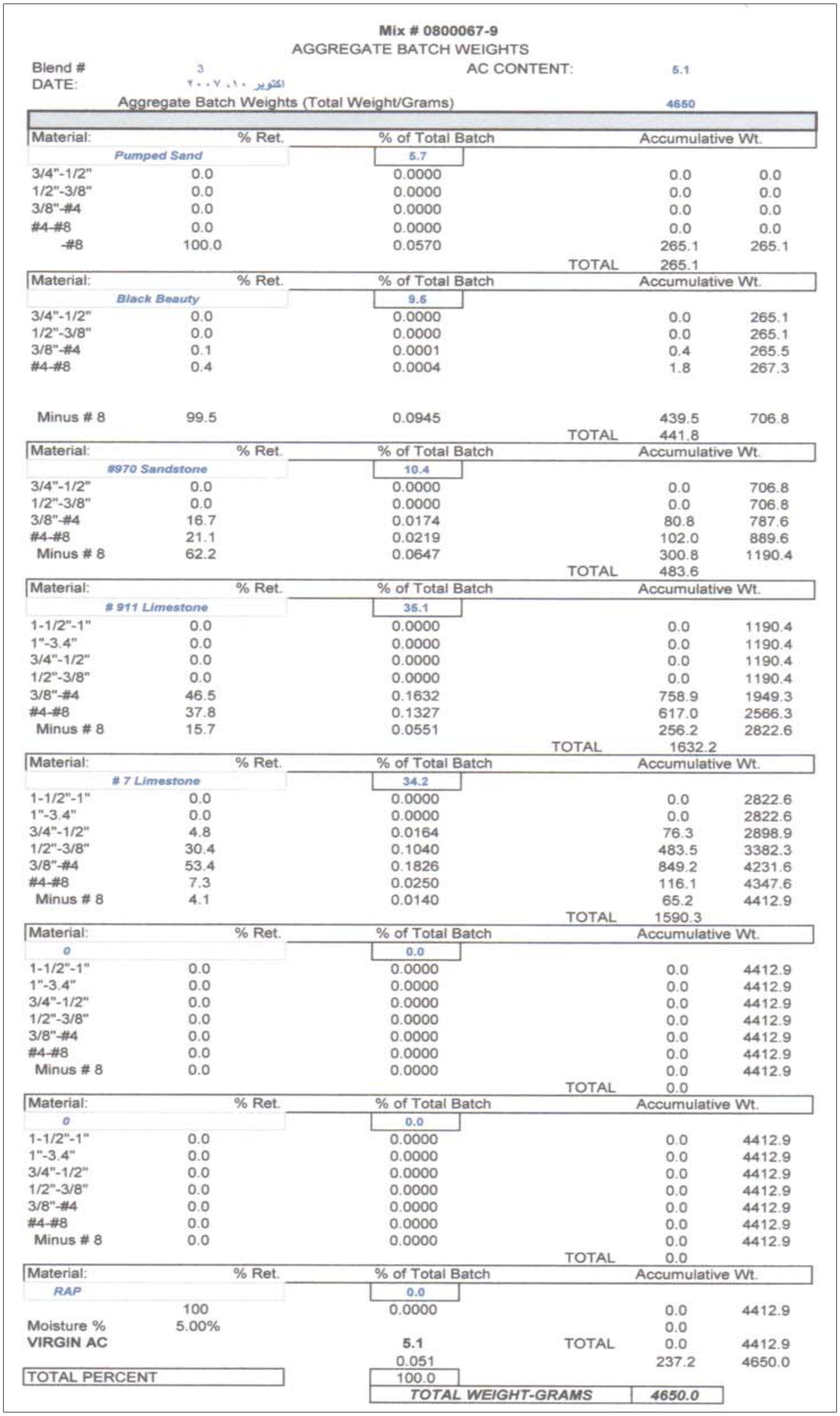


Fig 3.27: Selection of optimum asphalt binder content



Mix # 0800067-9

AGGREGATE BATCH WEIGHTS

Blend # 3 AC CONTENT: 5.1

DATE: اكتوبر ١٠، ٢٠٠٧

Aggregate Batch Weights (Total Weight/Grams) 4650

Material:	% Ret.	% of Total Batch		Accumulative Wt.	
Pumped Sand		5.7			
3/4"-1/2"	0.0	0.0000		0.0	0.0
1/2"-3/8"	0.0	0.0000		0.0	0.0
3/8"-#4	0.0	0.0000		0.0	0.0
#4-#8	0.0	0.0000		0.0	0.0
-#8	100.0	0.0570		265.1	265.1
			TOTAL	265.1	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
Black Beauty		9.5			
3/4"-1/2"	0.0	0.0000		0.0	265.1
1/2"-3/8"	0.0	0.0000		0.0	265.1
3/8"-#4	0.1	0.0001		0.4	265.5
#4-#8	0.4	0.0004		1.8	267.3
Minus # 8	99.5	0.0945		439.5	706.8
			TOTAL	441.8	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
#970 Sandstone		10.4			
3/4"-1/2"	0.0	0.0000		0.0	706.8
1/2"-3/8"	0.0	0.0000		0.0	706.8
3/8"-#4	16.7	0.0174		80.8	787.6
#4-#8	21.1	0.0219		102.0	889.6
Minus # 8	62.2	0.0647		300.8	1190.4
			TOTAL	483.6	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
# 911 Limestone		35.1			
1-1/2"-1"	0.0	0.0000		0.0	1190.4
1"-3.4"	0.0	0.0000		0.0	1190.4
3/4"-1/2"	0.0	0.0000		0.0	1190.4
1/2"-3/8"	0.0	0.0000		0.0	1190.4
3/8"-#4	46.5	0.1632		758.9	1949.3
#4-#8	37.8	0.1327		617.0	2566.3
Minus # 8	15.7	0.0551		256.2	2822.6
			TOTAL	1632.2	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
# 7 Limestone		34.2			
1-1/2"-1"	0.0	0.0000		0.0	2822.6
1"-3.4"	0.0	0.0000		0.0	2822.6
3/4"-1/2"	4.8	0.0164		76.3	2898.9
1/2"-3/8"	30.4	0.1040		483.5	3382.3
3/8"-#4	53.4	0.1826		849.2	4231.6
#4-#8	7.3	0.0250		116.1	4347.6
Minus # 8	4.1	0.0140		65.2	4412.9
			TOTAL	1590.3	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
0		0.0			
1-1/2"-1"	0.0	0.0000		0.0	4412.9
1"-3.4"	0.0	0.0000		0.0	4412.9
3/4"-1/2"	0.0	0.0000		0.0	4412.9
1/2"-3/8"	0.0	0.0000		0.0	4412.9
3/8"-#4	0.0	0.0000		0.0	4412.9
#4-#8	0.0	0.0000		0.0	4412.9
Minus # 8	0.0	0.0000		0.0	4412.9
			TOTAL	0.0	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
0		0.0			
1-1/2"-1"	0.0	0.0000		0.0	4412.9
1"-3.4"	0.0	0.0000		0.0	4412.9
3/4"-1/2"	0.0	0.0000		0.0	4412.9
1/2"-3/8"	0.0	0.0000		0.0	4412.9
3/8"-#4	0.0	0.0000		0.0	4412.9
#4-#8	0.0	0.0000		0.0	4412.9
Minus # 8	0.0	0.0000		0.0	4412.9
			TOTAL	0.0	
Material:	% Ret.	% of Total Batch		Accumulative Wt.	
RAP		0.0			
	100	0.0000		0.0	4412.9
Moisture %	5.00%			0.0	
VIRGIN AC		**5.1**	TOTAL	0.0	4412.9
		0.051		237.2	4650.0
TOTAL PERCENT		100.0			
		TOTAL WEIGHT-GRAMS		*4650.0*	

Table 3.10: one example of trial blend for HMA with ABM

The Superpave analysis to assure the volumetric relation for the new mix, and the results for all volumetric parameters are presented in chapter 4 Section 4.5.

3.6 Simulation of Hurricane Katrina Conditions on Hot Mix Asphalt

The condition of hot mix asphalt pavements in the metropolitan New Orleans area has deteriorated at an accelerated rate after submersion caused by Hurricane Katrina storm surge and the subsequent failure of the hurricane protection system. There has been no comprehensive test program done in order to ascertain the cause or mechanisms involved in the increased rate of deterioration. Katrina-affected pavements not only were subjected to long term submersion by storm surge, but also increased heavy truck traffic as part of debris removal after the flooding subsided. Use of recycled ABM in HMA in the New Orleans area may require further modification to the mix design if potential degradation caused by long term submergence is found to be needed.

There are no procedures for estimating degradation of HMA after long term submergence in the ASTM, ASSHTO or DOTD Manuals. The researchers developed a procedure after consulting the asphalt pavement experts in the local area (LTRC, DOTD, and Barriere Construction Company personnel). Stripping was identified as the most likely cause of this degradation. Since modified tensile test is used by DOTD to predict stripping problems. In wet climates, it was decided to use this test to determine the deterioration of asphalt pavement due to Katrina flooding.

First, specimens were design and prepared based on Marshall hot mix design method. The specimens were then conditioned. Salt water was prepared to simulate seawater by using aquarium salt and fresh water from the tap. The target salinity was 3.5 %, or 35 ppt (parts per thousand). This means that every 1 kg of seawater has approximately 35 grams of dissolved salts. The next step was to prepare conditioning containers fit the 4 in samples and the desired water column. PVC commercial pipe with an end cap was used to submerge the samples and keep them loaded for three week or six week duration as shown in Figure 3.28.

Figure 3.28: PVC with asphalt specimens submerged

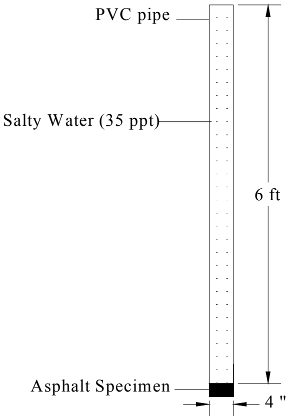


Figure 3.29: PVC with asphalt specimens submerged at the bottom

After conditioning specimens were taken to the lab to run a Tensile Strength Ratio test (TSR). The tensile stress ratio can be calculated based on the tensile strength formula. DOTD developed a test method to determine moisture damage susceptibility of hot mix asphalt. The test procedure measured moisture susceptibility using tensile strength of moisture conditioned samples compared to the tensile strength of control samples. A TSR, which is S_{tm}/S_{tc}, of 80 % or greater is considered acceptable DOTD.

Figure 3.30: shown the tensile strength mold

The tensile strength of each specimen of each set to the nearest psi is calculated as follows

$$S_{tc} = \frac{2P}{\pi TD}$$

$$S_{tm} = \frac{2P}{\pi TD}$$

where:

S_{tm} is the tensile strength of moisture- conditioned specimen in psi,

S_{tc} is the tensile strength of control specimen in psi,

P is the maximum load in Ib,

T is the average thickness in inches, and

D is the average diameter in inches.

Test results and analysis are presented in chapter 4 Section 4.7.

3.7 ENVIRONMENTAL TESTING

Environmental testing is required in order to ascertain if the modified hot mix asphalt is hazardous. If so, an assessment of the risks posed to human or ecological receptors by the recycling process or by the product itself must be done (Means, 1995). Usually hot mix asphalt with recycled abrasives has metal concentrations similar to those found in native soils (Table 3.11). Both shipyards periodically have Toxicity Characteristic Leaching Procedures (TCLPs) done in order to ensure that the spent abrasives are not hazardous in nature. Historically, the shipyards' spent abrasives TCLP results indicated that it was safe to dispose the wastes in nonhazardous landfills.

However, both total metal concentrations and TCLP tests were run on each modified mix and the control mix in order to verify that each mix met environmental regulations.

Metal	**Common Range (mg/kg)**	**Typical Average (mg/kg)**
Arsenic	1-50	5
Barium	100-3000	430
Cadmium	0.01-0.7	0.06
Chromium	1-1000	100
Lead	2-200	10
Mercury	0.01-0.3	0.03
Selenium	0.1-2	0.3
Silver	0.01-5	0.05

Table 3.11: Typical total metal RCRA test results for native soils (US EPA, 1983)

Results from the Environmental Tests and Analysis are presented in chapter 4 Section 4.6.

CHAPTER 4 TEST RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the results obtained from all tests, including the physical and chemical evaluation of the new aggregates (Black Beauty coal slag and silica sand), the modified hot mix asphalt based on Marshall and Superpave design methods, and Katrina simulation test.

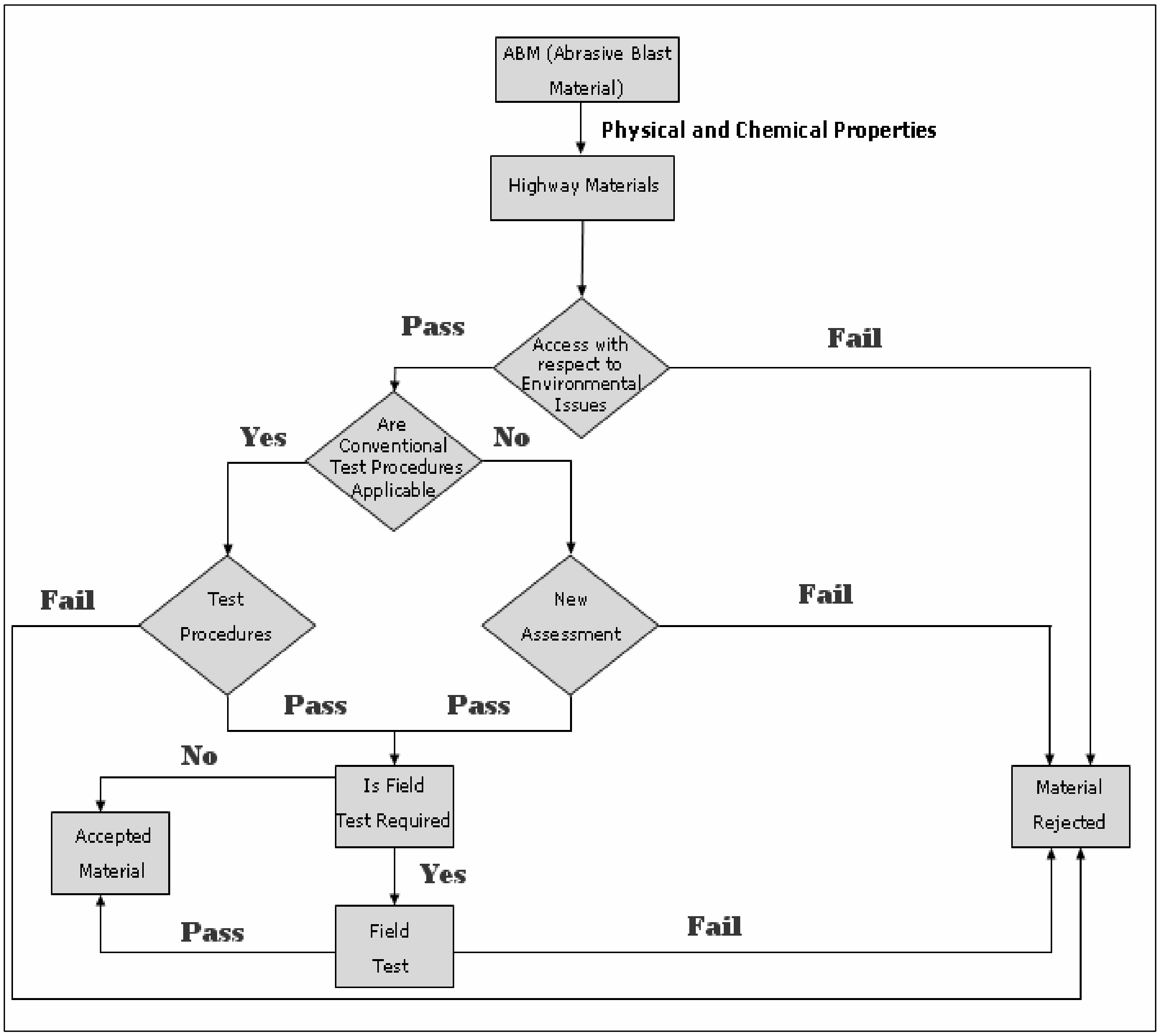


Fig 4.1 Recommended Design Methodologies for substituting ABM into HMA

4.2 Aggregate and Mix Design, Evaluation and Optimization

Barriere Construction Company has several standard mix designs used in asphaltic concrete production. All mixes in this research were either for an incidental wearing course or a binder course. The spent ABMs replaced a portion of the conventional fine aggregates ordinarily used. Concentrations of spent ABMs used in similar recycling in other states range from 9-14 wt% with, theoretically, a maximum of 25-35%. Table 4.9 and 4.10 list Marshall Test results for two examples hot mix designs containing 12% coal slag spent ABM and 12% silica sand ABM, respectively. Both mixes are for a Type 8 binder course. Both contain conventional aggregates: pump sand, sandstone, and limestone. Acceptable Marshall Test results are 1800 lbs (See Table 3.3), and both mixes easily met requirements.

The first design step in hot mix asphalt technology is the evaluation of the aggregates based on their physical and chemical properties. Therefore, the first analysis step presented in this chapter is aggregate evaluation and selection. All tests had been conducted at Barriere Construction Company's labs. And a spreadsheet for each test was designed and modified to adopt the recommended methodology for the new spent ABM aggregate characterization.

4.3 Aggregate Evaluation and Selection

The next few sections are concerned with the results of the evaluation the virgin aggregates and their acceptability to be substituted in HMA based on the previously discussed tests. The first test given is the gradation of the new materials, followed by physical and chemical test results used to obtained volumetric and engineering properties.

4.3.1 Aggregates evaluation and gradation

The results from sieve analysis and gradation are plotted in the 0.45 Power Curve. The Black Beauty material and the silica sand spent ABMs both show a well graded curve which creates more particle to particle contact and it would increase stability and reduce water infiltration in the modified HMA. Figure 4.2 and Figure 4.4 show the relationship between the percent passing of the two materials (Black Beauty and Silica Sand), and sieve opening which is called gradation curve. By comparing it to 0.45 power curve it is determined that both are well graded materials. Figure 4.3 and figure 4.5 also show the composite materials are well graded.

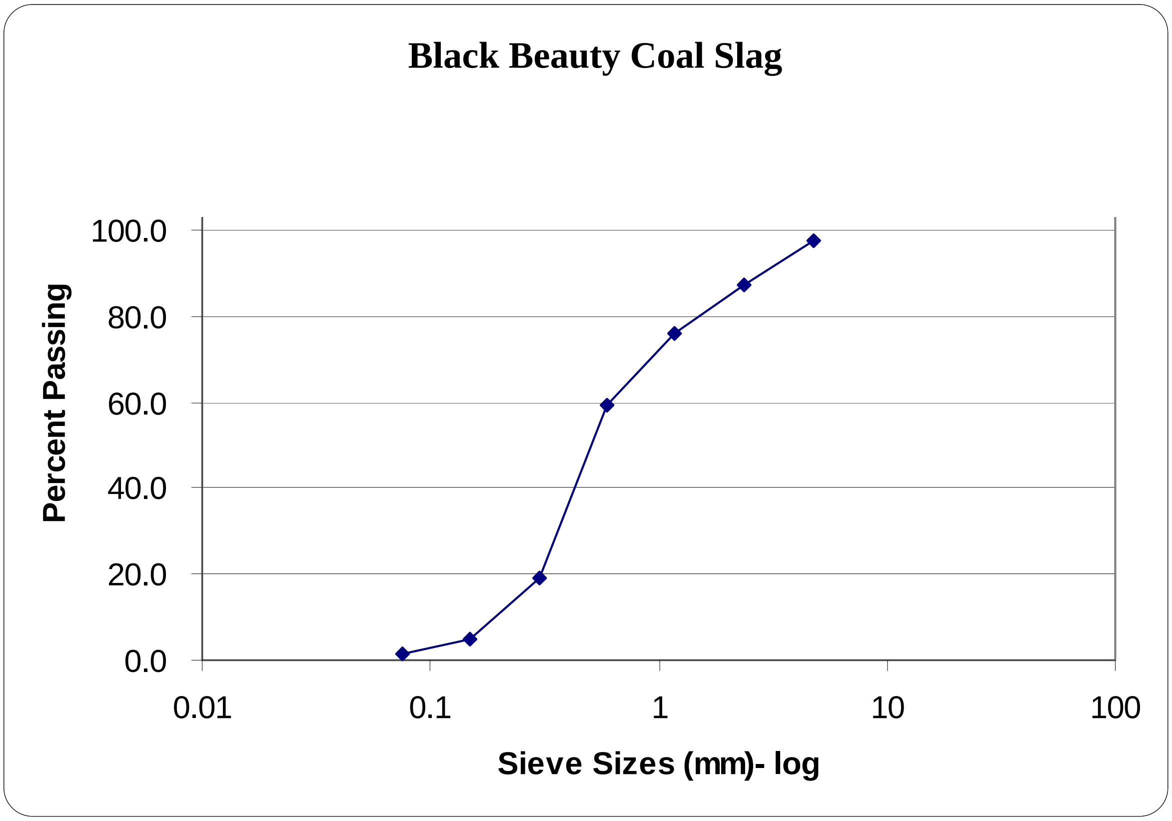


Fig 4.2: Black Beauty gradation curve

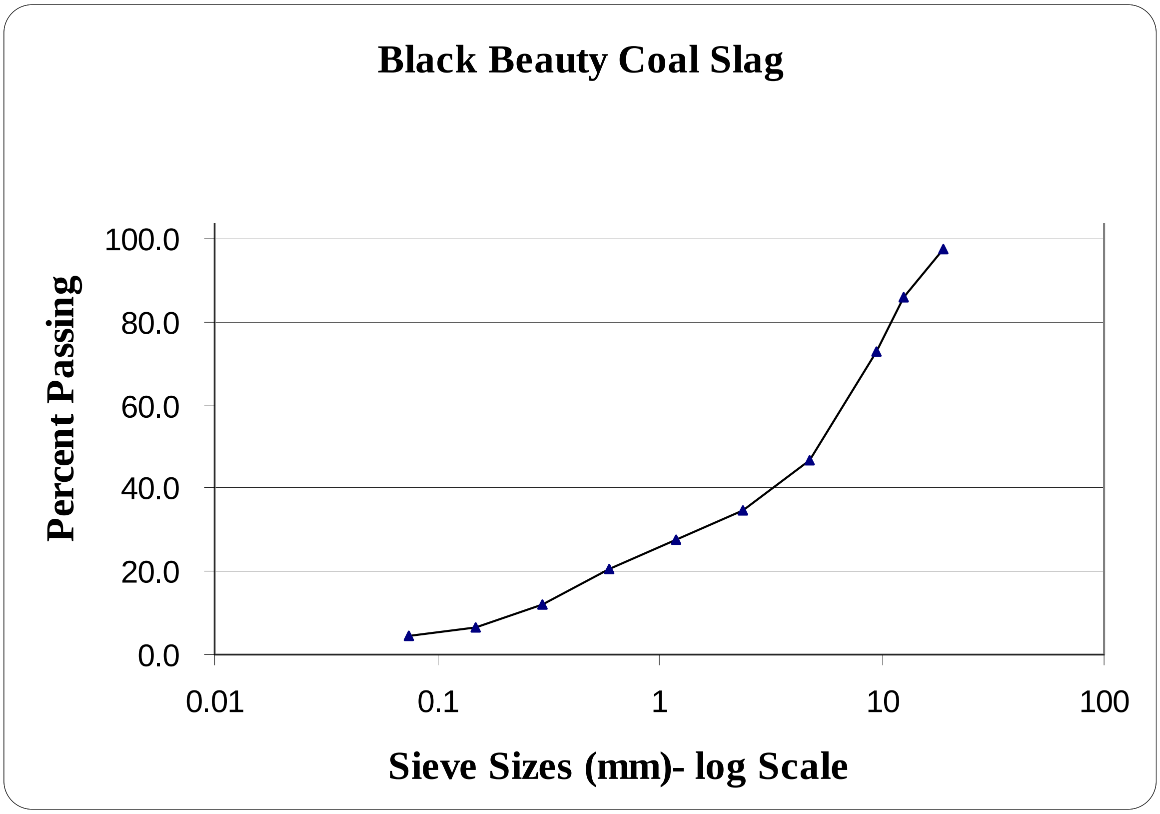


Fig 4.3: Composite materials with Black Beauty gradation curve

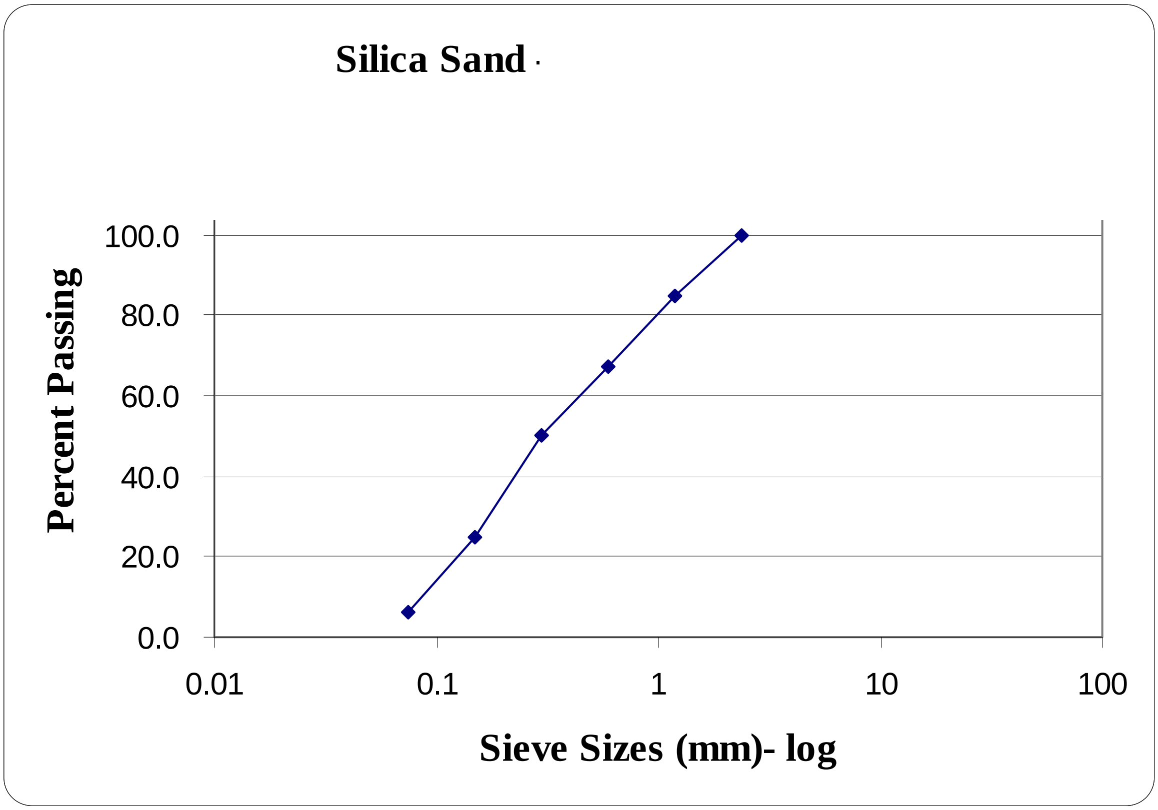


Fig 4.4: Silica Sand gradation curve

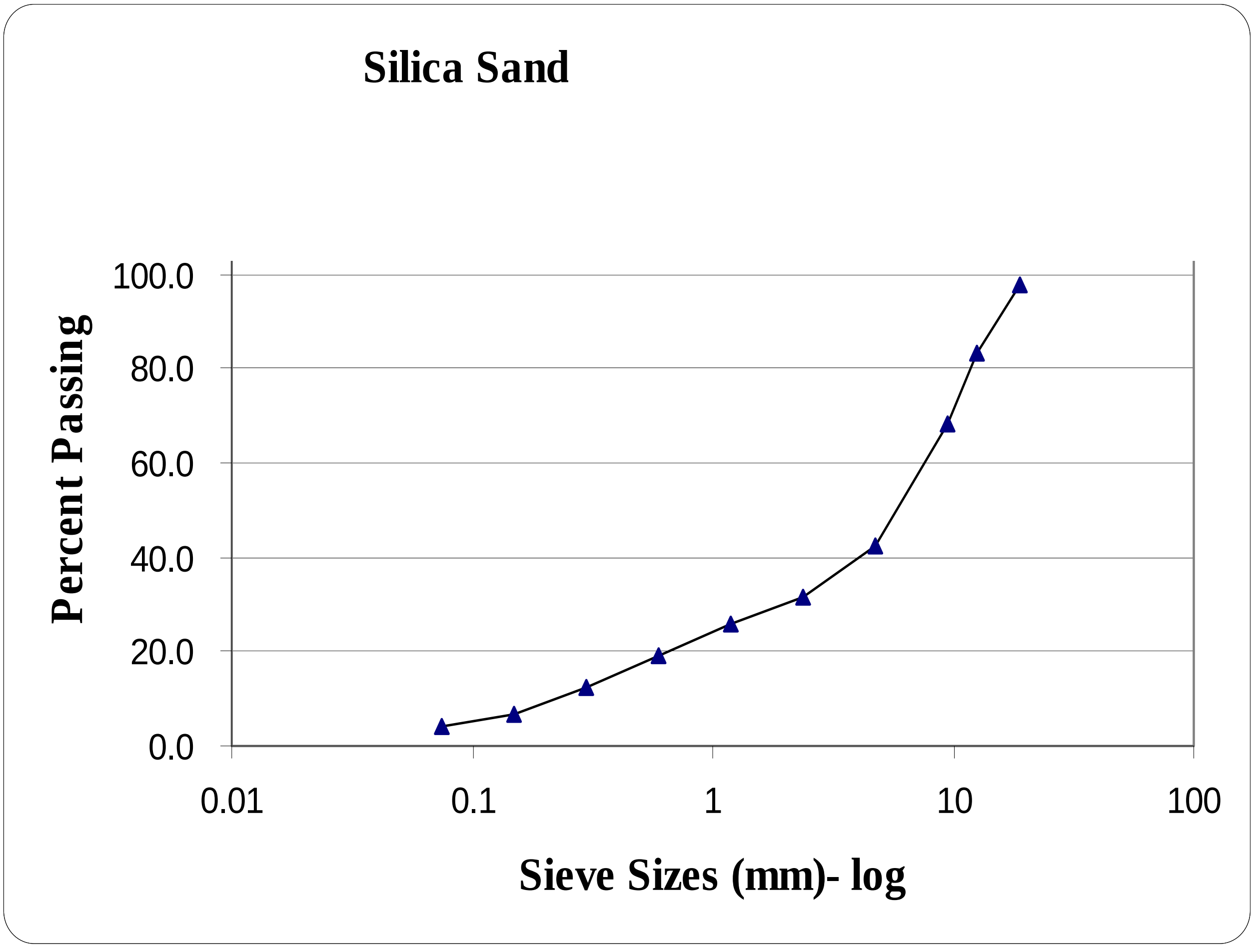


Fig 4.5: Composite materials with Silica sand gradation curve

4.3.2 Sand Equivalency Test

The sand equivalency test was used to determine the relevant proportion of plastic fines and dust in fine aggregate. The results from the sand equivalency tests are shown in Table 4.1 and Table 4.2. A 96 % SE indicates that the material has low plastic fines and dust and thus will not affect the modified hot mix design with the new characterized materials.

According to the results obtained from this test, these materials can be considered as clean materials with very low clay content and no deleterious particles.

Plastic Fines in Graded Aggregates by Sand Equivalent Test (T 176)

Specimen #: 1	1	2	3
Sand Reading, mm (A):	4.5	4.5	4.5
Clay Reading, mm (B):	4.7	4.7	4.7
Sand Equivalent (SE): ((A / B) * 100)	96	96	96
Average Sand Equivalent (SE):			**96**

Note: All values are rounded to the next higher integer value if the measured or calculated results have a decimal portion.

Table 4.1: Plastic fines in graded Black Beauty aggregates by sand equivalent

Plastic Fines in Graded Aggregates by Sand Equivalent Test (T 176)

Specimen #: 1	1	2	3
Sand Reading, mm (A):	4.5	4.5	4.5
Clay Reading, mm (B):	4.7	4.7	4.7
Sand Equivalent (SE): ((A / B) * 100)	96	96	96
Average Sand Equivalent (SE):			**96**

Note: All values are rounded to the next higher integer value if the measured or calculated results have a decimal portion.

Table 4.2: Plastic fines in graded silica sand aggregates by sand equivalent

4.3.3 Fine aggregate angularity

Fine aggregate angularity is quantified by an indirect method often called the National Aggregate Association (NAA) flow test. This test consists of pouring the fine aggregate into the top end of a cylinder and determining the amount of voids. The more voids, the more angular the aggregate. Voids are determined by the following equation:

$$\text{Uncompacted Voids} = \frac{V - \frac{W}{G_{sb}}}{V}$$

where: V = volume of cylinder (mL)
W = weight of loose fine aggregate to fill the cylinder (g)
G_{sb} = bulk specific gravity of the fine aggregate

Results are from two tests that have been conducted, one for Black Beauty aggregate and the other for the silica sand, and are tabulated in Table 4.4 and Table 4.5. Test results confirm that both materials are within the specifications (see Table 4.3).

20-yr Traffic Loading (in millions of ESALs)	Depth from Surface	
	< 100 mm (4 inches)	> 100 mm (4 inches)
< 0.3	-	-
0.3 to < 3	40	40
3 to < 10	45	
10 to < 30		
³ 30		45

Table 4.3: Fine aggregate angularity requirements

Uncompacted Void Content of Fine Aggregate - Method A (T 304)				
Test #: 3		**1**	**2**	**3**
Mass of sample:	(190 g +/- 0.2 g)	190.0	190	190
Mass of Cylinder + Glass + Grease + Water (A):		286.0	286	286
Mass of Cylinder + Glass + Grease (B):		186.9	186.9	186.9
Mass of Water (C):	(A - B)	99.1	99.1	99.1
Volume of Cylinder, mL (V):	(C / 0.998)	99.2986	99.2986	99.2986
Bulk Specific Gravity (Gsb):	(From T 84)	2.615	2.615	2.615
Mass of Cylinder + sample (Wcs):		334.2	334.9	334.8
Mass of empty Cylinder (Wc):		186.9	186.9	186.9
Mass of fine aggregate (W):	(Wcs - Wc)	147.3	148.0	147.9
% Uncompacted Voids (U): ((V - (W / Gsb)) / V) *100		**43.3**	**43.0**	**43.0**
Average of % Uncompacted Voids (Uavg):		**43.1**		

Table 4.4: Uncompacted void content of fine aggregate (Black Beauty)

Uncompacted Void Content of Fine Aggregate - Method A (T 304)				
Test #: 3		**1**	**2**	**3**
Mass of sample:	(190 g +/- 0.2 g)	190.0	190	190
Mass of Cylinder + Glass + Grease + Water (A):		286.0	286	286
Mass of Cylinder + Glass + Grease (B):		186.9	186.9	186.9
Mass of Water (C):	(A - B)	99.1	99.1	99.1
Volume of Cylinder, mL (V):	(C / 0.998)	99.2986	99.2986	99.2986
Bulk Specific Gravity (Gsb):	(From T 84)	2.632	2.632	2.632
Mass of Cylinder + sample (Wcs):		337	336.8	338.8
Mass of empty Cylinder (Wc):		186.9	186.9	186.9
Mass of fine aggregate (W):	(Wcs - Wc)	149.5	149.3	148
% Uncompacted Voids (U): ((V - (W / Gsb)) / V) *100		**42.8**	**42.8**	**43.3**
Average of % Uncompacted Voids (Uavg):		**43.0**		

Table 4.5: Uncompacted void content of fine aggregate (Silica Sand)

4.3.4 Particle Index Calculation and results

According to ASTM D 3398, Particle Index (PI) falls around 6 or 7 indicates particle composed of smooth and angular shape. A test at the quality control lab has been conducted on both materials to calculate the PI based on the equation presented in Chapter 3.

Particle Index	Black Beauty	Silica Sand
V 10	42	41
V 50	16	14
PI	16.5	16

Table 4.6: Particle Index for both materials

Table 4.6 indicates that the Particle Index is 6.5 for the spent Black Beauty and 6.0 for the spent Silica Sand. These results are acceptable and within the specifications for fine aggregate in HMA (ASTM D 3398).

4.3.5 Specific Gravity Calculation

Aggregate specific gravity is useful in making weight-volume conversions and in calculating the void content in compacted HMA.

Table 4.7 and Table 4.8 indicate that the Apparent Specific Gravity is 2.43 for the spent coal slag and 2.65 for the spent silica sand. These results are acceptable specific gravity for fine aggregate in HMA.

Specific Gravity and Absorption of Fine Aggregate (T 84)				
Sample ID:		1	2	
Pycnometer & SSD Sample (P&SSD):		434.0	353.7	
Pycnometer tare (P):		0.0	0.0	
Saturated Surface Dry Sample (S):	(P&SSD - P)	434.0	353.7	
Pycnometer & Water @ 25 º C (B):		1276.8	1259.4	
Pycnometer, Sample & Water @ 25 º C (C):		1498.2	1487.2	
Pan & Dry Sample (P&DS):		621.2	541.0	
Pan Tare (Pan):		187.9	187.9	
Oven Dry Sample (A):	(P&DS - Pan)	433.3	353.1	**AVERAGE**
Bulk Specific Gravity (Gsb):	A/(B+S-C)	2.038	2.805	2.422
Bulk SSD Specific Gravity (GsbSSD):	S/(B+S-C)	2.041	2.809	2.425
Apparent Specific Gravity (Gsa):	A/(B+A-C)	2.045	2.818	2.432
Percent Absorption (% Abs):	((S-A)/A)*100	0.16	0.17	0.165

Table 4.7: Specific Gravity and Absorption of Fine Aggregate (Black Beauty)

Specific Gravity and Absorption of Fine Aggregate (T 84)				
Sample ID:		1	2	
Pycnometer & SSD Sample (P&SSD):		200	200	
Pycnometer tare (P):		0.0	0.0	
Saturated Surface Dry Sample (S):	(P&SSD - P)	200	200	
Pycnometer & Water @ 25 º C (B):		622.8		
Pycnometer, Sample & Water @ 25 º C (C):		786.7	789.3	
Pan & Dry Sample (P&DS):		199.0	199.0	
Pan Tare (Pan):		0.0	0.0	
Oven Dry Sample (A):	(P&DS - Pan)	199.0	199.0	**AVERAGE**
Bulk Specific Gravity (Gsb):	A/(B+S-C)	2.615	2.615	2.615
Bulk SSD Specific Gravity (GsbSSD):	S/(B+S-C)	2.628	2.628	2.628
Apparent Specific Gravity (Gsa):	A/(B+A-C)	2.650	2.650	2.650
Percent Absorption (% Abs):	((S-A)/A)*100	0.50	0.50	0.50

Table 4.8: Specific Gravity and Absorption of Fine Aggregate (Silica Sand)

4.4 Marshall Tests and Analysis

The Marshall Test method was used in this study to evaluate the modified hot mix asphalt specimens. The test, as previously stated, measures the stability and the flow of the mix. This is correlated to the strength, the shear and the optimum asphalt content

AC of the pavement. Results in Tables 4.9, 4.10, and 4.11 indicate that the Black Beauty modified mix meets all DOTD requirements.

This section contains the results of Marshall Tests for one mix with 7 % spent Black Beauty substituted in the HMA. In this mix, three trial blends (3.5 %, 4 %, and 4.5 % of AC) were used to evaluate the new HMA and to obtain the optimum AC.

Three sets of 3 specimens were tested to evaluate this modified HMA (see Table 4.9 for VMA, VFA, Stability and Flow results). A spreadsheet was designed for calculating the design parameters. An important parameter, the air voids in the specimen, should be 4 % in order to find the optimum AC % graphically.

Results of Marshall Design tests for the 7 % Black Beauty coal slag are shown Tables 4.9, and 4.10.

Specifications	**Measured Values Average**
Marshall Stability	2577 lb
Flow (1/100")	12
VMA	14 %
VFA	65 %

Table 4.9: Marshall Test results: mix with 7% coal slag spent ABM

MARSHALL TEST DATA- 1 set at 3.5 % AC- Black Beauty				
Specimen	**1**	**2**	**3**	**AVERAGE**
Wt. in Air	1218.6	1218.2	1227.8	
Wt. SSD in Air	1226	1225.4	1235.8	
Wt. in Water	704.8	706.3	711.3	
Difference	521.2	519.1	524.5	
Bulk Sp. Grav.	2.338	2.347	2.341	**2.341**
Density-(lbs/CF)	145.9	146.4	146.1	**146.1**
Sp.Gr.-Aggregate	2.633	2.633	2.633	**2.633**

Cont Table 4.10:

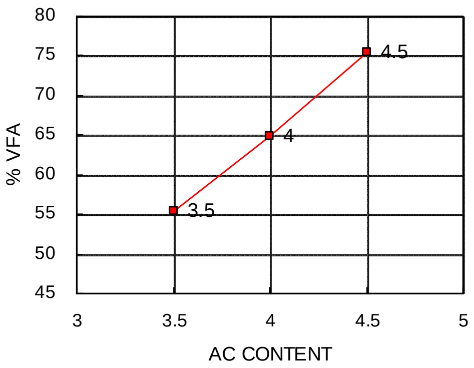
Max.Sp.Gr.	2.500	2.500	2.500	**2.500**
Effective Sp.Gr.	2.636	2.636	2.636	**2.636**
Absorded AC %	0.050	0.050	0.050	**0.050**
Effective AC %	3.452	3.452	3.452	**3.45**
% VMA	14.3	14.0	14.2	**14.18**
%VFA	54.8	56.2	55.2	**55**
% Voids	6.5	6.1	6.4	**6.3**
Corr. Stability	2291	2483	2365	**2362**
Flow 1/100"	9	9	10	**9**
Temperature	325	325	325	**325**
MARSHALL TEST DATA- 1 set at 4 % AC. Black Beauty				
Specimen	**1**	**2**	**3**	**AVERAGE**
Wt. in Air	1230.1	1225.9	1235.4	
Wt. SSD in Air	1235.4	1229.1	1238.7	
Wt. in Water	712.8	710.4	717.5	
Difference	522.6	518.7	521.2	
Bulk Sp. Grav.	2.354	2.363	2.370	**2.360**
Sp.Gr.-Aggregate	2.633	2.633	2.633	**2.633**
Max.Sp.Gr.	2.482	2.482	2.482	**2.482**
Effective Sp.Gr.	2.636	2.636	2.636	**2.636**
Absorded AC %	0.050	0.050	0.050	**0.050**
Effective AC %	3.952	3.952	3.952	**3.95**
% VMA	14.2	13.8	13.6	**13.95**
%VFA	63.7	65.6	67.0	**65**
% Voids	5.1	4.8	4.5	**4.90**
Corr. Stability	2770	2846	2752	**2775**
Flow 1/100"	11	12	13	**12**
Temperature	325	325	325	**325**
MARSHALL TEST DATA- 1 set at 4.5 % AC. Black Beauty				
Specimen	**1**	**2**	**3**	**AVERAGE**
Wt. in Air	1229.2	1230.6	1240.5	
Wt. SSD in Air	1232.5	1232.9	1243.8	
Wt. in Water	718	716.6	721.4	
Difference	514.5	516.3	522.4	
Bulk Sp. Grav.	2.389	2.383	2.375	**2.381**
Density-(lbs/f^3)	149.1	148.7	148.2	**148.6**
Sp.Gr.-Aggregate	2.633	2.633	2.633	**2.633**
Max.Sp.Gr.	2.464	2.464	2.464	**2.464**

Cont Table 4.10:

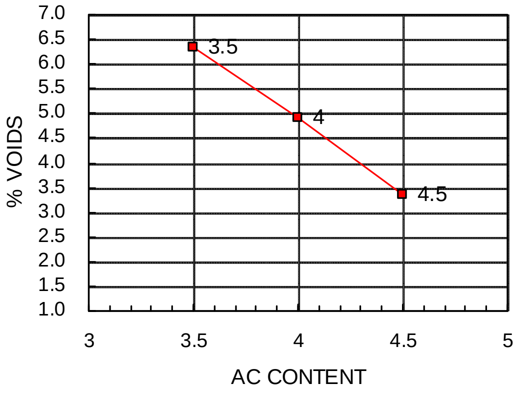
Effective Sp.Gr.	2.636	2.636	2.636	**2.636**
Absorded AC %	0.050	0.050	0.050	**0.050**
Effective AC %	4.452	4.452	4.452	**4.45**
% VMA	13.3	13.5	13.9	**13.64**
%VFA	77.4	76.0	74.0	**75**
% Voids	3.0	3.2	3.6	**3.35**
Corr. Stability	2548	2603	2584	**2594**
Flow 1/100"	14	13	13	**14**
Temperature	325	325	325	**325**

Table 4.10: Marshall Test results for spent Black Beauty

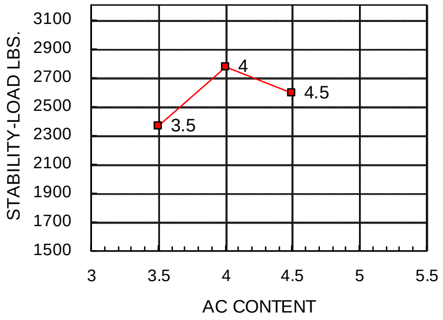
PERCENT VFA



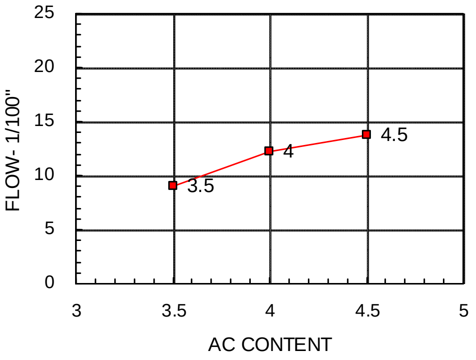
PERCENT VOIDS



MARSHALL STABILITY



MARSHALL FLOW



Cont Figure 4.6

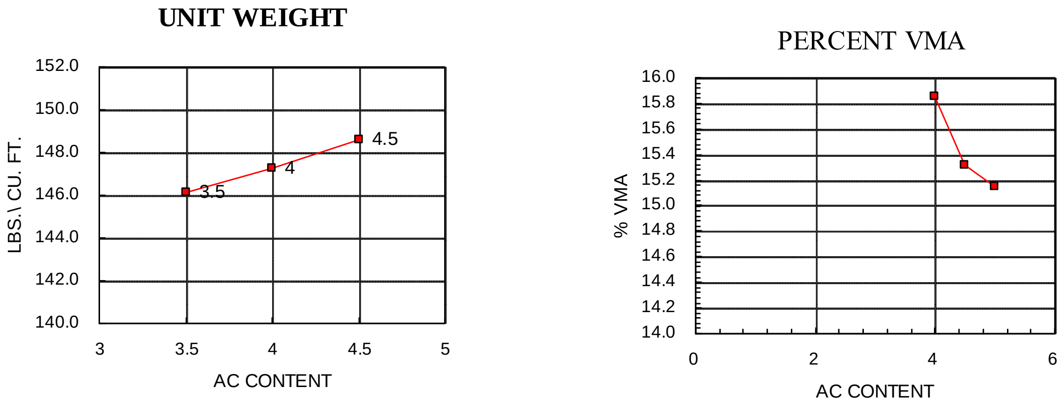


Fig 4.6: Optimum AC content Curves for Black Beauty

This section contains the results of Marshall Tests for one mix with 10 % spent silica sand substituted in the HMA. In this mix, three trial blends (4.0 %, 4.5 %, and 5.0 % of AC) were used to evaluate the new HMA and to obtain the optimum AC.

Three sets of 3 specimens were tested to evaluate this modified HMA (see Table 4.11 for VMA, VFA, Stability and Flow results). A spreadsheet was designed for calculating the design parameters. Again, an important parameter, the air voids in the specimen should be 4 % in order to find the optimum AC % graphically.

Results of Marshall Design tests for the 10 % spent silica sand are shown Tables 4.11 and 4.12 .

Specifications	Measured Values Average
Marshall Stability	3625 lb
Flow (1/100”)	15
VMA	15.5 %
VFA	73 %

Table 4.11: Marshall Test results: mix with 10% silica sand spent ABM

MARSHALL TEST DATA- 1 set at 4 % AC- silica sand.				
Specimens	**1**	**2**	**3**	**AVERAGE**
Wt. in Air	1242.4	1237.8	1275.1	
Wt. SSD in Air	1245.2	1243.6	1278.1	
Wt. in Water	712.9	712.7	733.2	
Difference	532.3	530.9	544.9	
Bulk Sp. Grav.	2.334	2.332	2.340	**2.330**
Density-(lbs/CF)	145.6	145.5	146.0	**146.0**
Sp.Gr.-Aggregate	2.664	2.664	2.664	**2.664**
Max.Sp.Gr.	2.478	2.478	2.478	**2.478**
Effective Sp.Gr.	2.632	2.632	2.632	**2.632**
Absorded AC %	-0.480	-0.480	-0.480	**-0.480**
Effective AC %	4.460	4.460	4.460	**4.46**
% VMA	15.9	16.0	15.7	**15.85**
%VFA	63.5	63.0	64.5	**63.67**
% Voids	5.8	5.9	5.6	**5.76**
Corr. Stability	3338	3461	3489	**3429**
Flow 1/100"	15	7	11	**11**
Temperature	300	300	300	**300**
MARSHALL TEST DATA- 1 set at 4.5 % AC- silica sand				
Specimen	**1**	**2**	**3**	**AVERAGE**
Wt. in Air	1231.9	1234.3	1255.1	
Wt. SSD in Air	1234.6	1236.3	1256.7	
Wt. in Water	713.9	712.8	725.7	
Difference	520.7	523.5	531.0	
Bulk Sp. Grav.	2.366	2.358	2.364	**2.362**
Density-(lbs/CF)	147.6	147.1	147.5	**147.416**
Sp.Gr.-Aggregate	2.664	2.664	2.664	**2.664**
Max.Sp.Gr.	2.460	2.460	2.460	**2.460**
Effective Sp.Gr.	2.632	2.632	2.632	**2.632**
Absorded AC %	-0.480	-0.480	-0.480	**-0.480**
Effective AC %	4.958	4.958	4.958	**4.958**
% VMA	15.2	15.5	15.3	**15.32**
%VFA	74.8	73.2	74.4	**74.12**
% Voids	3.8	4.2	3.9	**3.96**
Corr. Stability	3700	3750	3874	**3775**
Flow 1/100"	12	13	16	**14**
Temperature	300	300	300	**300**

Cont Table 4.12- Marshall Data for 4, 4.5, and 5 % Specimens

MARSHALL TEST DATA- 1 set at 5.0 % AC- silica sand				
Specimen	**1**	**2**	**3**	**AVERAGE**
Wt. in Air	**1224.1**	**1280.6**	**1243.5**	
Wt. SSD in Air	**1225.9**	**1282.0**	**1244.7**	
Wt. in Water	712.2	742.3	722.7	
Difference	513.7	539.7	522.0	
Bulk Sp. Grav.	2.383	2.373	2.382	**2.379**
Density-(lbs/CF)	150.0	148.1	149.0	**149.021**
Sp.Gr.-Aggregate	2.664	2.664	2.664	**2.664**
Max.Sp.Gr.	2.442	2.442	2.442	**2.442**
Effective Sp.Gr.	2.632	2.632	2.632	**2.632**
Absorded AC %	-0.480	-0.480	-0.480	**-0.480**
Effective AC %	5.456	5.456	5.456	**5.456**
% VMA	15.0	15.4	15.1	**15.16**
%VFA	83.8	81.5	83.7	**83.00**
% Voids	2.4	2.8	2.5	**2.58**
Corr. Stability	3750	3650	3680	**3693.333**
Flow 1/100"	22	22	24	**22.667**

Table 4.12: Marshall Test results for spent silica sand

The optimum asphalt content AC for both mixes (coal slag and silica sand) can be easily obtained by using the Marshall Stability graphs in Figure 4.6 and Figure 4.7. The optimum AC for coal slag is 4.6 % and for silica sand is 4.5 % respectively. A comparison among three mix coal slag, sand blast, and conventional mix shows that all of these mixes consume approximately the same amount of AC at the optimum. But the spent silica sands material gives a stronger structural aggregate matrix than spent Black Beauty due to shape factors and apparent specific gravity.

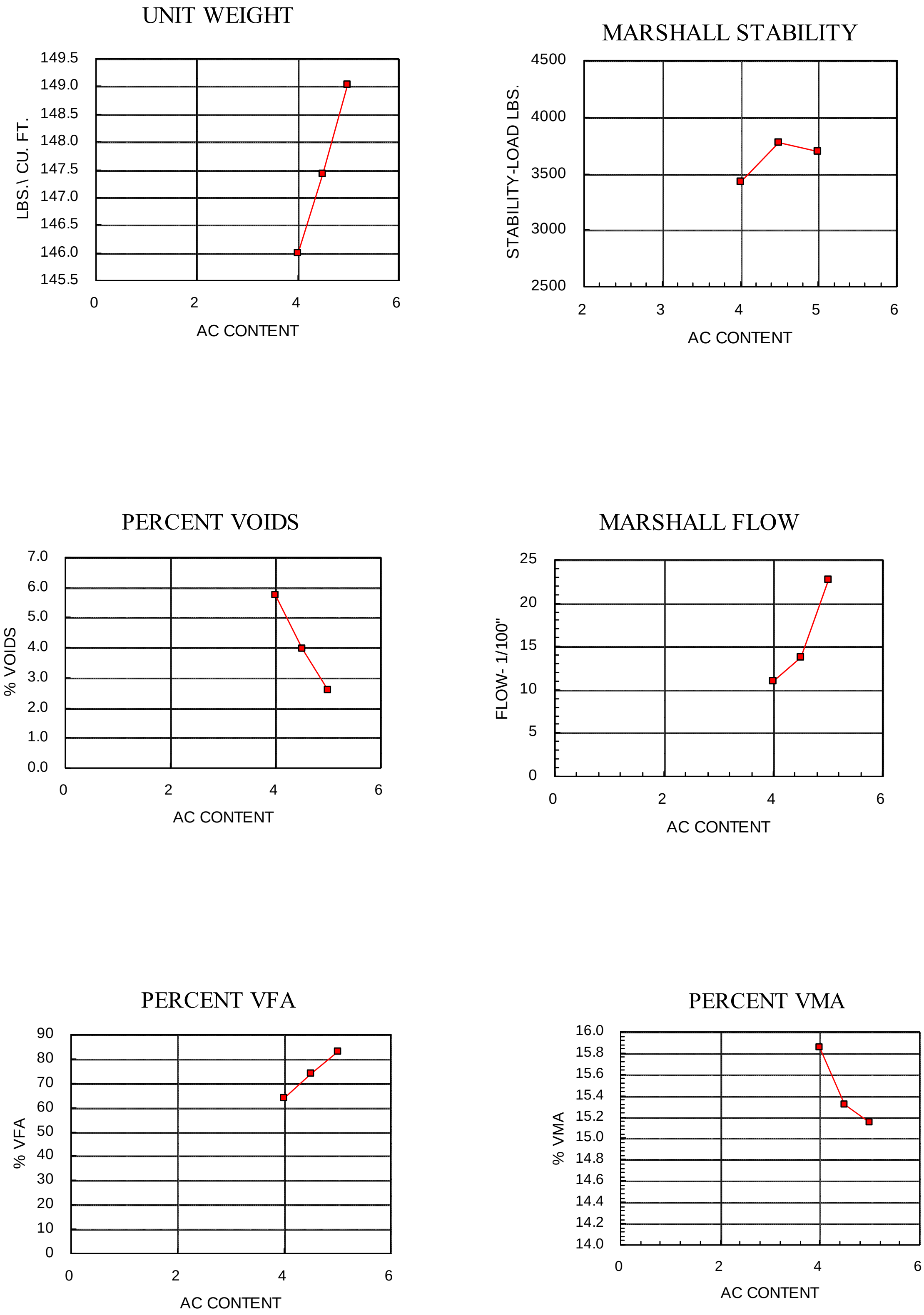


Fig 4.7: Optimum AC content Curves for Black Beauty.

4.5 Superpave Mixture Design

The Superpave Mixture Design was used to evaluate the volumetric relationships for the modified hot mixes and to obtain the optimum AC. Two sets of a modified mixtures with both spent materials (Black Beauty and silica sand) were designed based on the Superpave design method for a 20-yr traffic load with $N_{initial} = 7$, $N_{design} = 75$ and $N_{max} = 115$ (see Table 4.13).

20-yr Traffic Loading (in millions of ESALs)	Number of Gyrations		
	$N_{initial}$	N_{design}	N_{max}
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 10*	8 (7)	100 (75)	160 (115)
10 to < 30	8	100	160
³ 30	9	125	205

* When the estimated 20-year design traffic loading is between 3 and < 10 million ESALs, the agency may, at its discretion, specify $N_{initial} = 7$, $N_{design} = 75$ and $N_{max} = 115$.

Table 4.13: 20-year design traffic loading

Three sets of three specimens of Black Beauty (8 % by weight) and three sets of three specimens (10 % by weight) were created using Superpave design method. Each set was designed using a different AC %.

The first and the second sets of (Black Beauty and silica sand) are presented in Table A 1.1 and Table A 1.2 respectively. The optimum AC % for Black Beauty is 4.8 % (see Figure 4.10) and for silica sand is 4.9 % (see Figure 4.11). All volumetric and mechanical parameters required for design are listed.

Tests results show that all design LADOTD specifications (VMA, VFA, $N_{initial}$, N_{design}) are met for both materials (Black Beauty and silica sand).

Results for the Superpave design method indicate consistency with Marshall Design criteria for both mix, and the Tables 4.14 and 4.15 show the most important volumetric parameters for both materials.

	AC 4.1 %	**AC 4.6 %**	**AC 5.1%**
Bulk Sp. Grav.(Gmb)	2.331	2.436	2.357
Density-(lbs/f^3)	145.5	146.6	147.1
%VMA	15.5	15.4	15.4
%VFA	51.8	59.9	67.4
Gmm@Ninitial (89max)	84.2	84.9	85.9
Gmm@Ndesign(96.0)	92.5	93.8	95
%Voids @ Ndesign	7.5	6.2	5.0

Table 4.14: Superpave criteria to meet the specification – coal slag

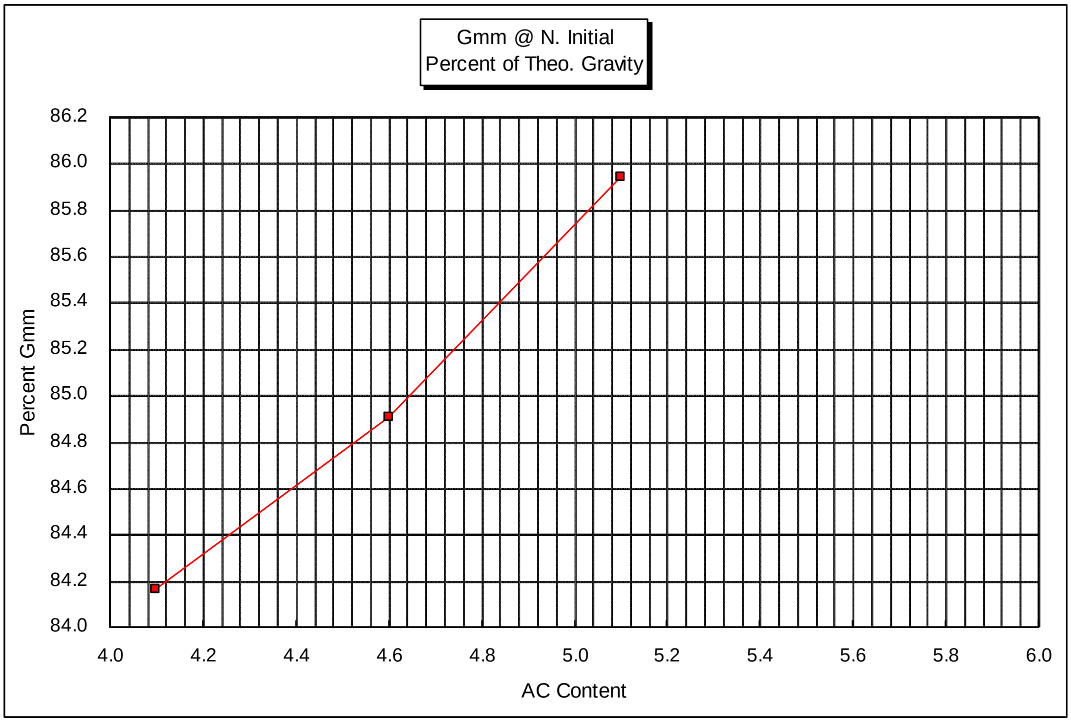


Fig 4.8: Asphalt Content with $N_{initial}$ –Coal Slag

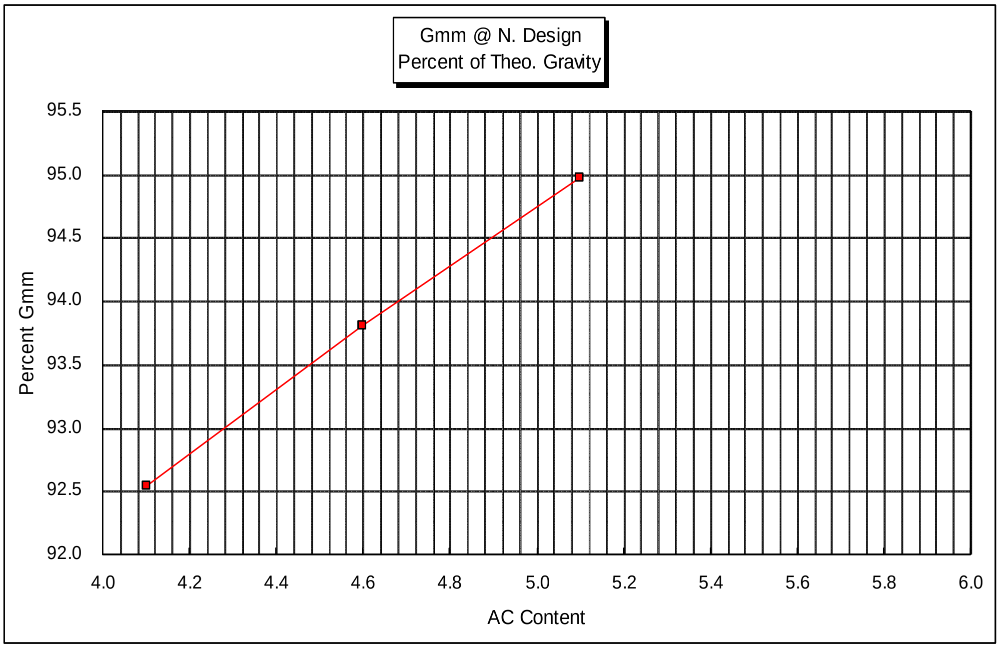


Fig 4.9: Asphalt Content with N_{design} –Coal Slag

The maximum AC % for Black Beauty was found graphically as shown below.

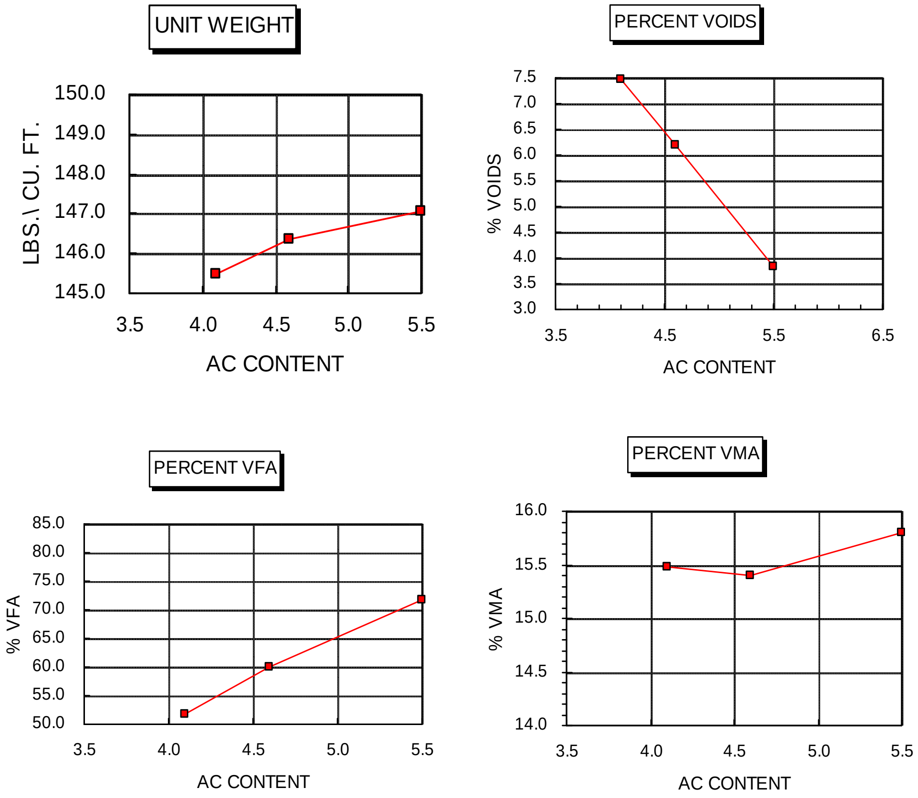


Fig 4.10: Optimum AC% for coal slag (Black Beauty)- Superpave

	AC 4.1 %	AC 4.6 %	AC 5.1 %
Bulk Sp. Grav.(Gmb)	2.336	2.344	2.383
Density-(lbs/CF)	145.8	146.2	148.7
%VMA	15.3	15.5	14.5
%VFA	57.3	64.1	77.4
Gmm@Ninitial (89max)	85.3	86.0	87.7
Gmm@Ndesign(96.0)	93.5	94.4	96.7
%Voids @ Ndesign	6.5	5.6	3.3

Table 4.15: Superpave criteria to meet the specification – Silica Sand

The maximum AC % for silica sand was found graphically as shown below

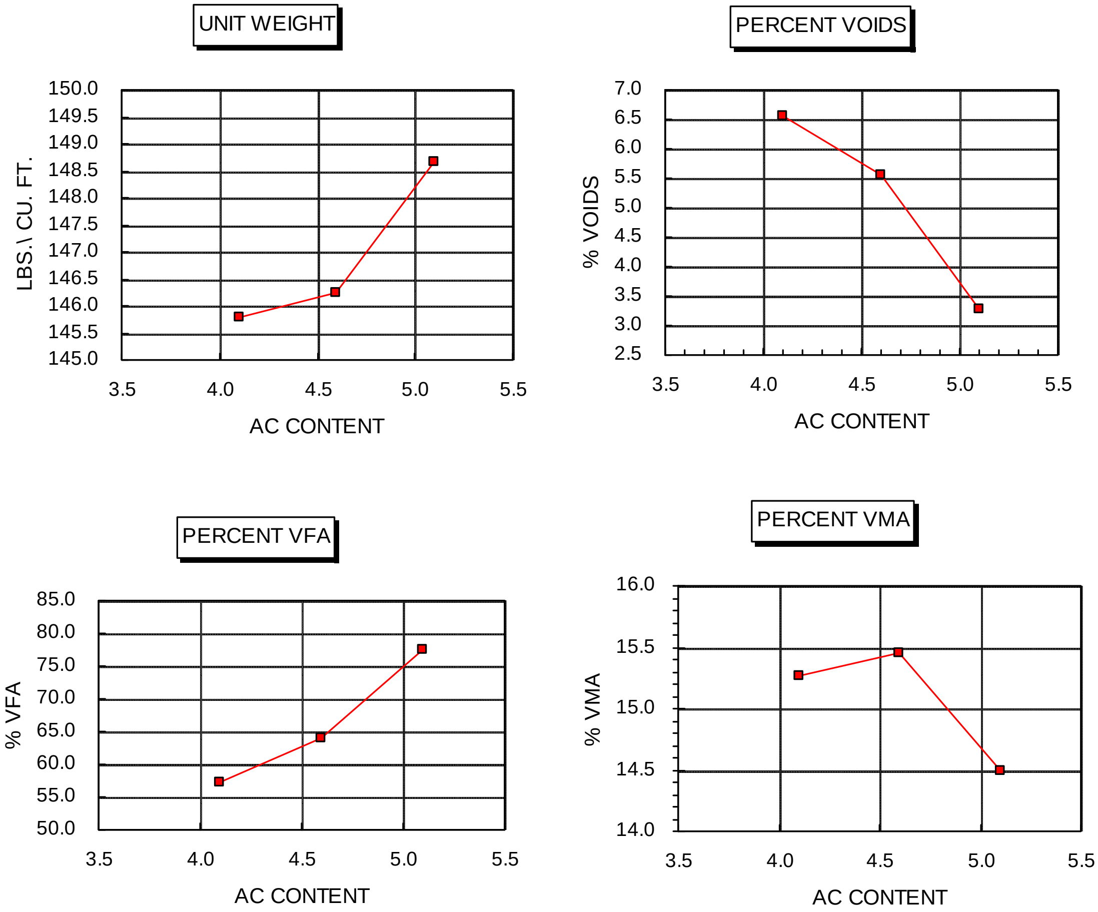


Fig 4.11: Optimum AC% for silica sand - Superpave

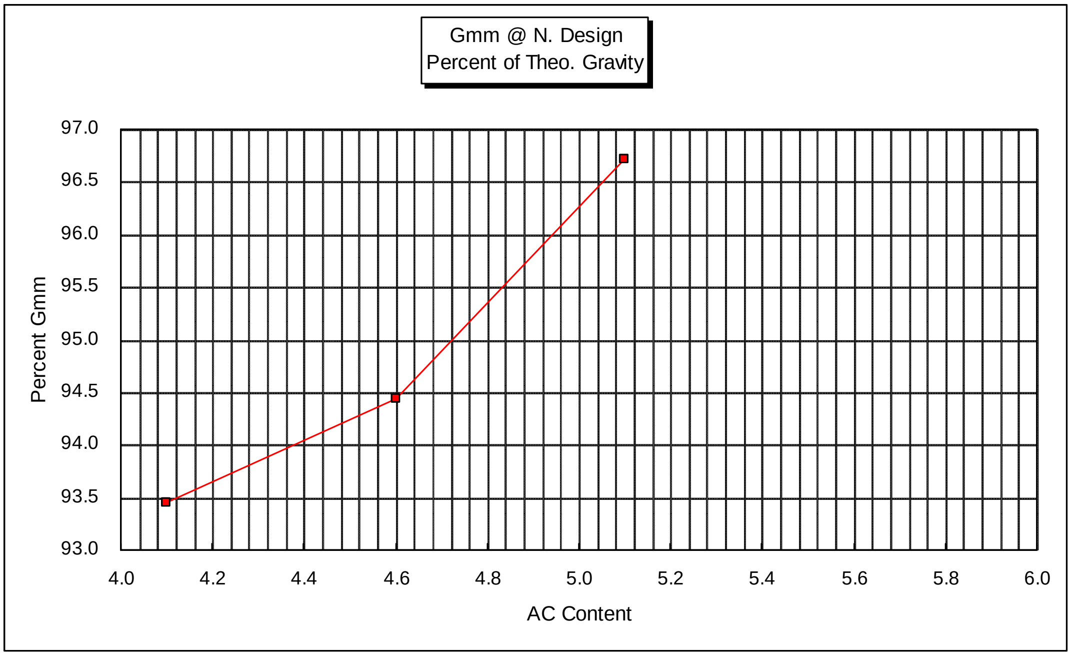


Fig 4.12: Asphalt Content with $N_{initial}$ –Silica Sand

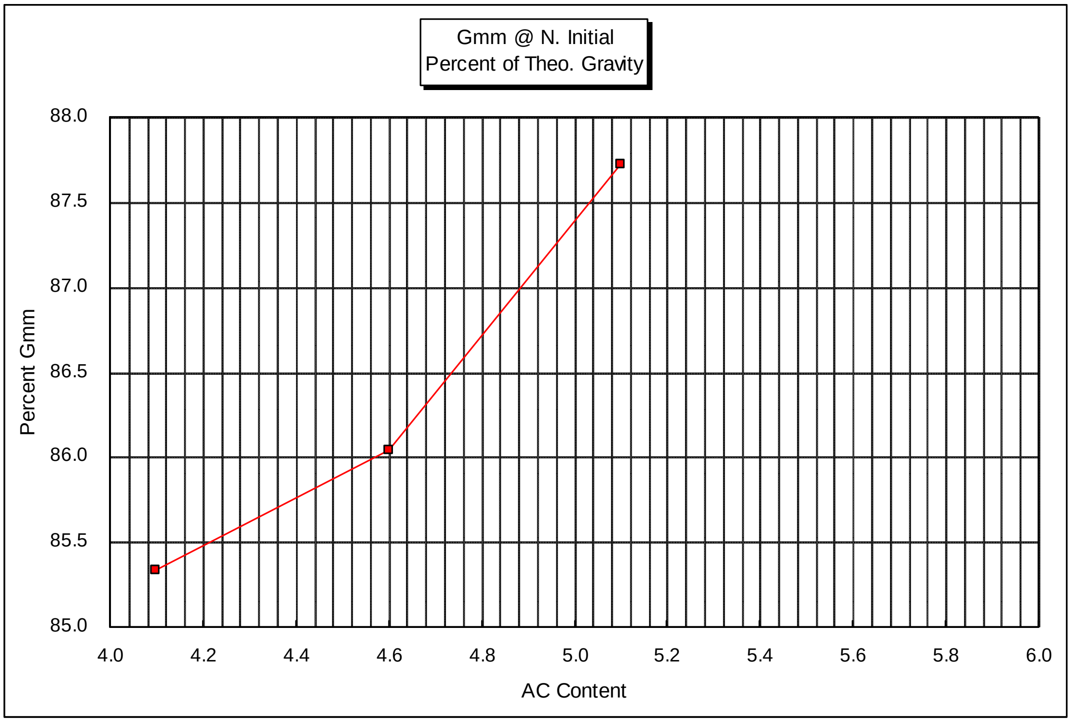


Fig 4.13: Asphalt Content with N_{Design}–Silica Sand

4.6 The Environmental Tests and Analysis

Total and leachable metal concentrations were determined using applicable EPA methods for samples of conventional, coal slag and silica sand hot mix asphalt. As shown in Table 4.16, total metal concentrations for all three types of samples are at or below concentrations found in native soils.

Metal	USEPA Physical Chemical Method	Practical Quantitation Limit, PQL (mg/kg)	Conventional Mix (mg/kg)	Spent Coal Slag Mix (mg/kg)	Spent Silica Sand Mix (mg/kg)
Arsenic	6010B	3.0	below PQL	below PQL	below PQL
Barium	6010B	5.0	21.7	437	33.0
Cadmium	6010B	0.5	below PQL	below PQL	below PQL
Chromium	6010B	2.0	6.3	11.5	10.4
Lead	6010B	5.0	below PQL	below PQL	below PQL
Mercury	7470-1A	0.014	below PQL	below PQL	below PQL
Selenium	6010B	5.0	below PQL	below PQL	below PQL
Silver	6010B	1.0	below PQL	below PQL	below PQL

Table 4.16: Total metal RCRA test results

Table 4.17 lists the results of TCLP tests run on the three types of samples. All concentrations are well below regulatory levels.

Metal	Practical Quantitation Limit (mg/l)	Regulatory Level (mg/l)	Conventional Mix (mg/l)	Spent Coal Slag Mix (mg/l)	Spent Silica Sand Mix (mg/l)
Arsenic	0.03	5.0	below PQL	below PQL	below PQL
Barium	0.05	100.0	0.21	0.10	0.08
Cadmium	0.005	1.0	below PQL	below PQL	below PQL
Chromium	0.010	5.0	below PQL	below PQL	below PQL
Lead	0.010	5.0	below PQL	below PQL	below PQL
Mercury	0.020	0.2	below PQL	below PQL	below PQL
Selenium	0.05	1.0	below PQL	below PQL	below PQL
Silver	0.010	5.0	below PQL	below PQL	below PQL

Table 4.17: TCLP test results, USEPA Method 1311

4.7 Submerged Asphalt Specimen Test

A preliminary limited testing program done by the City of New Orleans on cores taken from asphaltic concrete pavement at various locations along Canal Street in Orleans Parish indicated that the extracted asphalt did experience accelerated aging which correlated with the height of Katrina flooding experienced by the pavement at the location of the cores. It was speculated that stripping maybe a factor in this type of degradation. A modified hot mix asphalt containing spent ABM may perform similarly to a conventional mix under Katrina flooding, or the presence of spent ABM may increase the rate of degradation.

In order to determine if long term flooding would negatively impact performance of modified hot mix asphalt beyond that measured for conventional asphalt, a testing program was developed and implemented. Eighteen Marshall Test type specimens were made for each of three mixes. The first mix was typical conventional hot mix asphalt containing pump sand, lime stone gravel, and sandstone. The second mix was a mix modified with 7 % of the sandstone replaced by spent coal slag ABM. The third and final mix as a modified hot mix with 10 % of the sandstone replaced with spent silica sand ABM. One specimen from each mix was used for environmental tests. Three specimens per mix were used as control specimens. The rest were then submitted to a conditioning program:

- Set A- Six week duration with a three foot fresh water head,
- Set B- Six week duration with a three foot saltwater head, and
- Set C- Six week duration with a six foot saltwater head.

The Tensile Strength Ratio (TSR) of the six week conditioned specimens were calculated in order to evaluate impact of the salinity and height of submergence in water on tensile strength (an indicator of potential stripping). Results of the tensile tests are listed in Table 4.18 for control samples, Table 4.19 for set A, Table 4.20 for set B and Table 4.21 for set C respectively.

Mix	Samples	P (Ib)	T (in)	D (in)	Stc (psi)	Average S_{tc} (psi)	Standard Deviation (psi)
Modified mix with Black Beauty	No. 1	4099	2.59	4	251.88	243	6.47
	No. 2	3900	2.57	4	241.5		
	No. 3	3816	2.57	4	236.3		
Modified mix with Silica Sand	No. 1	4299	2.59	4	264.1	254.3	9
	No. 2	4156	2.56	4	258.3		
	No. 3	3873	2.56	4	240.7		
Conventional mix	No. 1	3303	2.41	3.99	218.60	228.86	12.36
	No. 2	3386	2.43	4.0	221.76		
	No. 3	3729	2.41	4	246.26		

Table 4.18: TSR for control samples specimens

The second phase of this test used conditioned specimens submerged under fresh and salt water (35 ppt), for six week duration. Once the six week conditioning was completed, the specimens were tested in order to measure the TRS.

Mix	Samples	P (Ib)	T (in)	D (in)	Stm (psi)	Avg. S_{tm} (psi)	TSR (%)	Avg. TRS (%)	SDV (%)
Modified mix with Black Beauty	No. 1	3960	2.56	4	238.1	230.8	97.8	94.8	2.81
	No. 2	3787	2.58	4	233		95.8		
	No. 3	3589	2.58	4	221.3		91.0		
	No. 1	3699	2.59	4	227.3		89.3		0.08

Table 4.19 Cont

Modified mix with Silica Sand	No. 2	3699	2.6	4	226.4	226.7 (0.42)	89.2	89.2	
	No. 3	3699	2.6	4	226.4		89.1		
Conventional mix	No. 1	3739	2.52	4	226.1	218 (15.7)	99.1	95.1	5.77
	No. 2	3960	2.59	4	226.7		99.4		
	No. 3	3012	2.41	4	198.9		87.0		

Table 4.19: TSR for the 6 week test under fresh water (3 ft)

Mix	Samples	P (Ib)	T (in)	D (in)	Stm (psi)	Avg S_{tm} (psi)	TSR (%)	Avg TRS (%)	SDV (%)
Modified mix with Black Beauty	No. 1	3470	2.56	4	215.7	230	88.4	92.7	4.88
	No. 2	3960	2.55	4	241.1		99.2		
	No. 3	3846	2.56	4	239.1		98.3		
	No.4	3526	2.57	4	218.3		89.7		
Modified mix with Silica Sand	No. 1	3443	2.56	3.96	216.2	221.4	85.1	87.1	2.64
	No. 2	3500	2.58	3.98	216.9		85.3		
	No. 3	3792	2.59	4	233		91.6		
	No. 4	3589	2.60	4	219.6		86.4		
Conventional Materials	No. 1	4019	2.56	4	219.8	208	96	90.2	7.52
	No. 2	4019	2.58	4	217.9		95.1		
	No. 3	3816	2.51	4	211.9		92.5		
	No. 4	2673	2.41	4	176.5		77.4		

Table 4.20: TSR for the 6 week test under saltwater (3 ft)

Mix	Samples	P (Ib)	T (in)	D (in)	Stm (psi)	Avg S_{tm} (psi)	TSR (%)	Avg. TRS (%)	SDV (%)
Modified mix with Black Beauty	No. 1	3665	2.55	4	235.8	223.3	97.0	91.6	3.41
	No. 2	3526	2.6	4	215.8		88.0		
	No. 3	3509	2.57	3.99	217.5		89.5		
	No.4	3509	2.58	3.98	224.2		92.2		

Table 4.21 Cont

Modified mix with Silica Sand	No. 1	3244	2.6	4	198.5	207.9	78	81.4	2.91
	No. 2	3443	2.55	3.97	216.7		85.0		
	No. 3	3443	2.58	4	212.3		83.5		
	No. 4	3244	2.57	4	200.9		79.1		
Conventional Materials	No. 1	3665	2.58	3.99	226	222.1	99.1	96.2	4.18
	No. 2	3554	2.41	4	234		98.2		
	No. 3	3303	2.58	4	203		89		
	No. 4	3665	2.6	3.98	225.7		98.6		

Table 4.21: TSR 6 week test under saltwater (6 ft)

Three graphs have been plotted. Eash graph shows TSR and standard deviation (SDV) for all three mixes based on duration of submergence, height of submergence and salinity of the water. All mixes' TSR values were acceptable, although there was a statistically significant decrease in tensile strength as duration or head increased. Slat water had a grater impact on TSR than fresh water for all sets.

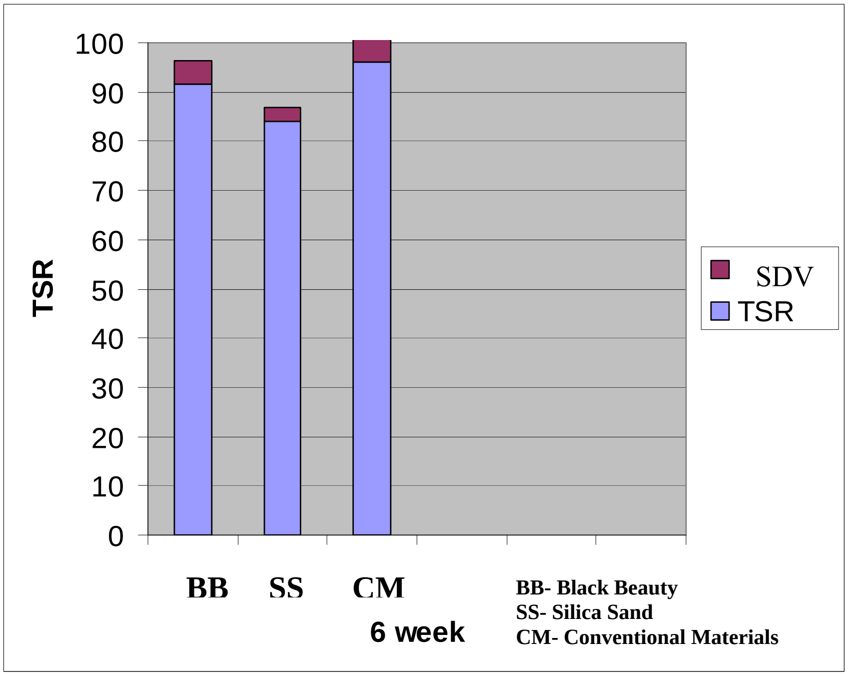


Fig 4.14: TSR based on 6 week duration of submergence

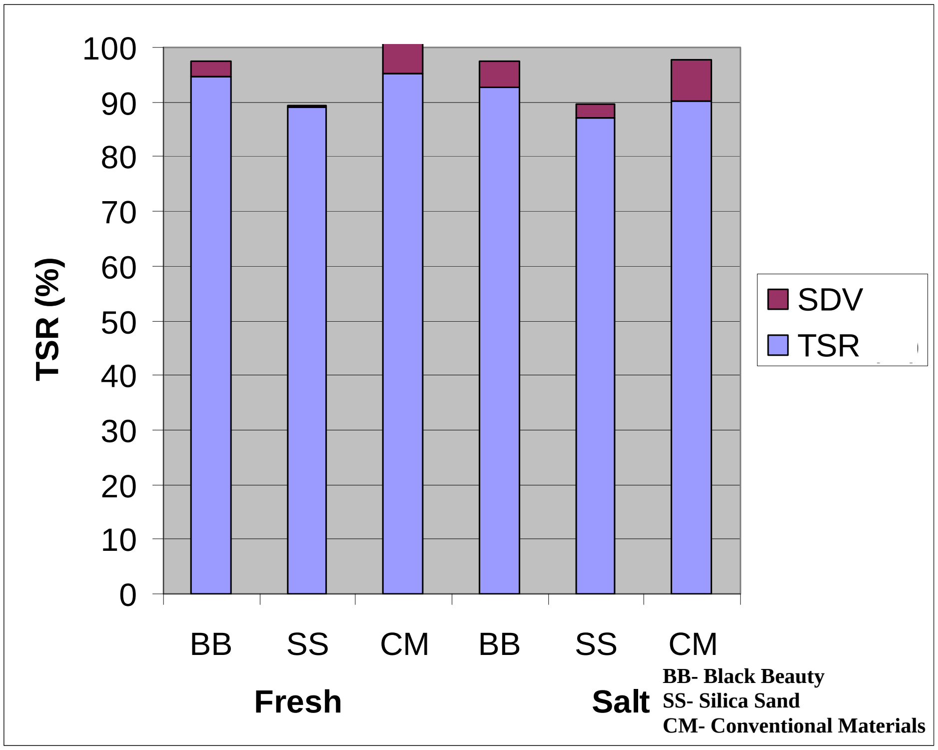


Fig 4.15: TSR based on salinity

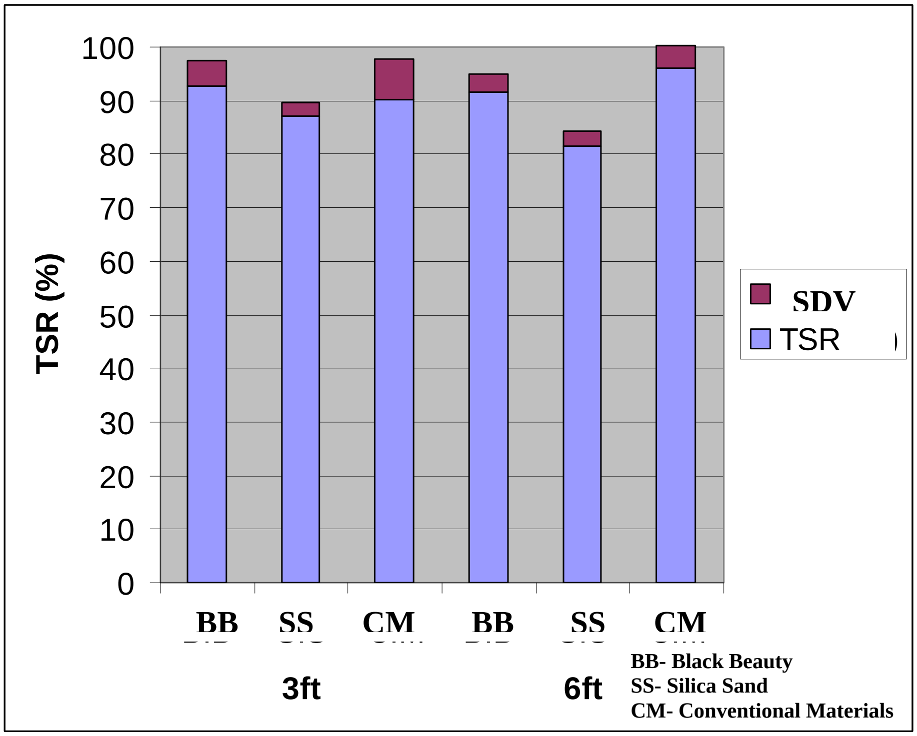


Fig 4.16: TSR based on height of submergence

Chapter 5 CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusion

This report documents the finding of an extensive research study on using spent ABM in hot mix asphalt to replace part of the fine aggregates used in the production of conventional hot mix asphalt. This thesis is concerned with recycling the spent abrasive materials that are generated at two shipyards in New Orleans, Bollinger Shipyards Inc, and Northrop-Grumman Avondale, as opposed to storage onsite at shipyard facilities with subsequent disposal in non-hazardous landfills. At the end of this research, it is concluded that the two spent ABM used in this study can be successfully recycled in hot mix asphalt due to the following reasons:

1- The results from aggregate evaluation tests were within required limits
    a. Sand Equivalency (96 % for Black Beauty and 96 % for silica sand),
    b. Gradation (well graded for both materials),
    c. Particle index (6 for Black Beauty and 6.5 for silica sand),
    d. Specific gravity (2.43 for Black Beauty and 2.6 for silica sand), and
    e. Aggregate angularity (43.1 for Black Beauty and 43.0 for silica sand).

2- The behavior of the spent ABM with the virgin aggregates and binder is compatible. Modified mixes tested using two standard specifications indicated no significant negative impact due to inclusion of spent ABM. For the Marshall Test, all required design parameters are within the range of specification
    a. Stability measurements of 2577 for Black Beauty and 3652 for silica sand are well above the 1800 minimum.

   b. VMA measured 14 for Black beauty and 15.5 for silica sand, within the required range of 16.
   c. VFA measured 65 for Black Beauty and 73 for silica sand, also well within the 65 recommended range.

3- For the Superpave Test, all required design parameters are within the range of specification
   a. Asphalt content (AC) optimum was 4.9 % (minimum required is 4.5 %).
   b. VMA was 15 (minimum required is 13).
   c. VFA was 68 (minimum required is 65).

The other part of this research was to simulate the impact Hurricane Katrina flooding on performance of the hot mix asphalt pavement using specimens made from either conventional or one of the two modified mixes. After the analysis of mixes based on three functions (duration, height, and salinity), the TRS measurements of all six week conditioned specimens were above the minimum required level. However, tensile test results did indicate that long term submergence did negatively impact tensile strength.

1- Specimens conditioned in salt water had less tensile strength after six weeks of submergence than specimens conditioned in freshwater
2- Specimens conditioned using six foot of salt water had less tensile strength than those conditioned under three feet of salt water.

5.2 Future Research

Based on the results of the first part of this study, it is suggested that several additional studies be conducted in the future:

1- The sensitivity of the binder with modified HMA.

2- Estimation the rutting life for the modified mix.

3- Substitution ABM in other construction composite materials.

Based on the results of the final phase of this research, future research could be:

1- Measurement more parameters such as Marshall Stability and Flow of all mixes

2- Testing of specimens at varying temperature and duration.

3- Conditioning of specimens using contaminated water.

4- Testing of specimens using the Superpave design method.

5- Extraction of asphalt from conditioned specimens and determine the impact of various submergence heads and duration on permeability and penetration.

References

AASHTO T 85-85 "Specific Gravity and Absorption of Coarse Aggregate" Washington D.C.: American Association of State Highway Transportation Officials. 2002.

AASHTO T 96-94 "Standard Test Method for Resistance to Degradation of Small Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine" Washington D.C.: American Association of Highway Transportation Officials.2002.

AASHTO T 103-83. "Standard Method of Test for Soundness of Aggregates by Freezing and Thawing" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO T 104-86 "Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO PP19 "Volumetric Analysis of Compacted HMA" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO TP4 "Density of HMA Gyratory Specimens" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO PP28 "Superpave Volumetric Design" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO T166 "Bulk Specific Gravity (Gmb)" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO T209 "Maximum Specific Gravity (Gmm)" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO T 304 "Fine Aggregate Angularity (Method A)" Washington D.C.: American Association of State Highway Transportation Officials.2002.

AASHTO R12 "Marshall Mix Design" Washington D.C.: American Association of State Highway Transportation Officials.2002.

Ahmed, I., Use of Waste Materials in Highway Construction, Noyes Data Corp, Park Ridge, NJ.1993.

Asphalt Recycling and Reclaiming Association (ARRA). Directory. ARRA, Annapolis, MD, 1994, 1993-1994.

Asphalt Institute, “Mix Design Methods for Asphalt, 6th ed., MS-02”, Asphalt Institute. Lexington, KY, 1997.

ASTM D75, “Sampling of Aggregate” American Society of Testing Materials, 2004.

ASTM C702, “Standard practice for reducing Samples of aggregate to testing size” American Society of Testing Materials, 2004.

ASTM C 88, “Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate” American Society of Testing Materials 2004.

ASTM D 5821 “Determining percent of fractured particles in coarse aggregate” American Society of Testing Materials 2004.

Austin, G.T. “Blasting Abrasives in the U.S. Market, “Balancing Economics and Compliance for Maintaining Protective Coatings” SSPC 95-09, Steel Structures Painting Council, Washington, DC, pp.204-215, 1995.

Brown, E.R. Insuring Quality in Hot Mix Recycling, Transportation Research Board, Transportation Research Record 885, 1992.

DOTD TR 109, “Determining the Unit weight of the ABM” Department of transportation and Development”.2003.

DOTD TR 120, “Sand Equivalency” Department of transportation and Development”, 2003.

DOTD TR 119, “Flat and Elongated” Department of transportation and Development” 2003.

DOTD TR306, “Coarse Aggregate Angularity (% Crushed)” Department of transportation and Development” 2003.

DOTD TR112, “Sieve Analysis –P200 by Washing” Department of transportation and Development” 2003.

DOTD TR113 “Sieve Analysis of Fine and Coarse Aggregates”, Department of transportation and Development” 2003.

DOTD TR428, “Liquid Limit and PI” Department of transportation and Development” 2003.

Heath, J.C., L.A. Smith, J.L. Means, and K.W. Nehring, “Recycling and Reuse Options for Spent Abrasive Blasting Media and Similar Wastes”, Tech Memorandum TM-2178-ENV, Naval Facilities Engineering Service Center, Port Hueneme, CA. 1996.

Heath, J.C., L.A. Smith, J.L. Means, and K.W. Nehring, 1996, "Technology Transfer Report on Recycling Spent Sandblasting Grit into Asphaltic Concrete", Memorandum TM-2179-ENV, Naval Facilities Engineering Service Center, Port Hueneme, CA, 1996.

Heitzman, M.S. State of the Practice, "Design and Construction of Asphalt paving materials with Crumb Rubber Modifiers" , Federal Highway Administration Report No. FHWA-SA-92-022,1992.

Kandhal, P.S. Waste Materials in Hot Mix Asphalt- An Overview ASTM Special Technical Publication ,1993.

Kandhal, P S; Cooley Jr, L A, "THE RESTRICTED ZONE IN THE SUPERPAVE AGGREGATE GRADATION SPECIFICATION"
NCHRP Report 46, 2001.

Krchma, L.C. and Gagle, D.W. A U.S.A. History of Asphalt Refined from Crude Oil and Its Distribution. *Asphalt Paving Technology: Proceedings*, vol. 43A. Association of Asphalt Paving Technologists Historical Session, 26 February.Williamsburg, VA. 1974.

McGennis, R.B, Anderson,R.M, Kennedy, T.W, and Solaimanian, "M. Background of SUPERPAVE Asphalt Mixture Design and Analysis", Report No.FHWA-SA-95-003, Federal Highway Administration, Washington, D.C., 1995.

McLeod, N.W and J.K Davidson, "Particle Index Evaluation of Aggregates for asphalt Paving Mixtures" , Proceeding Association of Asphalt Paving Technologist, volume, 1981.

Means, J.L., K.W. Nehring, and J.C. Heath, "Abrasive Blast Material Utilization in Asphalt Roadbed Material", 3rd International Symposium of Stabilization of Hazardous Radioactive and Mixed Wastes, ASTM 1240, Eds. T.M. Gilliam and C.C. Wiles, ASTM, Philadelphia, PA, 1995.

Medford, W.M., "Containment and Beneficial Reuse of Blasting Sand in Asphalt Concrete: A Case History", Journal of Protective Coatings and Linings, January, pp. 36-44, 1990.

Monroe, C. K.. "Laboratory Investigation 88-3/59-R-323, Bituminous Concrete Glassphalt Route 37-86." NJDOT Bureau of Materials. October, 1990.

National Asphalt Pavement Association, Development of Marshall Procedures for Designing Asphalt Paving Mixtures, Information Series 84. National Asphalt Pavement Association. Lanham, MD, 1982.

Naval Facilities Engineering Service Center, “Recycling Spent Sandblasting Grit and Similar Wastes as Aggregate in Asphaltic Concrete”, Tech Data Sheet, December, TDS-2065-ENV, Port Hueneme, CA. 1998.

National Cooperative Highway Research Program (NCHRP), 2001.

Paumanok, “The U.S. Market for Blasting Abrasives Analysis”, Paumanok Publications, Shoreham, NY. 1992.

Roberts, F.L.; Kandhal, P.S.; Brown, E.R.; Lee, D.Y. and Kennedy, T.W. “Hot Mix Asphalt Materials, Mixture Design, and Construction”. National Asphalt Pavement Association Education Foundation. Lanham, MD, 1996.

Weyand, T.E., and W.F. Sutton, Identification of Acceptable Beneficial Reuses for Spent Bridge Painting Blast Material, FHWA-PA-89-037+89-02, prepared by Pittsburgh Mineral and Environmental Technology for PennDOT, Harrisburg, PA.1990.

White, T.D, “Marshall Procedures for Design and Quality Control of Asphalt Mixtures Asphalt Paving Technology”, Proceedings, vol. 54. Association of Asphalt Paving Technologists Technical Sessions, 1985.

U.S. Environmental Protection Agency. Potential Reuse of Petroleum Contaminated Soil, A Directory of Permitted Recycling Facilities. EPA/600/R-92/096. 1992.

Appendix A

SAMPLE # 1-1						
Wt. in Air	4653.7	Max. Sp.Gr (ASTM2041)		**2.519**		
Wt. SSD in Air	4692.0	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2694.7	7	127.1	2.072	2.116	84.0
Difference	1997	10	125.2	2.103	2.148	85.2
Bulk Sp. Grav.(Gmb)	2.330	20	121.5	2.167	2.213	87.8
Density-(lbs/CF)	145.4	30	119.5	2.204	2.250	89.3
Gmm@Ninitial (89max)	84.0	40	118.1	2.230	2.277	90.4
Gmm@Ndesign(96.0)	92.5	50	117.1	2.249	2.296	91.1
		75	**115.4**	**2.282**	**2.330**	**92.5**
%VMA	15.53					
%VFA	51.6					1.0210
% Voids	7.52					
SAMPLE # 1-2						
Wt. in Air	4656.1	Max. Sp.Gr (ASTM2041)		**2.519**		
Wt. SSD in Air	4691.0	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2695.8	7	125.9	2.093	2.124	84.3
Difference	1995	10	124.1	2.123	2.155	85.5
Bulk Sp. Grav.(Gmb)	2.334	20	120.5	2.187	2.219	88.1
Density-(lbs/CF)	145.6	30	118.6	2.222	2.255	**89.5**
Gmm@Ninitial (89max)	84.3	40	117.3	2.246	2.280	90.5

Table A.1 Cont

Gmm@Ndesign(96.0)	92.6	50	116.3	2.266	2.300	91.3
		75	114.6	2.299	2.334	92.6
%VMA	15.40					
%VFA	52.1					1.0150
% Voids	7.37					
SAMPLE # 1-3						
Wt. in Air	4703.0	Max. Sp.Gr (ASTM2041)		**2.519**		
Wt. SSD in Air	4738.3	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2720.0	7	127.2	2.092	2.121	84.2
Difference	2018	10	125.3	2.124	2.154	85.5
Bulk Sp. Grav.(Gmb)	2.330	20	121.8	2.185	2.215	87.9
Density-(lbs/CF)	145.4	30	119.8	2.221	2.252	**89.4**
Gmm@Ninitial (89max)	84.2	40	118.5	2.246	2.277	90.4
Gmm@Ndesign(96.0)	92.5	50	117.5	2.265	2.296	91.2
		75	115.8	2.298	2.330	92.5
%VMA	15.53					
%VFA	51.6					1.0139
% Voids	7.51					
AVERAGES						
Bulk Sp. Grav.(Gmb)	***2.331***	Gmm@Ninitial (89max)			***84.2***	
Density-(lbs/CF)	***145.5***	Gmm@Ndesign(96.0)			***92.5***	
%VMA	***15.5***	Gmm@Nmax (98 max)				
%VFA	***51.8***	%Voids @ Ndesign			***7.5***	

Table A.1 Cont

SAMPLE # 2-1						
Wt. in Air	4664.7	Max. Sp.Gr (ASTM2041)		**2.501**		
Wt. SSD in Air	4681.7	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2709.4	7	125.5	2.103	2.135	85.4
Difference	1972	10	123.5	2.137	2.170	86.8
Bulk Sp. Grav.(Gmb)	2.365	20	119.7	2.205	2.239	89.5
Density-(lbs/CF)	147.6	30	117.6	2.245	2.279	**91.1**
Gmm@Ninitial (89max)	85.4	40	116.1	2.274	2.308	92.3
Gmm@Ndesign(96.0)	94.6	50	115.1	2.293	2.328	93.1
		75	**113.3**	2.330	2.365	94.6
%VMA	14.71					
%VFA	63.2					1.0151
% Voids	5.41					

SAMPLE # 2-2						
Wt. in Air	4688.2	Max. Sp.Gr (ASTM2041)		**2.501**		
Wt. SSD in Air	4709.9	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2699.2	7	126.6	2.096	2.114	84.6
Difference	2011	10	124.6	2.129	2.148	85.9
Bulk Sp. Grav.(Gmb)	2.332	20	121.0	2.193	2.212	88.5
Density-(lbs/CF)	145.5	30	118.9	2.231	2.251	**90.0**
Gmm@Ninitial (89max)	84.6	40	117.6	2.256	2.276	91.0
Gmm@Ndesign(96.0)	93.2	50	116.5	2.277	2.298	91.9
		75	114.8	2.311	2.332	93.2
%VMA	15.91					

Table A.1 Cont

%VFA	57.6					1.0089
% Voids	6.75					
SAMPLE # 2-3						
Wt. in Air	4633.2	Max. Sp.Gr (ASTM2041)		**2.501**		
Wt. SSD in Air	4657.7	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2678.1	7	125.0	2.097	2.120	84.8
Difference	1980	10	123.0	2.132	2.154	86.1
Bulk Sp. Grav.(Gmb)	2.340	20	119.4	2.196	2.219	88.7
Density-(lbs/CF)	146.0	30	117.4	2.233	2.257	**90.3**
Gmm@Ninitial (89max)	84.8	40	116.0	2.260	2.284	91.3
Gmm@Ndesign(96.0)	93.6	50	115.0	2.280	2.304	92.1
		75	113.2	2.316	2.340	93.6
%VMA	15.59					
%VFA	59.0					1.0105
% Voids	6.40					
AVERAGES						
Bulk Sp. Grav.(Gmb)	***2.346***	Gmm@Ninitial (89max)			***84.9***	
Density-(lbs/CF)	***146.4***	Gmm@Ndesign(96.0)			***93.8***	
%VMA	***15.4***	Gmm@Nmax (98 max)				
%VFA	***59.9***	%Voids @ Ndesign			***6.2***	

Table A.1 Cont

SAMPLE # 3-1						
Wt. in Air	4617.2	Max. Sp.Gr (ASTM2041)		**2.482**		
Wt. SSD in Air	4634.6	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2672.9	7	123.2	2.121	2.130	85.8
Difference	1962	10	121.3	2.154	2.164	87.2
Bulk Sp. Grav.(Gmb)	2.354	20	117.7	2.220	2.230	89.8
Density-(lbs/CF)	146.9	30	115.6	2.260	2.270	**91.5**
Gmm@Ninitial (89max)	85.8	40	114.2	2.288	2.298	92.6
Gmm@Ndesign(96.0)	94.8	50	113.2	2.308	2.318	93.4
		75	111.5	2.343	2.354	94.8
%VMA	15.56					
%VFA	66.8					1.0044
% Voids	5.17					

SAMPLE # 3-2						
Wt. in Air	4646.4	Max. Sp.Gr (ASTM2041)		**2.482**		
Wt. SSD in Air	4664.7	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2691.2	7	124.8	2.107	2.132	85.9
Difference	1974	10	122.9	2.139	2.165	87.2
Bulk Sp. Grav.(Gmb)	2.354	20	119.2	2.206	2.232	89.9
Density-(lbs/CF)	146.9	30	117.2	2.243	2.270	**91.5**
Gmm@Ninitial (89max)	85.9	40	115.8	2.271	2.297	92.6
Gmm@Ndesign(96.0)	94.9	50	114.8	2.290	2.317	93.4
		75	113.0	2.327	2.354	94.9
%VMA	15.54					

Table A.1 Cont

%VFA	66.9					1.0118
% Voids	5.14					
SAMPLE # 3-3						
Wt. in Air	4659.4	Max. Sp.Gr (ASTM2041)		**2.482**		
Wt. SSD in Air	4671.8	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2700.0	7	124.5	2.118	2.137	86.1
Difference	1972	10	122.6	2.151	2.170	87.4
Bulk Sp. Grav.(Gmb)	2.363	20	118.9	2.218	2.238	90.2
Density-(lbs/CF)	147.5	30	116.9	2.256	2.276	**91.7**
Gmm@Ninitial (89max)	86.1	40	115.5	2.283	2.304	92.8
Gmm@Ndesign(96.0)	95.2	50	114.4	2.305	2.326	93.7
		75	112.6	2.342	2.363	95.2
%VMA	15.23					
%VFA	68.5					1.0091
% Voids	4.79					
AVERAGES						
Bulk Sp. Grav.(Gmb)	***2.357***	Gmm@Ninitial (89max)			***85.9***	
Density-(lbs/CF)	***147.1***	Gmm@Ndesign(96.0)			***95.0***	
%VMA	***15.4***	Gmm@Nmax (98 max)				
%VFA	***67.4***	%Voids @ Ndesign			***5.0***	

Table A.1: Black Beauty Superpave design

SAMPLE # 1-1						
Wt. in Air	4648.4	Max. Sp.Gr (ASTM2041)		**2.500**		
Wt. SSD in Air	4681.0	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2683.7	7	124.8	2.108	2.130	85.2
Difference	1997	10	123.0	2.139	2.161	86.4
Bulk Sp. Grav.(Gmb)	2.327	20	119.6	2.199	2.222	88.9
Density-(lbs/CF)	145.2	30	117.9	2.231	2.254	90.2
Gmm@Ninitial (89max)	85.2	40	116.7	2.254	2.277	91.1
Gmm@Ndesign(96.0)	93.1	50	115.8	2.272	2.295	91.8
		75	**114.2**	**2.303**	**2.327**	**93.1**
%VMA	15.60					
%VFA	55.7					1.0104
% Voids	6.90					

SAMPLE # 1-2						
Wt. in Air	4653.3	Max. Sp.Gr (ASTM2041)		**2.500**		
Wt. SSD in Air	4685.9	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2680.9	7	124.7	2.112	2.124	84.9
Difference	2005	10	123.0	2.141	2.153	86.1
Bulk Sp. Grav.(Gmb)	2.321	20	119.8	2.198	2.210	88.4
Density-(lbs/CF)	144.8	30	117.9	2.233	2.246	**89.8**
Gmm@Ninitial (89max)	84.9	40	116.7	2.256	2.269	90.8
Gmm@Ndesign(96.0)	92.8	50	115.7	2.276	2.289	91.6
		75	114.1	2.308	2.321	92.8
%VMA	15.83					

Table A.2 Cont

%VFA	54.8					1.0056
% Voids	7.16					
SAMPLE # 1-3						
Wt. in Air	4680.1	Max. Sp.Gr (ASTM2041)		**2.500**		
Wt. SSD in Air	4695.4	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2713.0	7	124.7	2.124	2.147	85.9
Difference	1982	10	122.9	2.155	2.178	87.1
Bulk Sp. Grav.(Gmb)	2.361	20	119.4	2.218	2.242	89.7
Density-(lbs/CF)	147.3	30	117.4	2.256	2.280	**91.2**
Gmm@Ninitial (89max)	85.9	40	116.1	2.281	2.306	92.2
Gmm@Ndesign(96.0)	94.4	50	115.1	2.301	2.326	93.0
		75	113.4	2.335	2.361	94.4
%VMA	14.39					
%VFA	61.3					1.0109
% Voids	5.57					
AVERAGES						
Bulk Sp. Grav.(Gmb)	***2.336***	Gmm@Ninitial (89max)			***85.3***	
Density-(lbs/CF)	***145.8***	Gmm@Ndesign(96.0)			***93.5***	
%VMA	***15.3***	Gmm@Nmax (98 max)				
%VFA	***57.3***	%Voids @ Ndesign			***6.5***	

Table A.2 Cont

SAMPLE # 2-1						
Wt. in Air	4658.9	Max. Sp.Gr (ASTM2041)		**2.482**		
Wt. SSD in Air	4679.2	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2696.0	7	124.0	2.126	2.141	86.3
Difference	1983	10	122.2	2.157	2.172	87.5
Bulk Sp. Grav.(Gmb)	2.349	20	118.9	2.217	2.233	90.0
Density-(lbs/CF)	146.6	30	117.0	2.253	2.269	**91.4**
Gmm@Ninitial (89max)	86.3	40	115.7	2.279	2.294	92.5
Gmm@Ndesign(96.0)	94.7	50	114.7	2.299	2.314	93.3
		75	**113.0**	2.333	2.349	94.7
%VMA	15.25					
%VFA	65.0					1.0069
% Voids	5.33					

SAMPLE # 2-2						
Wt. in Air	4664.4	Max. Sp.Gr (ASTM2041)		**2.482**		
Wt. SSD in Air	4686.7	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2701.7	7	124.4	2.122	2.138	86.2
Difference	1985	10	122.6	2.153	2.170	87.4
Bulk Sp. Grav.(Gmb)	2.350	20	119.1	2.216	2.233	90.0
Density-(lbs/CF)	146.6	30	117.2	2.252	2.270	**91.5**
Gmm@Ninitial (89max)	86.2	40	115.9	2.277	2.295	92.5
Gmm@Ndesign(96.0)	94.7	50	114.9	2.297	2.315	93.3
		75	113.2	2.332	2.350	94.7
%VMA	15.23					

Table A.2 Cont

%VFA	65.2					1.0078
% Voids	5.31					
SAMPLE # 2-3						
Wt. in Air	4656.6	Max. Sp.Gr (ASTM2041)		**2.482**		
Wt. SSD in Air	4693.0	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2696.1	7	124.8	2.111	2.126	85.7
Difference	1997	10	122.9	2.144	2.159	87.0
Bulk Sp. Grav.(Gmb)	2.332	20	119.5	2.205	2.221	89.5
Density-(lbs/CF)	145.5	30	117.6	2.241	2.257	**90.9**
Gmm@Ninitial (89max)	85.7	40	116.3	2.266	2.282	92.0
Gmm@Ndesign(96.0)	94.0	50	115.4	2.283	2.300	92.7
		75	113.8	2.316	2.332	94.0
%VMA	15.87					
%VFA	62.0					1.0071
% Voids	6.03					
AVERAGES						
Bulk Sp. Grav.(Gmb)	***2.344***	Gmm@Ninitial (89max)			***86.0***	
Density-(lbs/CF)	***146.2***	Gmm@Ndesign(96.0)			***94.4***	
%VMA	***15.5***	Gmm@Nmax (98 max)				
%VFA	***64.1***	%Voids @ Ndesign			***5.6***	

Table A.2 Cont

SAMPLE # 3-1						
Wt. in Air	4676.1	Max. Sp.Gr (ASTM2041)		**2.463**		
Wt. SSD in Air	4686.0	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2730.0	7	122.7	2.157	2.165	87.9
Difference	1956	10	120.8	2.191	2.199	89.3
Bulk Sp. Grav.(Gmb)	2.391	20	117.2	2.258	2.266	92.0
Density-(lbs/CF)	149.2	30	115.2	2.297	2.306	**93.6**
Gmm@Ninitial (89max)	87.9	40	113.8	2.325	2.334	94.7
Gmm@Ndesign(96.0)	97.1	50	112.8	2.346	2.355	95.6
		75	111.1	2.382	2.391	97.1
%VMA	14.21					
%VFA	79.2					1.0037
% Voids	2.95					
SAMPLE # 3-2						
Wt. in Air	4664.0	Max. Sp.Gr (ASTM2041)		**2.463**		
Wt. SSD in Air	4674.6	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2710.0	7	123.4	2.139	2.153	87.4
Difference	1965	10	121.5	2.172	2.186	88.8
Bulk Sp. Grav.(Gmb)	2.374	20	117.9	2.239	2.253	91.5
Density-(lbs/CF)	148.1	30	115.9	2.277	2.292	**93.0**
Gmm@Ninitial (89max)	87.4	40	114.6	2.303	2.318	94.1
Gmm@Ndesign(96.0)	96.4	50	113.6	2.323	2.338	94.9
		75	111.9	2.359	2.374	96.4

Table A.2 Cont

%VMA	14.80					
%VFA	75.5					1.0065
% Voids	3.62					
SAMPLE # 3-3						
Wt. in Air	4664.0	Max. Sp.Gr (ASTM2041)		**2.463**		
Wt. SSD in Air	4674.1	**Gyrations**	**Ht, mm**	**Gmb(est)**	**Gmb(corr)**	**%Gmm**
Wt. in Water	2716.8	7	123.5	2.137	2.165	87.9
Difference	1957	10	121.7	2.169	2.197	89.2
Bulk Sp. Grav.(Gmb)	2.383	20	118.1	2.235	2.264	91.9
Density-(lbs/CF)	148.7	30	116.1	2.273	2.303	**93.5**
Gmm@Ninitial (89max)	87.9	40	114.8	2.299	2.329	94.5
Gmm@Ndesign(96.0)	96.7	50	113.8	2.319	2.349	95.4
		75	112.2	2.352	2.383	96.7
%VMA	14.49					
%VFA	77.5					1.0130
% Voids	3.27					
AVERAGES						
Bulk Sp. Grav.(Gmb)	***2.383***	Gmm@Ninitial (89max)			***87.7***	
Density-(lbs/CF)	***148.7***	Gmm@Ndesign(96.0)			***96.7***	
%VMA	***14.5***	Gmm@Nmax (98 max)				
%VFA	***77.4***	%Voids @ Ndesign			***3.3***	

Table A.2: silica sand Superpave design

VITA

Amer Khanfar was born on July 10th, 1978, in a nice city called Heron in Palestine. Amer had finished a Masters Degree in the Department of Civil and Environmental Engineering at the University of New Orleans on December 17th, 2004. Amer has worked as a graduate research assistant at the University of New Orleans since 2005, and he has worked as a teaching assistant from 2003-2005 in the Civil and Environmental Engineering Dept.