It is truly an honor to be invited to participate in this program. Also I am indebted to Mr. W. B. Drake for selecting my subject: "Quality Crushed Stone Construction." I intend to break this down into the two essential components: quality crushed stone, and quality construction.

How do we define quality crushed stone? How do we define quality aggregates in general? Parenthetically, to listen to some of our asphalt friends, the quality of aggregate in pavements is of minor importance. What these "friends" are really trying to say, I think, is that if we can no longer afford a quality controlled processed aggregate and an asphalt binder to hold it together to form a pavement, the quality of aggregate is the feature that can be most readily dispensed with. They would have us believe that almost any common "granular material" glued together to form a hard, more or less impervious layer can provide a base that is more durable and more capable of supporting loads than the best unbound aggregate base that can be devised. Speaking from personal experience of some 20 years duration, I am forced to dispute this concept.

Returning to the definition of quality aggregate, it is amazing how much research money has been spent trying to find a clear usable definition of quality aggregate. One $55,000 project in particular, performed at the Virginia Polytechnic Institute cooperatively with Penn State University, whose objective was to define "Research Needs Relating to Performance of Aggregates in Highway Construction," developed recommendations for some 53 additional research projects. High on the list of those of critical importance was one bearing the title "Criteria for Evaluating Aggregate Performance," this project estimated to cost $90,000. Among the other projects closely related to this same problem of aggregate quality definition which were recommended are presented in Table I.

Some of the research defined in the VPI-Penn State study is actually underway, but the most important ones seem to have been considered too tough to handle without a great many more funds than have been made available so far.

Interestingly, the trend in research dealing with aggregates more recently has been toward attempting to find ways to do without them. The University of Illinois has reported on a $50,000 project on the subject "Promising Replacements for Conventional Aggregates for Highway Use," and an even more recent project which will soon be put underway deals with "Waste Materials as Potential Replacements for Highway Aggregates." Obviously, there is great appeal in this attempt to solve two major problems at once, to provide relief for the shortage of aggregates in certain critical areas as well as to find ways to get rid of our trash.

Before leaving this subject of aggregate quality, and before someone asks what the laboratories of the National Crushed Stone Association and the National Sand and Gravel Association have been doing for the last 50 years, let me say we do know a great deal about aggregate quality. There are many aggregates that our present test methods tell us will perform quite well; there are many other aggregates that our present test methods tell us will not perform quite well; there are many other aggregates that our present test methods tell us will not perform well enough in certain environments and for certain uses. There is still a great need for research to find the correct aggregate for each environment and each use.

### Table I. Projects Related to the Problem of Aggregate Quality Definition

<table>
<thead>
<tr>
<th>Project</th>
<th>Estimated Cost</th>
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<tbody>
<tr>
<td>Role of Aggregates in D-line Cracking</td>
<td>$100,000</td>
</tr>
<tr>
<td>Influence of Aggregate Particle Characteristics... on Properties of Concrete</td>
<td>$118,000</td>
</tr>
<tr>
<td>Soundness of Aggregate Particles in Bituminous Mixtures</td>
<td>$163,000</td>
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<tr>
<td>Degradation of Aggregate Leading to the Production of Deleterious Fines</td>
<td>$232,000</td>
</tr>
<tr>
<td>Identification of Aggregate Properties that Influence Bituminous Coating and Adhesion</td>
<td>$232,000</td>
</tr>
<tr>
<td>Development of Base Course Aggregate Criteria</td>
<td>$169,000</td>
</tr>
<tr>
<td>Relationship of Aggregate Properties to Base Course Performance</td>
<td>$115,000</td>
</tr>
<tr>
<td>Aggregate Type and Susceptibility to Damage from Studded Tires</td>
<td>$115,000</td>
</tr>
<tr>
<td>Investigation of Waste Products as Potential Sources of Aggregates</td>
<td>$36,000</td>
</tr>
</tbody>
</table>
for improvement in aggregate test methods to relate the results to actual performance.

Fortunately Kentucky is not one of those areas which is critically short of good quality conventional aggregates. The last figures published by the Bureau of Mines indicate that Kentucky had 199 operating limestone quarries in 67 counties in 1969, plus 40 sand and gravel operations in 22 counties, all attempting to produce quality aggregates for quality construction. Kentucky’s 30 million tons of stone produced in 1969 ranked 13 in the nation. The slightly less than 30 million tons in 1970 dropped Kentucky to 13 in the nation.

The crushed stone industry began the hard way. Stone was broken by hand up until 1858, when Blake invented the Stone Breaker. It is only through great ingenuity that the quarrying industry has been able to come up with new equipment and new techniques to handle the enormous increase in demand for crushed stone products, that reached its peak during the interstate highway construction era, with minimal increase in unit costs.

And while the stone industry has been increasing its capacity, it has also been increasing its ability to control the process so that the purchaser can count on getting just the right product to meet his needs.

The more progressive stone producers have modern testing laboratories at their plants, and trained technicians are constantly running tests on the various products for compliance with specifications. Since the sampling of aggregate materials is at least as important as the testing, the sampler should use every precaution to obtain samples that will show the true nature and condition of the materials as they are produced. One way is to get a sample from the conveyor belt, but producers don’t like the idea of stopping their main conveyor belts for sampling purposes since this stops production for a significant period.

An ingenious method was developed a few years ago up in Connecticut to avoid this interruption to production. A full truckload of the material to be sampled is drawn from the bin or from the belt discharge and taken to one side. Incidentally this small truckload should be collected in several random increments from the production. The ingenious feature of the Connecticut system was in the manner of collecting a test portion from this large truckload sample. The truck was equipped with a small orifice in the tailgate through which the contents were dumped on the ground. While this dumping is in process, technicians cut two or three random increments from the full cross-section of the discharge stream. This insures that the test sample’s gradation is as nearly identical as is humanly possible to that which would be obtained if the entire truckload were fed through the testing sieves. The small test sample is then taken to the laboratory for analysis, and the balance of the material is reloaded into the truck and returned to the stockpile for delivery to a customer.

Extensive research has been performed by the National Crushed Stone Association in its Washington laboratory to discover the optimum gradation of coarse and fine fractions as well as the character of the coarse and fine fractions which might comprise a high class unbound base material such as Kentucky’s DGA.

One thing we firmly believe is that it is more important in most cases that the gradation of DGA be uniform from load-to-load than for every DGA product from every quarry to have the same gradation. We believe that a wide variety of gradations may be entirely suitable for a given job, but there should be a very minimum of variation in these gradations. Obviously there must be some restraint on the variety of permissible gradations: there must not be too many fines, and the top size must be appropriate for the type of equipment expected to be used and the thickness of the layer.

Some producers have learned through experience, how to manufacture good quality base material as a simple crusher-run product with very little variation in gradation. The trend in the industry, however, is toward blending coarse and fine fractions into the pugmill feed to minimize segregation and optimize uniformity. A considerable investment is involved in setting up these blending plants to assure that variability is kept at a minimum and optimum gradation is delivered to the truck at its optimum moisture content.

Every effort should be made to insure that optimum gradation and moisture content are maintained all the way to the job and preferably directly into the mechanical spreader which will place it with a minimum of manipulation to a controlled thickness. With this type of careful control all the way from the plant to the job, crushed stone base material can be used with complete confidence for all classes of construction.

Of course, quality crushed stone is used to advantage in a great many applications other than as base material. In concrete for pavements and structures its angular, rough textured particles generally produce higher strength properties, especially flexural strength so important in concrete pavements. Much research needs to be done to establish more realistic limits of acceptable gradation for manufactured fine aggregate. Here again, end-result specifications would permit the realization of maximum economy at no sacrifice to concrete quality.

In bituminous concretes, the important properties of stability, durability, and even flexibility can be
maximized by the use of crushed stone coarse and fine aggregates. The finer sand-type mixes cannot accommodate thick films of bituminous binder, thus they tend to dry out, become brittle, and develop cracks at an early age.

Returning to the subject of road base material, the distinct advantages of continuing the use of DGA, dense graded crushed stone aggregate, must not be overlooked. I must say that I have never been an advocate of full-depth bituminous concrete bases, particularly where total structural thickness above the subgrade has to be sacrificed. To use an all-asphaltic construction is to build a pavement without a foundation. The most unpredictable element—the most variable element—of the pavement system is the native soil the structure must rest upon. Regardless of the care given to subgrade preparation during construction, there will always be discontinuities in supporting power from variations in soil type from cut-to-fill, from cut-to-cut, and even from station-to-station within the same cut. This is where "rational" design methods fall down; these are based on the highly questionable assumption that the soil is a "semi-infinite solid," homogeneous and isotropic, and that it can be characterized in terms of such fundamental parameters as Young's modulus and Poisson's ratio.

Substitution of thinner but much more costly black bases for untreated crushed stone bases brings the subgrade discontinuities that much closer to the surface where the loads are. There is a major advantage to the use of thicker cushions of quality controlled crushed stone to provide uniformity of support that is so important to good performance from bituminous surfacing layers. Quality controlled crushed stone base materials, thoroughly compacted to as uniform a degree as possible, need no costly cementing agents to maintain their stability. The supporting power of untreated stone bases tends to increase with age (as long, of course, as the parent rock is sound enough to resist degradation) and there is no need to worry that they will become brittle and crack as the seasons roll by.

NCSA Laboratory Research Results

Briefly, the results of NCSA research in recent years may be summarized in terms of the results of tests made by the Texas Triaxial Method and by modifications of this test. With regard to particle shape:
(a) the crushed stones tested were distinctly superior to crushed gravels in the same gradations; (b) crushed gravel is superior to uncrushed gravel, but greater benefit is derived from using all-crushed fine aggregates with uncrushed coarse than from using all-crushed coarse with uncrushed fine.

With respect to gradation: (a) the strength of stone mixtures increases as the top size of particle increases, within top size ranges from 3/8-inch to 1-1/2-inch; (b) for a given top size, the fines content (minus No. 200) found to be optimum from a strength standpoint is not necessarily optimum from a density standpoint; (c) for a given top size there is no disadvantage—possibly even a distinct advantage—to be realized from leaving a gap in the grading at a strategic size. (In some cases strength gains may be achieved by leaving out all of the minus 1/2-inch plus 3/8-inch size in a DGA mixture.) This finding indicates that real economic benefit may be obtainable from processing so as to draw off the premium sizes for use where demand is greatest, rather than letting all sizes fall into the crusher run bin; (d) considering such important properties as strength and voids in the compacted mixture, the optimum fines content, determined by washing, is probably somewhere between 5 and 12 percent, but where drainability and resistance to possible frost action may be of critical importance, the lower end of this range is recommended.

NCSA's staff, with the assistance of an able technical committee (now headed by B. N. Davidson of Kentucky Stone Company) has developed a set of recommended gradation specifications for crushed stone base. These specifications, originally published by NCSA in 1968, have formed the basis for a tentative standard ASTM specification, Designation D 2940.

Probably the two most important keys to success in crushed stone base construction are: (1) uniformity of grading from load-to-load, and (2) just enough fines to permit the material to be properly compacted. Good compaction truly pays off and cannot be over emphasized. One set of data show that merely by increasing the percent solids of a given compacted stone base mixture from 75 to 85 increased the laboratory CBR by a factor of about 5.

But we must not get the impression that it is density per se, or percent solids, that ensures strength in an aggregate base. If it were, the problem could be solved by grading the material for maximum density—by adding the optimum percentage of fines for density—even adding a certain amount of dirt. This obviously is not the correct solution. The answer is to specify a fines content for maximum strength, to allow very little tolerance from your specified gradation, and to insist on compaction to the maximum density obtainable for that gradation. For a given gradation the maximum density obtainable may be 83 percent solids, for another gradation it may be 87 percent solids. Research is underway in the area of defining the standard density to which crushed stone bases should be compacted in the field. This standard density should be defined in terms of some percentage of the maximum density obtainable on a material with a given gradation. Since this maximum obtainable density will vary appreciably with appreciable variations in gradation, the importance of uniformity of gradation from load-to-load is extremely important. Such uniformity is dependent upon good plant control and good job control, but it pays off in value.

I certainly hope the foregoing has given you something to think about and remember in terms of ways in which Kentucky can use its valuable asset, crushed stone, available in such quantity and quality, to your best advantage. Thank you very much for your kind attention.