# IMPLICATION OF AGGREGATES in the Design, Construction, and Performance of FLEXIBLE PAVEMENTS

Schreuders/Marek, editors

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# *Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements*

*Hans G. Schreuders and Charles R. Marek, editors*

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# Foreword

The symposium on Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements was held in New Orleans, Louisiana, 3 December 1986. ASTM Committee D-4 on Road and Paving Materials sponsored the symposium. Hans G. Schreuders, Westvaco Corporation, Charles R. Marek, Vulcan Materials Company, and Ken R. Wardlaw, National Crush Stone Association, served as symposium cochairmen. H. G. Schreuders and C. R. Marek are editors of this publication.

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# Overview

A symposium, entitled "Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements," was held at the Sheraton New Orleans in New Orleans, Louisiana, in conjunction with the 2–5 December 1986 standards development meetings of the ASTM Committee D-4 on Road and Paving Materials. The focus of this symposium was on the characteristics of aggregates that influence the performance of asphalt paving mixtures. Included were presentations on mixture instability problems (for example, rutting, shoving, bleeding, etc.) which are more prevalent today because of increased axle loads and tire pressures. A total of ten papers were prepared and submitted to the D-4 Papers Review Subcommittee in response to the "call for papers" for this symposium. Five of the papers were selected for presentation at the symposium. All ten papers were considered to contain significant information on the symposium subject and were accepted for publication in this resulting ASTM Special Technical Publication.

Crushed stone and sand and gravel are the two main sources of aggregates used in the construction of flexible pavements. These natural aggregates are widely distributed and exist in a variety of geologic environments. However, although widely distributed, natural aggregates are not universally available for consumptive use. Many areas are devoid of sand and gravel. In some areas potential sources of crushed stone may be covered by great thicknesses of overburden which makes surface mining impractical. In other areas, many aggregates do not meet the physical/chemical property requirements for certain end uses, or they may contain deleterious constituents that react adversely with binding agents used to produce concrete mixtures. Finally, many areas having an abundance of natural aggregate find that the aggregate is not available or accessible because of existing land uses, zoning, or regulations that preclude commercial exploitation of the aggregate. As a consequence, flexible pavements must be designed and constructed with economically available aggregates, possessing quality levels that ensure desired performance of the flexible pavements in which used.

Hot-mix asphalt (HMA) mixtures used in flexible pavements contain approximately 90–95 percent aggregate by weight. Because of this, aggregates are the principal consideration in influencing the properties of HMA mixtures.

The first paper by Abdulshafi and Al-Dhalaan discusses utilization of low quality aggregates in flexible pavements constructed in Saudi Arabia and in the Gulf area. The authors describe use of cement-coated coarse aggregate as one effective solution to rutting, bleeding, and shoving of asphaltic mixtures. Results of laboratory testing are provided to support the conclusions of the authors. The benefits of use of cement-coated aggregate include: increased stability, improved resistance to stripping, increased tensile strength, increased resilient modulus and increased fatigue life.

The paper by Barksdale and others describes the performance of an experimental pavement constructed as a quarry access road in Georgia. The flexible pavement consisted of a triple surface treatment over 18 inches of well-compacted crushed stone base. This thin asphalt surface-thick crushed-stone base pavement performed in a very acceptable manner without major distress when subjected to heavy truck traffic for more than seven years and in excess of 1.4 million equivalent 18 kip single axle loads.

The paper by Brown and others presents data obtained from various studies that show the effect of aggregate grading on the performance of asphalt mixtures. Factors influencing performance of asphalt mixtures that are discussed in the paper include: (1) grading, (2) particle shape, (3) maximum aggregate size, (4) compacted lift thickness, (5) mineral filler content, and (6) aggregate quality. The authors concluded that a well-graded crushed aggregate should be used to provide the highest quality asphalt concrete. In addition, the maximum size of aggregate should be increased to provide higher stability, to improve skid resistance, and to reduce asphalt binder content.

The paper by Dukatz describes one of several recent test roads designed to provide information about the effectiveness of pavements constructed with thin asphalt surfaces over thick aggregate base courses. This test road was a section of SR 1508 in North Carolina constructed in 1985 which also serves as a quarry access road. The section consists of 2 in. of asphalt concrete mix (NC I-2) over 13 in. of well-compacted aggregate base course (ABC). After 18 months of service and achieving 60% of the design traffic, the section is performing as expected with minimal distress. The author states that a back-calculated structural coefficient of 0.20 was appropriate for the crushed stone base used in this test section.

The paper by Dukatz and Phillips describes several problems faced by the hot-mix asphalt engineer in predicting the behavior of asphalt concrete mixtures exposed to moisture. The authors recommend modifications to a test procedure for evaluating moisture susceptibility to permit more accurate interpretation of resulting test data. The authors believe that specimens made for determination of moisture susceptibility (tensile strength before and after conditioning) should be prepared at low (4 to 6%), midpoint (6 to 8%), and high (8 to 10%) air void contents, and that all specimens be used in the analysis procedure. The test results of tensile strength versus air voids for both the conditioned and unconditioned specimens should be plotted separately, and the strength at 7% voids should be obtained by graphical interpolation. The authors also suggest that a minimum conditioned tensile strength at 7% voids in conjunction with a minimum retained tensile splitting ratio (TSR) should be specified.

The paper by Hughes and Maupin addresses the increase in moisture damage that has been experienced in asphalt pavements during the past decade. The authors define moisture damage, and discuss the many factors that may cause the damage. Several methods of evaluating mixtures for moisture susceptibility are reviewed. The need for standardization of a predictive procedure (as also advocated in the paper by Dukatz and Phillips) is emphasized. The authors also discuss several methods for reducing moisture damage potential.

Lee and Al-Dhalaan discuss in detail the pavement distress being experienced in Saudi Arabia as a consequence of changing traffic characteristics due to the crash development programs of the country. A feasibility study was performed to formulate rehabilitation alternatives for pavements experiencing severe rutting problems. Potential solutions include: (1) use of reduced asphalt contents, (2) use of coarser aggregate in the asphalt mixtures, (3) improved quality control, and (4) use of sulfur extended asphalt.

Lundy and others investigated the effects of (1) percent fracture, (2) fines content, and (3) aggregate source on the performance of laboratory prepared asphalt mixtures at a temperature of 10°C (50°F). The repeated load diametral test device was used by the researchers to measure mixture performance. Conclusions drawn by the authors are: (1) an increase in required binder content results from increasing fracture levels, and (2) increase in fines content from 3 to 6% reduces required asphalt content. The authors recommend that additional testing be performed at other temperatures to further quantify the effects of fracture level and fines content on asphalt concrete mixtures.

The paper by Selim and Heidari describes a procedure for measuring the susceptibility of seal coats to stripping. Details of a newly developed laboratory test called the Seal Coat Debonding Test (SDT) are provided. Criteria for evaluating the degree of vulnerability of seal coats to moisture damage are also suggested. The test method presented in the paper is simple and may offer a sound quantitative approach for evaluating potential moisture damage in seal coats, and may assist engineers in selecting the "right" materials for use in seal coat construction.

The last paper, by Tseng and Lytton, presents a method to predict the permanent deformation (rutting) in flexible pavements. The method uses a mechanistic-empirical model of material characterization. Material testing is performed in the laboratory to establish three permanent deformation parameters which represent the curved relationship between permanent strains and number of load cycles. Equations are provided to permit analysis of how the three parameters are affected by (1) material properties, (2) moisture and temperature, and (3) stress state. Permanent deformations calculated from the method are compared with results measured in the field, and "reasonable agreement" is shown.

The ten papers in this publication provide excellent information on aggregate factors that influence the design, construction, and performance of flexible pavements. The information will be of value to all highway/materials engineers working to improve the performance of flexible pavement systems within current economic constraints.

*Charles R. Marek*
Vulcan Materials Company, Birmingham, AL 35253: symposium cochairman and editor.

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# Utilization of Low-Quality Aggregates in Asphaltic Mixtures in the Eastern Province of Saudi Arabia

**REFERENCE:** Abdulshafi, A. and Al-Dhalaan, M. A., **"Utilization of Low-Quality Aggregates in Asphaltic Mixtures in the Eastern Province of Saudi Arabia,"** *Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements, ASTM STP 1016,* H. G. Schreuders and C. R. Marek, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 4–18.

**ABSTRACT:** Utilization of low-quality aggregates in the eastern province of Saudi Arabia as well as in most Gulf areas is becoming a necessity. In this area, the definition of low-quality aggregates is more related to surface chemistry characteristics and salt content than to particle strength, porosity, surface texture, organic and fines or any other deficiency measures. Stripping, ravelling, and rutting are the major distress manifestations observed in asphaltic mixtures. Rutting is related to mix flow. Bleeding and shoving problems are also observed but to a lesser extent. One effective solution to the above is the cement coating of the coarse aggregate, thereby eliminating surface chemistry debonding behavior (stripping) and increasing the overall mixture stiffness. Several laboratory testing methods on aggregates (such as specific gravity, water absorption, abrasion, and soundness) and on asphaltic mixtures (such as stability, modulus of resilience, creep and rutting, fracture toughness, and index of retained strength) have been performed. Laboratory test results on cement-coated and uncoated aggregates as well as on their asphaltic mixtures clearly indicate the improvements obtained by cement coating technique. These improvements include more than 30% increase in Marshall stability with flow remaining within specification range, improved coating and resistance to stripping, increased tensile strength and resilient modulus, more than 90% immersion-tensile strength ratio, and increased fatigue life.

**KEY WORDS:** low-quality aggregates, cement coating, aggregates upgrading, rutting, asphaltic mixtures, stripping

Aggregate, an important component of asphaltic mixtures, is regularly subjected to degradation actions under load and environmental conditions. The structural integrity of asphaltic mixtures is governed by the aggregate quality which, in turn, is a function of such factors as mineral composition, surface texture and chemistry, type and amount of deleterious content, size and shape of the particles, pore phase characteristics, etc. The physical and chemical breakdown of aggregate due to interaction with water and other aggressive environmental factors has been reported as a potential mechanism contributing to pavement distress [*1*]. Furthermore, a major factor contributing to pavement failures is the mechanical degradation during construction and service life. Because aggregates in the upper layer of the pavement structure are subjected to significant abrasive forces of wheel load traction and severe climatic conditions of freeze and thaw cyclic action, aggregate durability and

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soundness assume greater importance. At lower pavement layers, degradation results in increased fines percentage, which may reduce the stability and increase frost susceptibility of those layers.

### *Aggregate Quality*

The definition of aggregate quality and expected performance of locally available materials is becoming a control factor in the design of asphaltic pavements. The determination of acceptable levels of inferior-quality aggregate that can be tolerated at various pavement structural layers depends upon the "use" conditions (that is, whether or not in surface, intermediate, or base course), environmental exposure conditions, and loading type and duration.

Several research studies in the United States have investigated the effect of low-quality materials upon the reliability of performance evaluation; among the most recent is the work conducted at The Ohio State University [*2,3*]. In this work, the engineering properties and durability of various aggregate mixtures were investigated using environmental simulation techniques. The results led to the conclusion that the presence of deleterious materials, either in the fine or coarse aggregates, is equally detrimental to pavement performance. An exception to this conclusion was limestone sand, which has been shown to substantially improve the mixture performance. It has also been concluded that, although low-quality aggregate will result in a lower layer equivalency factor (that is, high pavement-thickness requirement), it is possible to counteract this deficiency by certain modifications, such as using limestone sand as a partial aggregate replacement, adding sulfur to the mixture, etc.

Deleterious aggregate has been defined as follows [*2*]: "A piece of aggregate is to be scraped against the bottom of a stainless steel pan using moderate finger pressure. If it leaves a residue on the pan, it is deemed deleterious; otherwise, it is judged good." In that research study [*2*], the shales were kept separate from other deleterious substances, which were mostly soft sandstones with some lumps of hardened clay and minute traces of soft chert. Based on the above definition, a deleterious material content test was conducted and coarse aggregate classified accordingly.

Deleterious fine aggregate was researched using the application of ultrasonic vibrations under controlled load, frequency, and time duration [*3*]. Test response characteristics of high-quality fine aggregates, including ottawa sand and limestone sand, have been identified and distinguished from low-quality sand. Test response characteristics were established by determining the percentage loss in gradation after exposure to ultrasonic vibrations and sieve analysis. However, more data are necessary before test results can be conclusively interpreted to define the levels of deleterious material content within locally available sand.

### *Beneficiation Methods*

Regardless of whether the amount of deleterious materials found in both coarse and fine aggregates can be known, the beneficiation of such materials is possible. General methods available for the improvement of low-quality materials include blending, impregnation, mechanical processing, or coatings, or a combination of these methods. *Impregnation* of porous aggregates by gaseous or liquid-phase monomeric plastics, chemical treatment, and radiation polymerization has been shown to increase the aggregates' properties, especially those of strength and resistance to freeze-thaw cycling [*4–6*]. *Mechanical processing* by such methods as crushing, washing, heavy media separation, and sieving is routinely used; however, other methods of selective processing by removal of soft and undesirable substances have been used for specific practical applications. *Blending* of low-quality aggregates with high-quality aggregates to upgrade material quality has also been used for specific applications. If, for example, the abrasion and skid resistance need to be enhanced for pavement wearing surface course applications, blending low-quality aggregates with slag or scrap steel can be a promising solution.

*Coating* of low-quality aggregates can be effected by several means: physical, chemical, thermal, use of admixture, or combined processes. Depending upon the "use condition" of the low-quality aggregates, one of the above-cited methods should prove suitable. *Physical and thermal processes* include moderate heating, 420 to 810°C (800 to 1500°F), or high-temperature heating, 420 to 1100°C (800 to 2000°F), using a fluxing agent. This process produces ceramic surfaces on the aggregate particles [*7,8*]. *Chemical processes* involve coating the particles with thin films of plastics, organic compounds, surface active agents, etc. This process enhances adhesive properties, improves durability, and increases soundness and abrasion resistance of the aggregates.

*Admixtures* have been used extensively to impart improved properties to low-quality aggregates for use in highways. Among the admixtures commonly used are lime, bitumen, and cement [*9*].

Beneficiation of low-quality aggregates using a cement-coating method is becoming a recognized technique. A laboratory/field study [*10*] has been performed to investigate the potential of cement-coating techniques for mixture performance improvement and practical field applications. In that study, powder cement was added in quantities of 2% to 10% by weight of the aggregates, mix dry, and then water was added to the mixture in a designed water/cement ratio. Mix variables and coating techniques have been optimized in order to achieve the final desired properties and goal of upgrading the aggregate quality, meeting Marshall mix design criteria, enhancing performance behavior and, at the same time, minimizing field application problems such as sticking, coating and bonding deficiencies, segregation, high voids content, etc. This study concluded that cement coating is a viable method that will improve asphaltic mixture properties and minimize potential failure from fatigue cracking and rutting. Because of cement-coating efficiency in upgrading low-quality aggregate properties, the authors believe that this method is more economically and practically feasible for application to asphaltic mixtures than the other methods mentioned above.

### Problem Statement for the Locally Available Aggregates

The Kingdom of Saudi Arabia has built over 35 000 km of roads during the past two decades. At present, highways, especially in the eastern province, are showing different degrees of pavement distress: severe rutting, stripping and raveling problems, and to a lesser degree, fatigue cracking. Among the factors contributing to these distresses are the ever-increasing traffic axle loads, high prevailing summer temperatures, and the hydrophilic characteristics of the local aggregates. Other factors include the quality of the produced aggregates as a result of quarry operations of intermixing different quality aggregates, crushing and sorting techniques, and deleterious material content. The specification for the quality of aggregates in the Kingdom of Saudi Arabia is set by specifying approved material sources and passing other American Association of State Highway and Transportation Officials (AASHTO) or American Society for Testing and Materials (ASTM) testing requirements as requested by the site engineers as follows:

| | |
|---|---|
| Loss of Sodium Sulfate Soundness Test (AASHTO T104) | 10% maximum |
| Loss of Magnesium Sulfate Soundness Test (AASHTO T104) | 12% maximum |

| | |
|---|---|
| Loss by Abrasion Test (AASHTO T96) | 40% maximum |
| Thin and Elongated Pieces, by Weight (larger than 1 in., thickness less than 1/5 length) | 5% maximum |
| Friable Particles (AASHTO T112) | 0.25% maximum |
| Sand Equivalent (AASHTO T176) | 45% minimum |

If the above specificiation is not met, the aggregate is judged to be of low quality. However, depletion of quality aggregate resources and the high cost of its transportation to road construction areas have caused the quarry operators to mix high- and low-quality aggregates. Based on sampling and testing aggregates from seven quarries in the eastern province (shown in Fig. 1), the majority of tests indicate high contents of deleterious material, high water absorption values, and low abrasion resistance. The solution to the above problem includes exploration for natural sources of aggregates within the large landmass of the kingdom, improving crushing and sorting techniques, and upgrading the aggregate quality by using additives such as lime or cement. The latter is the topic of this paper.

*Aggregates Location*

Geological studies of the eastern coastal regions indicate that bedrock formation has resulted in a varying degree of quality aggregates [*11,12*]. Data on physical and mechanical properties of rocks from the Jubail, Dhahran, and Hofuf areas are presented in Tables 1 and 2 [*13*]. Major categories of petrological classification of rock types are [*12*]: fine-grained crystalline limestone (micrite); medium-grained crystalline limestone (sparite); and detrital limestone (biosparite).

Rock mass properties were difficult to assess in detail due to the limited amount of exposure arising from surface ripping techniques. However, observations noted in several quarries make an appraisal of the general conditions possible [*12*]. Bedding was apparent on several occasions, and individual units ranged from 0.25 to 1.5 m in thickness. Where larger working surfaces were visible, inter-unit clay bands were in evidence; these were usually about 20 cm in thickness and composed of light- to dark-brown soft plastic clay. The bedding, when observable, was nearly always horizontal except at one location where a slight dip of 2 to 3 deg was discernible to the naked eye.

No definite or dominant joint patterns were in evidence. However, rock units near the surface, when relatively freshly exposed, did show a "blocky" (equidimensional) nature on

TABLE 1—*Physical and mechanical properties of source rocks, Jubail, Dhahran, and Hofuf quarries.*

| Location | Material | Specific Gravity | Absorption | Los Angeles Abrasion | Soundness |
|---|---|---|---|---|---|
| Jubail | sand (SP) | 2.64–2.71 | 0.9–2.4 | 14–40 | 7.1–23.4 |
| Dhahran | limestone aggregates | 2.59–2.71 | ... | ... | ... |
| Hofuf | limestone aggregates | ... | 3.9–5.6 | 31–44 | ... |

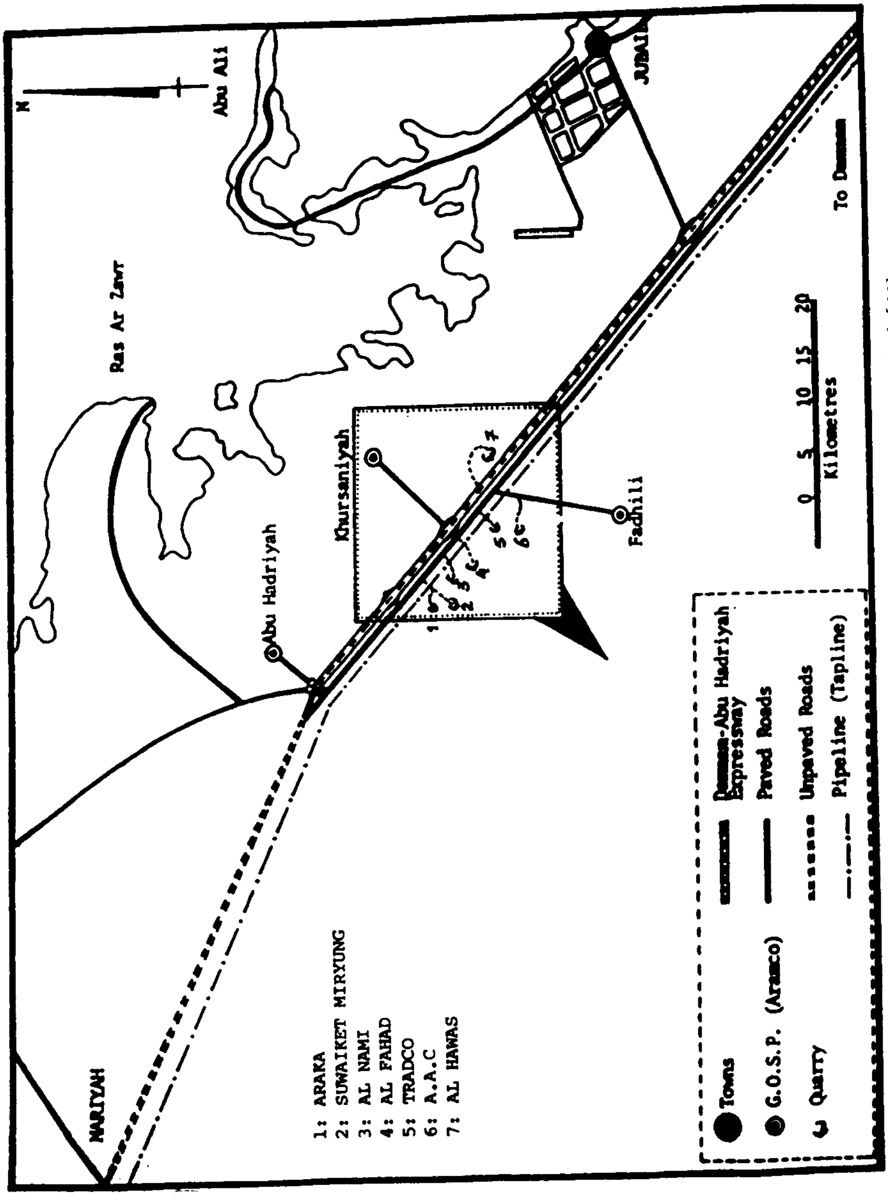


FIG. 1—*General location of study region: Al Hoty-Stanger, Ltd.* [11].

TABLE 2—*Physical and mechanical properties of source rocks, Jubail area quarries detailed test results.*[a]

| Location | Bulk Specific Gravity, SSD[b] | Water Absorption, % | Slake Durability Index, % | Point Load Test Strength Index,[c] MPa | | | | Sulfate Soundess, % | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | A | B | C | D | Sodium | Manganese |
| Al Raka | 2.57 | 1.3 | 99.1 | 10.0 | 9.5 | 18.5 | ... | 0.2 | 0.2 |
| | 2.54 | 1.5 | 99.2 | 11.5 | 10.0 | 20.6 | ... | 0.3 | 0.3 |
| Suwaiket | 2.46 | 2.0 | 98.8 | 12.5 | 11.7 | 10.5 | ... | 0.2 | 0.3 |
| Miryung | 2.56 | 1.0 | 99.3 | 13.2 | 10.0 | 13.8 | 12.5 | 0.3 | 0.3 |
| Al Naimi | 2.42 | 2.4 | 99.2 | 8.8 | 6.1 | 7.9 | ... | 0.2 | 0.2 |
| | 2.58 | 1.1 | 99.1 | 12.8 | 16.4 | 15.5 | ... | 0.2 | 0.1 |
| Al Fahad | 2.58 | 0.9 | 99.1 | 12.4 | 12.4 | 17.2 | ... | 0.1 | 0.2 |
| | 2.47 | 2.2 | 99.1 | 9.7 | 10.3 | 11.0 | ... | 0.1 | 0.1 |
| Tradco | 2.57 | 1.7 | 98.0 | 14.5 | 8.8 | 10.7 | 13.1 | 0.2 | 0.3 |
| A.A.C. | 2.48 | 2.1 | 99.0 | 13.0 | 8.8 | 11.7 | ... | 0.8 | 0.5 |
| Al Hawas | 2.56 | 1.4 | 99.1 | 13.1 | 18.7 | 15.1 | 11.7 | 0.1 | 0.3 |

[a] All tests performed according to relevant AASHTO standards.
[b] SSD = saturated surface dry basis.
[c] A, B, C, D = tests on four representative samples.

occasion. Whether this fracture pattern was directly related to planes of weakness within the rock mass was not clearly evident. (Fractures tended to be less than 200 mm in width.) Many of the fractures displayed a light-brown, friable "sandy" infill, probably of secondary origin, which was moderately weathered. No joint or fracture patterns appeared to be present below these uppermost units.

Voids and cavities were often evidenced and in some cases were quite extensive. Estimated rock strength ranged from moderately strong at uppermost layers to strong in deeper layers.

Regarding weathering, most ripped rocks appeared to be fresh, except for the uppermost unit which was exposed on overburden removal and showed slight to moderate weathering. (A slight brownish discoloration often penetrated to a depth of a few centimetres.) Stockpiled raw feed was also seen to have undergone similar slight weathering/alteration at several sites.

Aggregate, as was to be expected, reflected the properties of the source rock; particle shape was found to be sub-angular to angular. Surface texture ranged from rough and crystalline to relatively coarse. Stockpiled material, however, often showed slight weathering where it had been accumulated for some considerable time. This took the form of a brownish discoloration and surface pitting.

### *Physical and Mechanical Properties*

Aggregate samples from five of the quarries shown in Fig. 1 were obtained and tested in the laboratory. Tables 3 and 4 present a summary of the results of these tests.

Based on site visitations and test results shown in Tables 2 and 3, aggregates from three quarries were identified as being of low quality, medium quality, and high quality. This is required in order for us to study the characteristics of aggregates in each category in view of evaluating the effectiveness of the improvement techniques. However, it should be noted that delineation of those categories is primarily based upon aggregate source, chemical, physical, and mechanical properties rather than mixture characteristics and performance behavior. For example, although the aggregates may be classified as good quality, a stripping (debonding) problem could occur when used in an asphaltic mixture.

TABLE 3—*Summary of aggregates' physical mechanical properties test results.*

| | | Sieve Size, mm | | | | | | | Guideline Specifications (for *F*) |
|---|---|---|---|---|---|---|---|---|---|
| | | 40 | 25 | 20 | 15 | 12.5 | 10 | *F* | |
| Percent passing | $\bar{x}$[a] | 0.75 | 1.15 | 0.92 | 1.87 | 1.4 | 1.35 | 14.18 | 0.5% max. |
| | $n$[b] | 4 | 2 | 6 | 3 | 2 | 2 | 7 | (2%) |
| | $s$[c] | 0.25 | 0.5 | 0.3 | 1.13 | 0.28 | 0.9 | 6.1 | |
| Clay lump | $\bar{x}$ | 0.2 | 0.45 | 0.3 | 0.5 | 0.5 | 0.73 | 1.2 | 0.25% max |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | 7 | |
| | $s$ | 0.14 | 0.35 | 0.2 | 0.26 | 0.14 | 0.15 | 0.77 | (NA) |
| Flakiness Index | $\bar{x}$ | 22.3 | 14.5 | 19.2 | 26.67 | 32 | 35.67 | ... | 5% max. |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | ... | |
| | $s$ | 12 | 3.5 | 5.4 | 5.0 | 9.9 | 6.51 | ... | (NA) |
| Chloride Content, % | $\bar{x}$ | 0.01 | 0.01 | 0.012 | 0.01 | 0.015 | 0.01 | 0.0125 | 0.03 max |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | 7 | |
| | $s$ | 0.0 | 0.0 | 0.004 | 0.0 | 0.007 | 0.0 | 0.0046 | (0.05) |
| Sulfates Content, % | $\bar{x}$ | 0.24 | 0.185 | 0.115 | 0.17 | 0.095 | 0.073 | 0.195 | 0.5 max |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | 7 | (0.04) |
| | $s$ | 0.14 | 0.021 | 0.074 | 0.17 | 0.05 | 0.055 | 0.119 | |
| Bulk Specific Gravity, | $\bar{x}$ | 2.53 | 2.69 | 2.53 | 2.5 | 2.58 | 2.57 | 2.6 | ... |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | 7 | (...) |
| | $s$ | 0.064 | 0.23 | 0.064 | 0.084 | 0.035 | 0.044 | 0.022 | |
| Water Absorption, % | $\bar{x}$ | 2.15 | 2.1 | 2.12 | 3.13 | 2.7 | 2.7 | 2.08 | 2% max. |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | 7 | |
| | $s$ | 0.53 | 0.42 | 0.5 | 1.36 | 0.14 | 0.7 | 0.41 | (1%) |
| Fines Content, % | $\bar{x}$ | 0.475 | 0.5 | 0.33 | 1.3 | 0.8 | 0.97 | 8.67 | ... |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | 7 | |
| | $s$ | 0.36 | 0.14 | 0.1 | 1.23 | 0.14 | 0.57 | 3.45 | (...) |
| Slake Durability, % | $\bar{x}$ | 98.25 | 98.6 | 98.5 | 96.3 | 97 | 97.1 | ... | 99% min |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | ... | |
| | $s$ | 0.94 | 0.42 | 0.35 | 0.58 | 0.0 | 0.75 | ... | (...) |
| Elongation Index, % | $\bar{x}$ | 34 | 24 | 29.8 | 31 | 26 | 34 | ... | 5% max |
| | $n$ | 4 | 2 | 6 | 3 | 2 | 3 | ... | |
| | $s$ | 3.74 | 8.5 | 4.88 | 7.2 | 21.2 | 19.16 | ... | (NA) |

[a] $\bar{x}$ = samples average (seven quarries).
[b] $n$ = number of quarries.
[c] $s$ = standard deviation.

TABLE 4—*Summary of aggregate test results (for asphalt concrete).*[a]

| | Los Angeles Abrasion Test | | | | | | Sulfate Soundness Test, % | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 100/500 RETD[b] | | | Sodium | | Manganese | |
| Location | Grading A | Grading B | Grading C | A | B | C | Coarse | Fine | Coarse | Fine |
| Al Raka | ... | 41 | 40 | ... | 0.27 | 0.3 | 1.8 | 7.0 | 2.2 | 7.4 |
| Suwaiket Miryung | 37 | 38 | 36 | 0.3 | 0.29 | 0.28 | 1.5 | 7.8 | 1.1 | 9.7 |
| Al Naimi | 34 | 30 | ... | 0.26 | 0.27 | ... | 1.2 | 3.4 | 1.3 | 4.0 |
| Al Fahad | 35 | 36 | 41 | 0.29 | 0.28 | 0.29 | 0.9 | 3.0 | 0.8 | 3.0 |
| Tradco | ... | 39 | 42 | ... | 0.26 | 0.26 | 7.1 | 8.3 | 8.9 | 8.4 |
| A.A.C. | ... | 32 | 34 | ... | 0.25 | 0.24 | 2.3 | 7.0 | 1.6 | 6.9 |
| Al Hawas | 32 | 33 | 39 | 0.28 | 0.27 | 0.33 | 1.5 | 1.6 | 0.6 | 1.0 |
| Guideline Specifications | 40% max | | | 0.25% max | | | 10% max | | 12% max | |

[a] All tests performed according to relevant AASHTO standards.
[b] Ratio of loss. Refer to AASHTO T96 (Note 6).

## Laboratory Testing Program

### *AC Mixture Characterization*

*Marshall Design Criteria*—Table 5 presents laboratory test data on representative samples of low, medium, and high quality aggregates. Asphaltic mixtures were prepared in accordance with the Marshall method, and the test results are given in Table 6. Table 6 shows that the low-quality aggregates (LQA) mixture satisfies the Saudi specification limits; that is, if LQA is not rejected as a material, it would not be rejected in asphaltic mixtures. The Saudi asphalt concrete (AC) mixture limits (more stringent than Marshall criteria requirements, see Table 8) should not be the only criteria used in the quality control schemes.

*Short-Term Characterization*—The short-term characterization of asphaltic mixtures deals with properties of strength, elasticity, viscoelasticity, and fracture and water susceptibility. Laboratory tests conducted to reflect these properties include indirect tension tests (IT), modulus of resilience (MR), creep compliance ($J(t)$), fracture toughness ($K_{1c}$), and stripping (or, alternatively, index of retained strength) tests. These tests have been conducted and for comparison purposes are shown and discussed in other sections of this paper.

*Long-Term Characterization*—The long-term characterization of asphaltic mixtures deals with its performance in relation to the occurrence of distresses; the most common in Saudi are rutting, fatigue cracking, bleeding, stripping, and ravelling. Laboratory tests conducted to simulate (and quantify) these distresses include fatigue on disks, index of retained strength for stripping, and incremental static-dynamic series for rutting. Bleeding and raveling are controlled by mix proportioning in the Marshall design method. Since stripping test results indicated the moisture susceptibility of LQA mixtures, it was decided to improve aggregates quality and determine the effectiveness of the techniques rather than carry the fatigue and rutting testing program. Test results on LQA asphaltic mixtures are also cited and discussed for comparison purposes in other sections of this paper.

### *Laboratory Coating Method for LQA*

Test data and other research studies cited show that the problem with LQA for use in asphaltic mixtures is related more to surface debonding than to any other feature. The addition of lime or cement to the asphaltic mixture has slightly lessened the stripping problem [*13*]. Cement or lime coating-techniques have been effective in providing the separating surface that bonds equally well to both the aggregates and bitumen. The following laboratory procedure was followed for coating:

TABLE 5—*Laboratory test data of coarse aggregates.*[a]

| Aggregate Type | Bulk Specific Gravity, gm/cm$^3$ | Apparent Specific Gravity, gm/cm$^3$ | Absorption, % | Deleterious Content, % | Abrasion, % | Stripping, % | Sodium Sulfate Soundness, % |
|---|---|---|---|---|---|---|---|
| Low quality aggregate | 2.483 | 2.619 | 2.30 | 11.60 | 45.6 | <95 | 6.3 |
| Intermediate quality aggregate | 2.573 | 2.642 | 1.31 | 2.67 | 33.3 | >95 | 3.1 |
| High-quality aggregate | 2.619 | 2.694 | 1.06 | 1.10 | 26.6 | >95 | 1.1 |

[a] All tests performed according to relevant ASTM standards.