CONSTRUCTION OF AIR-COOLED BLAST FURNACE SLAG BASE COURSES

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Air-cooled blast furnace slag is an ideal material for use in base and subbase courses [1]. Inherent properties of the slag provide advantages in engineering performance and in economy. It provides outstanding durability and weight savings of 10 to 20 percent over natural aggregate materials in the same applications. Slag has been used in base courses since the time of the Roman Empire, with many examples of such use found in England[2]. Base course construction with slag in the United States dates back to the 1860's[3].

Gradations of slag base and subbase aggregates used have covered all types of applications: pit-run materials with varying top sizes in deep bases and fills, macadam construction and crushed aggregate bases (either open or dense graded). The crushed aggregate base materials may be "crusher run" or pug-milled mixtures of closely controlled coarse and fine aggregate sizes.

An NCHARP study[4] on density standards for base lists the principle factors influencing the strength and compressibility of a granular material under load as:

1. Relative density of the material
2. Confining pressure
3. Moisture content or degree of saturation
4. Gradation
5. Geometric characteristics of the particles

The relative density is the actual state of compaction as compared to the maximum density and the loosest possible state of the material. Strengths are increased greatly by increased densities; therefore, adequate compaction is an important requirement for base course construction. Confining pressures are dependent upon position in the pavement structure and the "overburden" load, and are primarily determined by the design. High degrees of saturation are undesirable in a base because of the weakening effects of water on many base course and sub grade materials. Excellent drainability and relative insensitivity of slag to moisture effects are important advantages in this respect. The gradation is important since it can affect the base drainability, compaction characteristics, inter-particle contact and interlock, tendencies toward segregation, etc. Specifications for gradations apply to all materials and can, at least in graded aggregates, be closely controlled. The last of the five factors, the particle geometric characteristics is very important in determining the strength characteristics. The angular, rough, pitted surfaces of blast furnace slag aggregates provide maximum values for stability and internal friction[5,6,7].

Of the factors listed above, that determine the load-carrying capacity of a base course, only the first one is controlled entirely by the contractor's operations in the field. It is looked upon by many as the most important single variable that should be specified by the design engineer, necessitating 1) a reliable procedure for determining an acceptable level of compaction for the aggregate to be used, 2) an accurate procedure for determining the in-place field density, and 3) contractor capability in equipment and procedures to obtain the necessary field densities.

Density Standards

Despite general recognition of the appropriate density standards and compaction control of granular bases to provide adequate pavement performance under current traffic loads, there seems to be little agreement among states as to the proper procedures. The NCHRP study[4] reported test results using seven different laboratory compaction test procedures. Percentages of lab densities specified for field compaction and methods of measurement of field densities were equally variable.

Reports of the occasional compaction problems with slag bases – inability of a contractor to obtain field densities meeting the specification requirements – led to a survey of current procedures in major slag using states. Information was obtained from states of California, Illinois, Indiana, Kentucky, Maryland Michigan, New Jersey, New York, Ohio, Pennsylvania and West Virginia and from the Province of Ontario. As expected, the procedures in use were quite variable.

Most of the specifications were for dense-graded materials in the ¾" to 1½" nominal top size range, except for Ontario's "Granular B" material which would permit particles up to 4" in size. The usual slag gradation used in this spec, however, is a 2" top size crusher run. (A ¾" crusher run is the other commonly used size in Ontario). The percentage of minus No.4 material permitted in the grading is usually around 25 – 55%, a range that can introduce wide differences in density of compacted base. Since the specific gravities of slag coarse and fine aggregates differ greatly, this effect can be much more pronounced than with natural aggregates. Few organizations seem to utilize the job-mix formula concept, with limited gradation variations permitted to insure uniformity, although in the asphalt concrete specs it is used.

Field Density Requirements

Two of the states, Ohio and West Virginia, depend upon field test sections to establish target densities. Ohio then requires 98% or more of the test section density in the following construction sections as measured by the sand-cone, rubber balloon, or nuclear gage procedures. West Virginia requires 95 to 105% of the test section density, using nuclear gages in most cases. This procedure should be – and apparently is – an ideal system since the aggregate is subjected to the same compaction and the same density test method both in establishing the target density and in the regular construction sections. If the aggregate gradation does undergo a change that produces a significant variation in density, a new test section can be built to establish the new target. No problems were reported with these procedures

Kentucky specifies that the field densities must be at least 84% of the solid volume density, based on oven-dry bulk specific density. Given accurate values for the bulk specific gravities and consistent aggregate gradations, this procedure seems to work satisfactorily with the ¾" to 0" size material used. Either the nuclear gage or rubber balloon method may be used to measure field density.

New York specifies the compactive effort to be used based on the material and type and weight of rollers. Field density tests are not required (state opinion), acceptance can be on the basis of visual observation and contractor compliance with specified compaction procedures. If density tests are run, only 90% of the ASTM D 698 (AASHTO T99) maximum density is required.

In all other states checked, the target density is established on the basis of laboratory tests, most commonly ASTM D 698 or AASHTO T99 (5.5 lb. rammer and 12" drop), with Michigan also using the Michigan Cone Test. Field densities usually required are 95% of the lab maximums in California and Michigan, while Indiana, Illinois, Pennsylvania and Ontario use 100%. New Jersey and Maryland use D1557 or T180 compaction (10 lb. rammer and 18" drop) modified to include the +¾" aggregate in the compacted sample. Required field densities are 95% of the D1557 lab maximum. While sand cone is the most commonly used field density test method, nuclear gages are permitted in all the specifications and are rapidly becoming more widely used due to the lesser time involved in obtaining a reading.

Rather frequent complaints are encountered regarding inability to obtain the specified density in the field when target values are set on the basis of laboratory tests using hammer (impact) compaction. This comes primarily from the failure to have the same gradation of material in the lab tests and in the field. Correction for density differences from this factor are not commonly made, although such provisions do exist in some specifications and in AASHTO test method T224. Another problem that has been reported on several occasions has been the apparently inaccurate density measurements obtained with nuclear gages, especially on larger sizes of base materials. These problems are discussed more fully in the following sections.

Determining Target Values

It seems obvious that target density values should be determined on the same gradation of aggregate as that used in the field. However, often it is not. Variations in density with gradation are well known; several theoretical approaches to determining a "maximum density" gradation have been used for many years. The NCHRP study4 of density standards recommends that the standard density be determined using a sample within ±5%passing the No.4 sieve of the gradation actually in the construction section, or that a field curve be developed relating density to the percentage of minus No.4. The percent passing No.4 in the sample taken from the density test hole is then used to determine the "target" value for each sample. The ±5% No.4 range where no correction is considered necessary is based on tests with natural aggregates with comparable specific gravities of coarse and fine fractions. Effects of varying the minus No.4 in slags where great differences exist between the specific gravities of the coarse and fine aggregate fractions would be much greater.

Differences in gradation between the lab compacted material and that existing in the field may be due either to actual differences between the sample submitted and actual fields grading, or to degradation of the aggregate during compaction. The NCHARP study indicated that the D1557 compactive effort was "the only test method that would be rejected, for certain materials, one the basis of excessive degradation". The effects on slag as compared to natural aggregates are similar to that of the Los Angeles test: the slag may have the greater degradation in the test, but the field degradation under rollers will be much less for all aggregates and will not correlate with the laboratory breakdown. Effects on slag density will be greater due to increased unit weight of smaller particles. With increased aggregate size, the breakage of particles will increase. The extent of aggregate degradation possible is shown in Table 1, taken from data obtained by the state highway department using a modified D1557 compaction in which all material up to 1½" was used. Tests were run with 20, 30, 40, 50, and 60% passing the No.4 sieve, using both an air-cooled blast furnace slag and crushed stone. Samples of known original grading were subjected to the modified test for moisture-density relationship, followed by determination of the final sieve analysis.

The gradation changes, at a given sieve size, such as the No.4, are quite large, especially when the tests were begun on the coarser grading. For the slag, beginning with 20% passing the No.4, the final minus No.4 figure was 35%. A logical question would be, what gradation does the density of 119.3 lb/ft3 represent? 20% minus No.4? 35% minus No.4? Some percentage between 20 and 35? As the amount of fines increased, breakdown during test decreased, probably due to the cushioning effect of the fine material on the coarser particles.

Degradation would increase as each sample was re-compacted at a higher moisture content, as permitted by the test methods. A fresh sample should, therefore, be used for each point on the moisture-density curve, as recommended by Kassal[8] to minimize gradation changes. Even when this is done, curves of density vs. % of minus No.4 material should use the gradation after compaction, If no corrections for gradation are made, it is easy to visualize a contractor's problem trying to meet a requirement based on a lab test that measured density at a level of 50% minus No.4, while he works in the field at the 35% level (within spec limits and with very little degradation in the field).

The slag and stone data in Table 1 indicate little difference in the gradation of the two aggregates during compaction. The differences in maximum density are greatly different, however, from 119.3 to 129.6 lb/ft3 (8.6%) for the slag; from 144.5 to 147.3 lb/ft3 (1.9%) for the stone. The differences here are due to the specific gravity differences: the crushed stone coarse and fine fractions differ in dry bulk specific gravity by 0.01; for the slag the difference is .30 – thirty times as large. Need for density corrections based on gradation may be slight for crushed stone, but are absolutely essential for slag. The problem could be minimized by furnishing slag aggregate near the upper limit (fine side) of the grading band – if this can be done without rejections for the out-of-spec material.

Table 1

Material		**Gradation % Passing by Weight**				**Max Density**	**Optimum Moisture**
Air-cooled slag		**1½”**	**¾”**	**#4**	**#200**	**lb/ft3**	**%**
20%<#4	Before	100	65	20	6	119.3	4.4
	After	100	78	35	7		
30%<#4	Before	100	69	30	6	124.8	4.8
	After	100	78	40	8		
40%<#4	Before	100	74	40	6	128.9	4.6
	After	100	78	46	6		
50%<#4	Before	100	78	50	6	129.6	4.5
	After	100	83	54	6		
60%<#4	Before	100	83	60	6	129.3	4.5
	After	100	84	61	9		
Crushed Stone							
20%<#4	Before	100	65	20	6	144.5	4.7
	After	100	73	32	9		
30%<#4	Before	100	69	30	6	145.9	4.3
	After	100	78	40	10		
40%<#4	Before	100	74	40	6	147.3	4.7
	After	100	79	46	9		
50%<#4	Before	100	78	50	6	146.4	4.0
	After	100	85	55	6		
60%<#4	Before	100	83	60	6	145.6	3.9
	After	100	87	64	9		

Laboratory compaction methods that are limited to ¾” maximize materials often use modified gradings, where +¾” material in the field sample is replaced by an equal weight if No.4 to ¾” particles. The NCHARP study4 states: “This procedure is not recommended because the gradation curve of the test sample changes and the maximum dry density test results will not be representative of the field sample.” These changes would also affect the degradation during compaction, and overall errors introduced would be magnified for slag because of the coarse–fine specific gravity differences. The study recommended compaction tests on -¾” material, with correction for the oversize (+¾”), assuming that the oversize particles float in a matrix of the finer materials:

$$D = \frac{0.95\, Dc \times Df}{0.95\, DcPf + DfPc}$$

Where: D = max. theoretical dry density of whole sample in lb/ft3
Dc= density of oversize (dry bulk sp.gr. x 62.4)
Df= lab density of finer fractions, lb/ft3
Pc= % oversize, as a decimal
Pf= % finer fraction, as a decimal

The factor, 0.95, is to compensate for the fact that some additional voids are introduced by the oversize particles. The report notes that, where oversize exceeds 25 or 30%, the equation will overestimate the true density of the whole sample because not enough fine material will be present to completely fill the voids between the larger particles. The specific gravity variations with size of slag particles might tend to make this statement inapplicable.

Various compaction methods will produce varying amounts of degradation, as shown both by the NCHARP study4 and by tests reported by Kassell[8]. The latter reported tests on blast furnace slag aggregates that showed 6-14% increase in material passing the No.4 sieve with D 1557 (T 180) compaction, compared to 1 to 2% ford 698 (T99) compaction. The current tendency is to go toward higher compactive efforts (such as D 1557) which can only compound the problems. An alternative would be to specify a higher percentage of the density produced by a lighter compactive effort.

Determination of an appropriate target value for field compaction is obviously not a simple, automatic operation. The important criteria is that the target density must be based on the same gradation as that found in the compacted base. This is of much greater importance in the case of slag than with natural aggregates. Among the means for minimizing these problems are:

1. Use slag aggregates of finer gradation and/or lower compactive efforts to minimize degradation.
2. Use only the -¾” material, as it occurs in the field samples for laboratory density tests, and use a separate sample for each point on the moisture density curve.
3. Correct the densities for any oversize (+¾”), using the formula on page 4.

(Alternatively, volume of the oversize in the field samples could be determined and subtracted from the test hole volume.)

4. Plot a curve of maximum density vs. percentage of minus No.4 material, based on the gradation of the sample after compaction.
5. Correct the target value for each field density sample to match the percentage of minus No.4 material actually present in the aggregate removed from the test hole.

Measuring Field Densities

None of the procedures for checking the field density attained during compaction are completely satisfactory under all conditions. Both the rubber balloon and calibrated sand procedures are time consuming and involve a large amount of labor in digging holes and weighing bulky samples and accuracy of volume determinations may be affected by smoothness or evenness of the sides of the hole dug in the base. These methods do, however, determine the average density throughout the entire depth of the base.

The nuclear test methods that have grown rapidly in use in recent years are much easier to run and permit many more tests to be conducted in a given time period. There are several factors in the use of this method which must be considered - factors that may result in low and/or erratic density values, especially with slag aggregates. The appendix of the method, D 2922 (or T 238), contains notes regarding the effects of these characteristics, but apparently they are frequently ignored.

The method states that the nuclear determination of density is “indirect” and that no theoretical approach exists that will predict the count rate for given equipment, geometry, material and density, making necessary correlation tests on materials of known density. Calibration curves supplied with the equipment “do not necessarily hold for all soils and soil-aggregate because of differences in chemical composition.” The calibration should, therefore, be done with the actual base material to be used, preferably compacted to varying densities with the same equipment to be used on the project. This can really be done only in the field, correlating the nuclear measurements with results obtained with sand-cone or rubber balloon tests.

The notes accompanying the nuclear test method also state that the volume of materials represented in a measurement is indeterminate and “will vary with the source-detector geometry of the equipment used and with the characteristics of the material tested. In general, and with all other conditions constant, the more dense the material, the smaller the volume involved in the measurement. The density so determined is not necessarily the average density within the volume involved in the measurement … the top 1” (25.4mm) of material determines about one-half of the measured count rate with the result that the observed density is largely determined by the density of the upper layers. For the usual density conditions the total count is largely determined by the upper 3” to 4” (75 to 100mm)… Where these materials are uniform density, this characteristic of this method is of no effect."

Base course aggregates are not uniform in density, especially in small volumes. This is particularly true of slags, where each size of particle differs from the others in bulk specific gravity, and individual large particles may vary greatly in density. Any segregation, chance of location of large particles near the surface, etc. can have large effects on the measured density. In aggregates that do not contain enough fines to completely fill the voids between larger particles; the fines will tend to accumulate at the bottom of the base, leaving a less-dense surface layer that will have a disproportionate effect on the density measurement. Thus, results of the nuclear tests will tend to be on the low side. Another factor that tends to produce consistently low readings from nuclear gages is the effect of surface irregularities (voids) that lower the readings for the top inch- which in turn is about one-half the total. As aggregate size increases, the effects of this factor also become larger.

The nuclear test method states that it is not possible to give precise numbers for system accuracy and precision. "It is believed, however, that if the procedures herein are carefully followed, the standard deviation of the nuclear measured values, in terms of accuracy, will not be greater than on the order of some 3 to 5 lb/ft3…" It may be necessary to run a large number of tests to obtain a good estimate of the density, and even then have only values biased downward because of the base material and test method characteristics.

It would appear that the best situation for use of nuclear gages on air-cooled blast furnace slag base courses would be with a relatively small top size, high percentage of minus No.4 with low variability, and calibration of the gage on the material in the field. A firm of consultants in Ontario has apparently reached a similar conclusion based upon their own experience – use of nuclear gages is not considered feasible on 2" top size aggregates, but is considered useful on ¾" material[9].

Summary

Air-cooled blast furnace slag is an excellent base material, possessing the best of durability and stability characteristics. It is widely recognized and used as a superior base course aggregate. Slag is subject to the problems from a compaction standpoint (actually obtaining the specified field density) that are found with other aggregates. A survey of 29 states in connection with NCHRP studies4 revealed only 15 that reported no such problems. Other states listed, in addition to slag, materials such as "volcanic cinder, igneous rock", "sandstones which degraded", "decomposed granites, schists", etc. as involved in such difficulties.

These problems, possible with any aggregates used on projects with reasonable compaction equipment available, seem to be due primarily to one or both of two causes: 1) a target density based on gradation different from that found in the base as constructed, or 2) field density measurements that are inaccurate because test method characteristics and limitations are ignored. The differences in specific gravity (or bulk density) of individual particles of large size and between average values for different sizes of slag simply makes the aggregates more susceptible to, or more severely affected by, these potential problems.

The variety of methods used by different organizations involve varying possibilities (or likelihoods) of problems of this nature being encountered. It is no unreasonable to expect that a logic of 1) basing spec requirements on the material being used, and 2) checking performance in an accurate manner should be recognized by all specification writers. The preceding discussions should provide suggestions for accomplishing these basic aims under the various methods that are used. It is recognized that no one set of recommended modifications can be applied to all procedures; each case may be different.

References

1. NSA 173-2, "Air-Cooled Blast-Furnace Slag Bases", National Slag Association, 1973.

2. Lee, A. R., "Blast Furnace and Steel Slag", Edw. Arnold, Ltd., 1974.

3. Josephson, G. W., Sillers, F., Jr., and Runner, D. G., "Iron Blast-Furnace Slag
4. Production, Processing, Properties, and Uses", Bulletin 479, U.S. Bureau of Mines, 1949.

5. NCHRP Report 172, "Density Standards for Field Compaction of Granular Bases and Subbases, Transportation Research Board, 1976

6. NSA 167-1, "Strength Characteristics of Slag Base and Subbase Materials", National Slag Association, 1967.

7. Aldons, W. M., Herner, R. C., and Price, M. H., "The Load Transmission Test for Flexible Paving and Base Courses, Part II: Triaxial Test Data on Structural Properties of Granular Base Materials", CAA Technical Development Report No. 144, U.S. Dept. of Commerce, 1951.

8. "Shearing Strength of Air-Cooled Slag Mixtures", A&H Materials Testing Corp. Report to National Slag Association, 1966.

9. Kassal, G. J., "The Moisture-Density Relationship of Dense-Graded, Blast-Furnace Slag Aggregates", Report to Technical Committee, National Slag Association, 1980.

10. Cotsworth, R. P., National Slag Limited, personal communication, July, 1982.