Construction Specifications for Volcanic Cinders Used as Road-Surfacing Aggregate

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The purpose of this study was to determine parameters that influence the performance of volcanic cinders when used as a wearing surface for unpaved forest access roads. The steady depletion of good, high-type aggregate sources has brought about renewed interest in other aggregate types, making this study particularly timely. A literature review, correspondence, and personal interviews were conducted to determine existing use and performance of cinders. A road rating system was developed, similar to the AASHO Road Test method, to determine which were "good roads" and which were "poor roads" based on a 0 to 5 numerical rating scale. Thirty of the rated roads and the corresponding cinder pits were sampled and the material was tested in the laboratory. The physical properties of the cinders were then statistically correlated with the road rating. It was found that density, gradation, durability, and plasticity were the most significant independent variables. Based on these results, specifications for untreated cinder surface courses have been developed. These include (a) a minimum of 100 percent compaction relative to AASHO T 99; (b) gradation limits of 100 percent passing the 1-in. sieve, 80 to 95 percent passing the ¾-in., 35 to 60 percent passing the No. 4, 22 to 45 percent passing the No. 10, 8 to 25 percent passing the No. 40, and 3 to 12 percent passing the No. 200; (c) a plastic index value between 2 and 10; and (d) a maximum Los Angeles abrasion value of 50 prior to processing. In most cases this will require crushing of the harder (purple, gray, and black) cinders.

•VOLCANIC CINDERS occur in many areas of the world and are particularly common in central Oregon, which is the location of this study. The Forest Service of the U. S. Department of Agriculture builds many miles of untreated aggregate-surfaced roads in the states of Oregon and Washington. In the central Oregon area, the use of volcanic cinders to surface those roads is very common. The performance of cinder-surfaced roads has varied, with both good and poor results. The general trend among many highway agencies is to avoid their use. However, the steady depletion of good, high-type aggregate sources has brought about renewed interest in other aggregate types, including volcanic cinders. Present use of volcanic cinders is primarily for low-class roads, either untreated or with a light asphaltic surface treatment.

PURPOSE OF STUDY

The purpose of the study was to determine the parameters that influence the performance of volcanic cinders when used as a wearing surface and base course for forest development roads. The approach to this problem suggested an evaluation of the

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performance of existing untreated cinder roads to determine which were "good roads" and which were "poor roads" based on a numerical rating scale. This, in turn, was related to the physical properties of the cinders in the roadway and from the borrow pit. Included in the study was a survey to determine current practice and associated problems involved in the use of cinders as road aggregates. These relationships, together with other field observations, were used to recommend specifications for selection of borrow material and for techniques of construction quality control.

This paper is concerned with the relationship between cinder properties and road-surfacing performance. The details of the entire study, giving the background of the road-rating system and the results of the survey to determine current use, are presented in a U. S. Forest Service report (1).

BACKGROUND INFORMATION

Cinders, as referred to in this report, are a pyroclastic material associated with volcanic activity (2, 3). Fragmented material of this type is generally classified according to size. Pieces larger than approximately 10 in. (256 mm) in diameter are called blocks or breccia if angular and ejected in a solid state and are called bombs if ejected in a plastic state, which produces a roundish or ellipsoidal shape with twisted ends. Pieces between 10 in. and ⅟₁₆ in. (4 mm) in diameter are called lapilli or cinders. Particles finer than approximately ⅟₁₆ in. in diameter are called ash or dust (4).

A cinder, unlike most rocks, does not have a set mineral or chemical composition because it is mainly a textural classification of rock. It may be either acidic (light-colored matter consisting principally of quartz and feldspars) or basic (dark-colored matter consisting principally of ferromagnesian minerals with no quartz). Color reflects the conditions prevalent during formation (i.e., temperature or oxygen available) and weathering. Oxygen-deficient cinders are darker in color, whereas red or brownish cinders generally indicate weathering and are located in the upper zone of a deposit. Minor accessory minerals, such as iron, may also contribute to the coloring of the cinder.

Scoria is a term used to describe any volcanic ejecta that is rough, sharp, and vesicular, either pyroclastic material or the upper surface of some lava flows. It is commonly black or reddish and principally basic in composition. The term is often used to include cinders.

Cinders are located throughout the world. The main areas in the United States are central Oregon east of the Cascades, northern and eastern California, Arizona, New Mexico, and Hawaii. Notable deposits are found in New Zealand, Japan, Turkey, Mexico, Central America, and the Caribbean. In other countries the terms scoria, scoriae, volcanic agglomerate, or grits are used more often than cinders, especially by British Road Research Laboratory reports (5, 6, 7).

Current Practice and Experience

According to an earlier publication (8), almost all agencies will avoid the use of cinders if other sources of mineral aggregate are available. When used, cinders are applied as surfacing material primarily on unpaved roads, such as logging, forest access, and low-traffic roads. On higher type roads cinders are used as subbase and base material and for asphalt-stabilized surfacing.

The best results with pit-run cinders have been with the softer types (generally the red-colored types; average Los Angeles abrasion in the 40s). The harder types (purple, gray, and black; average Los Angeles abrasion in the 30s) lack fines, and thus are unstable (Fig. 1). When crushed, the harder types perform more satisfactorily, because the necessary fines are obtained and thus the surface better withstands the abrasive effects of traffic. In addition, the rough riding quality resulting from the pit-run oversized material is eliminated.

Grid rollers are popularly used for breaking the larger pieces and for compaction. The effectiveness of this type of roller for compaction is questionable. Steel wheel, rubber-tired, and vibration rollers appear to achieve better results, as does compaction from logging and other heavy truck traffic.

Figure 1. Sycan Road, North of Bly, Oregon: Note contrast between washboard surface using purple cinders (foreground) and smooth surface using red cinders (background).

With increasing traffic, new road construction and pavement thickness upgrading, and the lack and depletion of good mineral aggregate sources, the use of cinders is being investigated in more detail. Many agencies feel that cinders can be used effectively with proper gradation and other quality controls. Asphalt treatment will probably give the best road surface and the most economical maintenance over an extended period.

CORRELATION OF CINDER PROPERTIES WITH SURFACING PERFORMANCE

Development of the Rating System

A road-rating system was developed similar to the AASHO Road Test methods. A major differentiation was that for this study the roads were rated over a period of time; thus, the roads were given a performance index (PI) rating rather than a serviceability rating. Forty-seven roads were rated on a scale from 0 to 5 with performance increasing with increasing rating values (Figs. 2 and 3). This rating was performed by people familiar with the long-term serviceability of the road. After the rating was obtained, it was correlated with maintenance frequency, rutting, watering, speed, and traffic volume by means of a multiple linear regression computer program. The resulting regression equation had a multiple correlation coefficient of 0.812. This equation was then used to determine the performance index of the various roads, which was, in essence, the performance rating with the individual rater's bias removed. Complete details of this rating technique can be obtained by referring to the U. S. Forest Service report (1).

Road- and Pit-Sampling Program

Once the road-rating system was established using the PI, the next step was to select typical examples of roads within each rating group and to sample the surface material. In all, 30 roads and their corresponding borrow-pit sources were sampled, including 15 in the Winema National Forest, and 5 each in the Fremont, Rogue River, and Deschutes National Forests. The general location of the sample sites is shown in Figure 4.

The purpose in sampling these roads and pits was to determine physical properties that could be identified with roads of high performance (PI) and those associated with

Figure 2. Kirk Road, Northeast of Chiloquin, Oregon: Rough surface contains black, uniformly graded cinders (PI = 2.1).

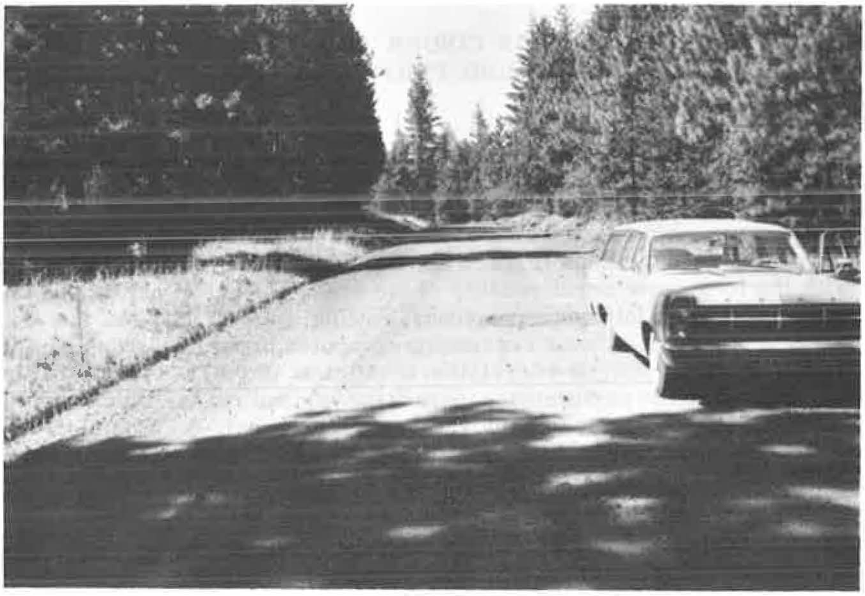

Figure 3. Twincheria Road, East of Butte Falls, Oregon: Cinders cemented with iron oxide produce a hard, compact riding surface (PI = 3.1).

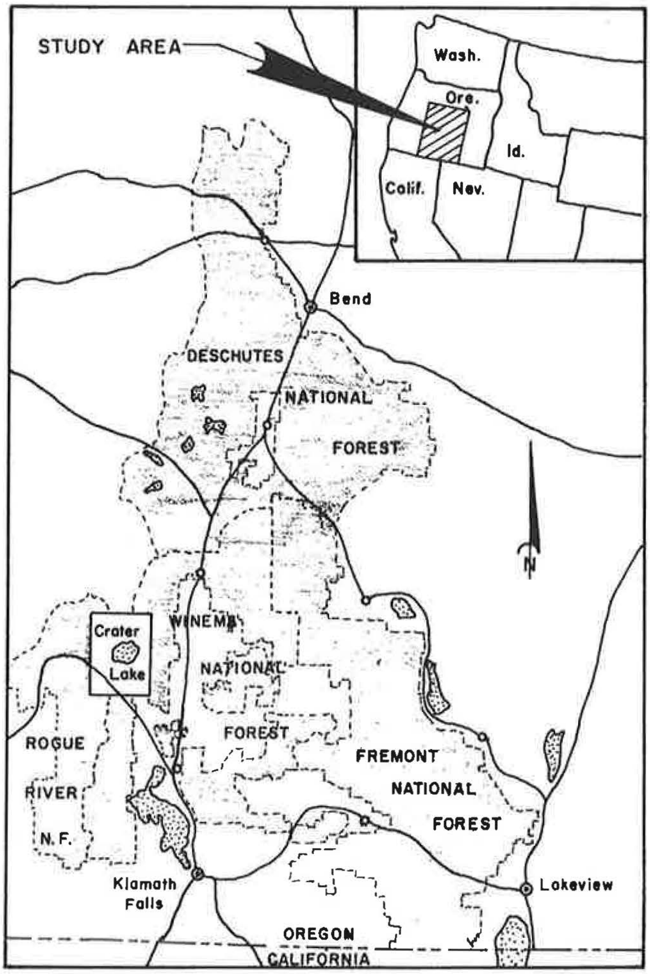

Figure 4. Study location map.

low performance, or more specifically the correlation between performance and physical property. All roads were constructed of pit-run material.

The testing program consisted of two parts, field sampling and testing, and laboratory testing. The field sampling and testing portion involved first selecting a straight section of the rated road and obtaining approximately 150 lb of material (2 sample sacks). This was obtained from a trench dug at least halfway across the road and through the majority of the surface course (approximately 4 to 6 in. deep). In addition, the following field tests were performed: (a) in-place density using the Washington densometer; (b) in-place moisture content using the Speedy moisture tester; (c) color identification; and (d) penetration test of surface and base material (later discontinued because there appeared to be no correlation).

The pit site was located next and a 75-lb sample (1 sample sack) was obtained from the approximate area in the pit where the road sample was obtained during construction. Obtaining a related sample was sometimes difficult because of the mixing of pit material and subsequent use of the pit for other construction projects.

The samples were sent to the Forest Service Regional Office in Portland, and in turn sent to the Federal Highway Administration laboratory in Vancouver, Washington, or to the Oregon State Highway Department (OSHD) laboratory in Salem (Table 1).

TABLE 1

TESTS PERFORMED ON ROAD SAMPLES

Test Description	Test Method	Tests Performed on	
		Road Samples	Pit Samples
Los Angeles abrasion	AASHO T 96	X	X
Specific gravity of fines	California 208B	X	
Unit weight, dry-rodded		X[a]	
Unit weight, loose		X[a]	X[a]
Plasticity index	AASHO T 90	X	X
Liquid limit	AASHO T 89	X	X
Sand equivalent	AASHO T 176	X	
Oregon air degradation	OSHD	X	X[a]
Moisture-density relationship	AASHO T 99 D	X	
Gradation (dry sieve analysis)	AASHO T 27	X	X

[a] These determinations were made only on samples sent to the Oregon State Highway Department (OSHD).

Splitting of the work was necessary because of the volume of testing involved and the time required. Some additional testing was also performed at the Forest Service Engineering Materials Laboratory in Portland, Oregon.

In addition to the testing, the following calculations were performed: (a) coefficient of uniformity (C_u) for both road and pit gradation; (b) coefficient of curvature (C_c) for both road and pit gradation; and (c) relative compaction of road sample (as compared to maximum density). Several points should be made in regard to the test results:

1. Los Angeles abrasion test—The actual values for the Los Angeles abrasion appear to be very good (low values) and this is due in part to the volume of material used in running the test. The standard charge is 5,000 grams of material. With the low bulk specific gravity of cinders, a greater volume of material is used than would be normally utilized (9). Because this study considers only cinder aggregate, relative values between various cinder samples should be acceptable for use in the analysis.
2. Specific gravity test—Unfortunately this test was run in a Le Châtelier flask, (Calif. 208B); thus, only material passing the No. 4 sieve was used and the apparent specific gravity was determined. As a result, the values were very uniform, whereas values for the coarse portion would probably have been more meaningful.
3. Plasticity index and liquid limit—In most cases the cinders had very few plastic fines, thus giving no plastic limit. However, the liquid limit could be determined for most samples (often only by one point and extrapolation) and was thus reported because it appeared to give good correlation.

Correlation With Performance Index

The results of the field sampling and laboratory testing were compared with the performance index (road rating) by means of the multiple regression program. Nineteen independent variables from road tests and 12 independent variables from pit tests were considered. These variables are listed in table 2 together with their average values, standard deviations, and correlations with the performance index.

According to the regression program, the following are the most significant variables (with correlation coefficients above 0.3) in decreasing order of importance. The values for the percent passing the 1½-and ¾-in. sieves are results from pit source samples.

Variable	Correlation With Performance Index
Relative compaction	0.395
Plasticity index	0.392
Percent passing No. 4 sieve	-0.341
Percent passing 1½-in. sieve	0.328
Percent passing No. 10 sieve	-0.325
Coefficient of curvature	0.323
Oregon air degradation—H	0.319
Percent passing No. 40 sieve	-0.312
Percent passing ¾-in. sieve	0.310

TABLE 2

CORRELATION OF ROAD AND PIT TEST VARIABLES

Variable	Mean	Standard Deviation	Correlation With Performance Index
	Road Test Variables		
Sand equivalent	49.4	24.0	-0.130
Los Angeles abrasion, percent	43.8	10.4	-0.099
Maximum density, pcf	102.5	7.6	-0.058
Relative compaction, percent	102.4	5.7	0.395
Specific gravity	2.72	0.12	-0.154
Plasticity index	0.1	0.4	0.392
Liquid limit	23.8	4.2	0.196
Oregon air degradation, sediment height, in.	3.5	4.7	0.319
Oregon air degradation, percent passing No. 20 sieve	26.4	9.8	-0.024
Color (red = 2, black = 1)	1.8	0.4	-0.183
Coefficient of uniformity	52.6	31.4	0.269
Coefficient of curvature	0.72	0.56	0.323
Gradation, percent passing sieves			
1½ in.	96.1	5.6	-0.119
¾ in.	88.9	6.9	-0.117
⅜ in.	76.2	7.4	-0.213
No. 4	61.4	8.6	-0.341
No. 10	50.1	9.5	-0.325
No. 40	31.1	8.0	-0.312
No. 200	9.6	2.8	-0.243
	Pit Source Variables		
Los Angeles abrasion, percent	46.7	10.6	-0.029
Liquid limit	28.5	3.3	-0.082
Unit weight, loose, pcf	67.1	7.5	-0.073
Coefficient of uniformity	38.1	22.6	-0.071
Coefficient of curvature	1.60	1.21	-0.127
Gradation, percent passing sieves			
1½ in.	96.1	2.8	0.328
¾ in.	86.0	6.5	0.310
⅜ in.	69.0	9.8	0.286
No. 4	50.5	12.8	0.247
No. 10	37.1	13.4	0.252
No. 40	18.5	8.4	0.090
No. 200	4.6	2.5	0.095

The multiple regression equation is as follows:

$$PI = -5.65 + 0.06(P) + 0.05(RC) + 0.08(OA\text{-}H) - 0.04(OA\text{-}20) + 0.06(PP1.5)$$

$$- 0.07(PP4) - 0.24(Color) + 0.09(PP10) - 0.02(PUW) + + 0.30(CC)$$

where

PI = performance index;
P = plasticity index;
RC = relative compaction;
OA-H = Oregon air degradation, sediment height;
OA-20 = Oregon air degradation, percent passing No. 20 sieve;
PP1.5 = percent passing 1½-in. sieve from pit;
PP4 = percent passing No. 4 sieve from pit;
Color = cinder color (red = 2, black = 1);
PP10 = percent passing No. 10 sieve from pit;
PUW = loose unit weight of material from pit; and
CC = coefficient of curvature from road.

This equation has a multiple correlation coefficient of 0.854. Individual equations were also determined for each of the 9 most significant variables. The equations and the individual correlation coefficients indicate the relationship between the physical test property and the performance index (rating). Unfortunately, 24 of the 32 roads had a performance index within the relatively narrow range of 2.1 to 3.5, with only 2 roads rated below this range. Thus, the regression analysis gave the greatest weight to this range, with the result that most of the regression lines have very steep slopes.

Several important trends were noted when comparing the test results with the performance index. They are summarized in the following:

1. Compaction—In the tests of road samples, the relative compaction is very important, whereas the maximum density is not.
2. Gradation—In the tests of road samples, the coefficient of curvature varies directly with the performance index (i.e., gradations with a concave-shaped curve on a semilog graph are associated with the higher performance index). This relationship is also reinforced by the trend showing less material passing the No. 4, No. 10, and No. 40 sieves with a higher performance index; the value for the other sieves appears not to be significant. In the tests of pit samples, the increased percentages passing the 1½-in. and ¾-in. sieves is desirable (i.e., less large-size material).
3. Plasticity—In the road sample tests, the significant characteristics of the fine material appear to be increased plasticity index, liquid limit, and sediment height in the Oregon air degradation test, and decreased sand equivalent with increasing performance index (i.e., cohesive binder is desirable).
4. Abrasion—In the road sample tests, the Los Angeles abrasion value varies inversely with the performance index (i.e., harder material with less abrasion is desirable). In the pit sample tests the decreased Los Angeles abrasion value is desirable.

Recommended Specifications and Field Quality Controls

Based on the physical test results, the cinder characteristics that appear to be significant are compaction, gradation, plasticity, and resistance to abrasion. Using these characteristics, the following specifications are recommended for the construction of cinder wearing surfaces.

Compaction—In all cases the final constructed surface should be compacted to at least 100 percent of standard compaction (AASHO T 99). This should extend to a depth of 6 in. below the surface. In most cases, it is recommended that a vibratory compactor be utilized, or as an alternate a pneumatic roller. Sheepsfoot and grid rollers should be avoided. Steel-wheel rollers can be used for finish or proof rolling.

Gradation—The maximum-sized particle should be 1 in. in diameter in the finished surface. In certain cases, this size could be increased to 1½ in. at the pit source, as some degradation will take place in the construction process. The following in-place road gradation is recommended (based on dry-sieving similar to AASHO T 27, with a maximum shaking time of 5 minutes):

Sieve Size	Percent Passing
1 in.	100
¾ in.	80 to 95
No. 4	35 to 60
No. 10	22 to 45
No. 40	8 to 25
No. 200	3 to 12

These limits will provide a dense gradation.

This gradation is similar to AASHO M 147-55, grading C, and U. S. Forest Service Item 151, grading B, Item R151, grading C, and Item R150, grading C-1. The gradation recommended in this report differs somewhat in that it has a smaller percentage passing in the No. 4 to No. 40 sieve range to allow for subsequent degradation of the cinders. Local practice may indicate that the standard specifications listed previously are adequate.

It is realized that in-place road gradations are often difficult to estimate on the basis of pit-sampling. The best technique for sampling cinder pits is to obtain as representative a sample as possible (i.e., for the portion of the pit to be used, or a blended sample). Based on results from this study, the pit gradation should have approximately 5 percent less passing a given sieve (below the $^3/_4$-in. size) than is desired for the finished product on the road. This allows for degradation in transporting and compacting the cinders. This value should be approximately 10 percent for the softer red and brown cinders.

The recommended gradation requirements could be met by selected blending and scalping at the pit source. However, in some cases it may be necessary to run the material through a primary crusher with some selective screening.

Control of gradation is felt to be extremely important because too much large material (above 1-in. size) causes a rough riding surface, and too much fine material will cause excessive and early washboarding and rutting.

Atterberg Limits—The material passing the No. 40 sieve should have the following characteristics: The liquid limit should be 35 at the maximum, and the plasticity index should range from 2 to 10.

Based on the trends illustrated, sand equivalent test results ranging from 50 to 30 would give an indication of the required plasticity. This value should not, however, be used as a specification requirement because it measures somewhat different properties of the fine material.

This requirement of plasticity is felt necessary to replace evaporated surface moisture through capillarity. In most cases, cinders do not produce this plasticity, and thus the addition of plastic binder is necessary. This binder may be available as a cap of weathered cinders over the cone, or can be generated in some cases by watering, mixing, and compacting the softer brown and red cinders. A pulvemixer attached to a small tractor would perform an effective job of blending the cinders and plastic borrow material. In some pits, the presence of an iron oxide binder will give a satisfactory binding action in the road. If this is the case, the plasticity requirements could be waived.

If immediate paving of the cinder surface with an impervious mat is anticipated, then the plastic material should be avoided. If paving is contemplated at a later date, then lime, asphalt, cement, or other additives should be considered to reduce or eliminate the plastic characteristics at this time.

Resistance to Abrasion—Maximum pit Los Angeles abrasion of 50 should be used to prevent excessive degradation of the material in the road surface, because excessive fines will cause early washboarding and rutting. With pit-run material, this degradation was necessary to generate sufficient fines for binder. However, with the recommended limits on gradation, this will no longer be necessary or desirable.

CONCLUSION

In most cases, the harder cinders (purple-, gray-, and black-colored ones) should have less degradation and provide a better riding surface over a longer period of time. However, this type of cinder usually lacks the necessary fines, and thus some crushing is required to meet the recommended gradation limits. The softer cinders (red- and brown-colored ones) sometimes have excessive degradation; thus, care must be exercised in selecting the necessary gradation. The Los Angeles abrasion requirement will eliminate the use of most of the softer types. In some pits, where several cinder colors are available, blending of the harder and softer types may produce the necessary gradation and plasticity to provide an adequate riding surface.

SUMMARY

The foregoing analysis shows that cinders behave much as any other granular material when used as an untreated road surface. The study revealed that several modifications were desirable to standard specifications to better fit the properties of cinder aggregates. The test data indicate that a Los Angeles abrasion value of 50 would be more appropriate than the usual limit of 40. The mean of all Los Angeles abrasion values is a 46.7 percent loss, with a standard deviation of 10.6 when sampled from the pit. Therefore, a maximum allowable limit of 40 is too restrictive. The test data show that both the plasticity index and the gradation are very important for good performance. The gradation should ideally be somewhat on the coarse side of the gradation band to allow for subsequent degradation under traffic. Relative compaction was also found to be very important, which further emphasizes that cinders behave much as any other granular material used as a road aggregate.

Reference to Table 2 shows a minor correlation (low value) between Los Angeles abrasion and performance index (PI) and a positive, strong correlation between the Oregon air degradation sediment height (H) value and PI. However, it is recommended that the Los Angeles abrasion test be used as a control test rather than the Oregon air degradation test. This is because high-quality aggregate gives low Oregon air H values. Because this study showed a positive correlation between H and PI, the statistics indicate that the poorer quality material yields higher PI values. This must, however, be considered in light of the fact that, for all the roads studied, the surfacing was placed with almost no gradation control and the surfacing was almost always lacking in fines. Therefore, when the material had a high H value, the cinders tended to break down under watering and traffic to produce the needed fines. Thus, there was a strong correlation between H value and PI. The recommendations in this report are to control the gradation before placing the material; consequently, the desirability of having a high H value is no longer valid. There was a negative correlation between the Los Angeles abrasion and PI; therefore, a specification for Los Angeles abrasion is recommended. If a similar study were performed on roads where cinders were applied under a controlled gradation specification, it is felt by the authors that the Los Angeles abrasion test would show a much stronger negative correlation. For this reason, and because of the obvious need to specify a material that will tend to hold its gradation, the Los Angeles abrasion test is recommended. The maximum allowable limit was based on the mean and the standard deviation of the test results.

It is believed that the specifications recommended are reasonable, based on test results of typical cinders in central Oregon and the proven, accepted practice for aggregate surfacing control. The typical specifications when inserted into the regression equation yield a performance index over 5.0, which is an indication that the criteria are consistent with the test results.

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