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# ABSTRACT

This study evaluated the Troxler Model 4730 infrared ignition furnace as compared to a standard Thermolyne ignition furnace. Comparisons were based on correction factor for aggregate loss during ignition, accuracy and variability of the measured asphalt content and aggregate degradation during ignition. Forty-eight samples, representing two nominal maximum aggregate sizes (9.5 and 19.0 mm), four aggregate types (granite, crushed gravel, limestone and dolomite) and two asphalt contents (optimum and optimum plus 0.5 percent asphalt content) were tested in each furnace.

The results indicated that the correction factors for aggregate loss during ignition were significantly different for each type of furnace, thus requiring a separate calibration for each type of furnace. Practically, the differences for all but the 9.5 mm NMAS limestone and both dolomite mixtures are less than 0.1 percent. The samples at optimum plus 0.5 percent asphalt content were tested using the calibration factors developed for a particular mix/furnace combination. The results were analyzed in terms of accuracy (bias) and variability (standard deviation). Neither the measured bias' nor standard deviations for the two types of furnaces were significantly different. Results from four sieve sizes (NMAS, 4.75, 2.36 and 0.075 mm) were evaluated for aggregate breakdown. A comparison of the recovered aggregate gradations from both furnaces indicated no significant difference in the degree of aggregate degradation during the ignition test. Therefore, based on the comparison of a single unit each of the standard and infrared furnaces, properly calibrated, they both should produce statistically similar asphalt contents and recovered aggregate gradations.

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## INTRODUCTION

The asphalt content of hot-mix asphalt (HMA) mixtures is critical to their performance, affecting the pavement's tendency for permanent deformation, fatigue life and susceptibility to moisture damage. Historically, the asphalt content of HMA samples was obtained using solvent extraction. However, due to environmental concerns, alternative methods to determine asphalt content were investigated in the 1990s.

The asphalt ignition test was developed at the National Center for Asphalt Technology (NCAT) for determining the asphalt content ($P_b$) in HMA mixtures (*1,2*). Asphalt content is calculated as the ratio of the difference between the initial mass of the HMA and the mass of the residual aggregate (after ignition) to the initial mass of the sample expressed as a percentage. The ignition test provides a clean aggregate sample, which can be used for gradation analysis. Several models of convection asphalt ignition ovens are in use and have given satisfactory results. Recently, Troxler has developed a new ignition oven (Model 4730), which uses an infrared heating element.

In a conventional ignition furnace, the furnace chamber is heated using a radiant heat source consisting of an electric heating element encased in a refractory ceramic material (*3*). These elements typically make up the walls of the ignition furnace. The heating elements heat the air in the furnace chamber, which in-turn heats the sample. This is known as convection heating. The asphalt binder ignites when the sample reaches a temperature of approximately 480˚C (896˚F). In order to maintain ignition, a blower pulls air into the sample chamber. The exhaust gases pass out of the main chamber into a secondary chamber, generally at a higher temperature (750˚C [1382˚F]), where additional oxidation occurs. This helps to reduce volatiles in the exhaust stream as required by AASHTO T308 and ASTM D6307.

The Troxler Model 4730 ignition furnace uses an infrared heating element to heat the sample. Infrared light (or radiation) is found between the visible light and microwave portions of the electromagnetic spectrum (*4*). Infrared heat is used in numerous other industries such as food preparation. Unlike convection heating, where the air in the sample chamber must first be heated, infrared heating uses electromagnetic energy waves to excite the molecules in the sample producing heat (*5*). However, the sample then heats the furnace chamber by conduction/convection. The Troxler Model 4730 furnace does not incorporate an after burner system. However, Troxler reports reduced emissions compared to the standard furnace.

## OBJECTIVE

The primary objective of this study is to determine if the infrared furnace measures asphalt content of HMA mixtures as accurately as a standard ignition furnace. The secondary objective is to compare the degradation of aggregate produced in the infrared and standard ignition furnaces.

## SCOPE

This project consisted of comparisons of the measured asphalt content and gradation determined from laboratory prepared HMA samples using the infrared and standard ignition furnaces. A Troxler Model 4730 infrared furnace and a Thermolyne Model F85930 "standard" furnace were used in the study. Forty-eight samples, representing two nominal maximum aggregate sizes (9.5

and 19.0 mm [3/8 and ¾ in]), four aggregate types (granite, crushed gravel, limestone and dolomite) and two asphalt contents (optimum and optimum plus 0.5 $P_b$) were tested in each furnace. The samples were batched and mixed at known asphalt contents using a single binder source.

## MATERIALS

Four aggregate types were used in the study: granite, crushed gravel, limestone and dolomite. The aggregates were selected to provide a range of commonly available materials and potential for aggregate loss during ignition. Some dolomites, in particular, have experienced excessive aggregate loss in the ignition furnace. Gradations meeting the requirements of the two nominal maximum aggregate sizes (Superpave definition) were prepared for each aggregate type. For each NMAS, the same gradation was targeted for all four aggregates. The target gradations are shown in Table 1. When blending test samples, the specified aggregate type was used for all of the sieve sizes except for the material passing the 0.075 mm sieve (No. 200). Aggregate from each source was first fractionated into each sieve size and then recombined to meet the gradation in Table 1. Marble dust was used to provide the material passing the 0.075 mm (No. 200) sieve in both the 19.0 mm (3/4 in) and 9.5 mm (3/8 in) NMAS mix gradations, with 4.0 and 7.5 percent being added, respectively. Unfortunately, the actual percent passing the 0.075 mm (No. 200) sieve varied for the dolomite and limestone mixes due to adherent fines on the coarse aggregate (fines that stuck to the coarse aggregate when it was fractionated). Table 2 shows the resulting gradation from batches of the 9.5 mm (3/8 in) and 19.0 mm (3/4 in) NMAS dolomite and limestone mixes without any material passing the 0.075 mm sieve (No. 200) being added to the batch. The material passing the 0.075 mm (No. 200) sieve shown in Table 2 results solely from adherent fines. Adding the 4.0 percent minus 0.075 mm (No. 200) material to the 19.0 mm NMAS mixes would result in total dust contents of 11.7 and 8.0 percent, respectively for the dolomite and limestone mixtures. Adding the 7.5 percent minus 0.075 mm (No. 200) material to the 9.5 mm NMAS mixes would result in total dust contents of 18.0 and 12.6 percent, respectively for the dolomite and limestone mixtures. Unfortunately, the amounts of adherent fines were not discovered until after the samples were prepared for ignition testing.

**Table 1. Design Gradations**

| **Sieve Size, mm (in)** | **Blend Percent Passing** | |
|---|---|---|
| | 9.5 mm NMAS | 19.0 mm NMAS |
| 25.0 (1.0) | 100 | 100 |
| 19.0 (3/4) | 100 | 95 |
| 12.5 (1/2) | 100 | 80 |
| 9.5 (3/8) | 95 | 68 |
| 4.75 (No. 4) | 74 | 45 |
| 2.36 (No. 8) | 56 | 29 |
| 1.18 (No. 16) | 42 | 19 |
| 0.600 (No. 30) | 30 | 14 |
| 0.300 (No. 50) | 20 | 11 |
| 0.150 (No. 100) | 12 | 9 |
| 0.075 (No. 200) | 7.5 | 4.0 |

**Table 2. Washed Gradation to Determine Adherent Fines**

| Sieve Size, mm (in) | Blend Percent Passing | | | |
|---|---|---|---|---|
| | 9.5 mm NMAS | | 19.0 mm NMAS | |
| **Aggregate** | **Dolomite** | **Limestone** | **Dolomite** | **Limestone** |
| 25.0 (1.0) | 100 | 100 | 100 | 100 |
| 19.0 (3/4) | 100 | 100 | 93 | 95 |
| 12.5 (1/2) | 100 | 100 | 80 | 81 |
| 9.5 (3/8) | 96 | 95 | 69 | 69 |
| 4.75 (No. 4) | 72 | 75 | 47 | 45 |
| 2.36 (No. 8) | 54 | 54 | 30 | 28 |
| 1.18 (No. 16) | 40 | 39 | 19 | 17 |
| 0.600 (No. 30) | 29 | 27 | 15 | 12 |
| 0.300 (No. 50) | 21 | 17 | 13 | 9 |
| 0.150 (No. 100) | 15 | 10 | 11 | 8 |
| 0.075 (No. 200) | 10.5 | 5.1 | 7.6 | 3.9 |

The optimum asphalt content was determined for each mix (NMAS and aggregate type) by compacting samples to 100 gyrations with the Superpave gyratory compactor according to AASHTO PP28-01 and selecting the asphalt content that produced 4 percent air voids. The optimum asphalt contents are reported in Table 3. Three samples were prepared at the optimum asphalt content for each mixture and three samples at optimum asphalt content plus 0.5 percent.

**Table 3. Optimum Asphalt Contents by Mix Type**

| Aggregate Type | Optimum Asphalt Content | |
|---|---|---|
| | **9.5 mm NMAS** | **19.0 mm NMAS** |
| Granite | 5.3 | 4.2 |
| Crushed Gravel | 4.7 | 4.2 |
| Limestone | 3.7 | 3.7 |
| Dolomite | 4.5 | 3.8 |

The aggregate mass of the samples batched for ignition testing was 2000 and 4500 grams for the 9.5 mm and 19.0 mm NMAS mixes, respectively. Asphalt was mixed with each hot mix sample to produce the respective optimum and optimum plus asphalt contents. The resulting hot mix samples were tested according to AASHTO T308. Samples were tested in the Troxler furnace using the default burn profile. The Troxler infrared furnace also has an “aggressive” burn profile for high asphalt mixtures, such as stone matrix asphalt, produced with aggregates that do not readily degrade during ignition and a less aggressive profile for mixtures produced with aggregates that degrade during ignition (such as some dolomites). The three samples prepared at optimum asphalt content were used to determine the correction factor ($C_f$) for aggregate loss during ignition. The experimental design is shown in Table 4.

**Table 4. Experimental Design**

| Furnace Type | Granite | | | | Crushed Gravel | | | | Limestone | | | | Dolomite | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9.5 mm NMAS | | 19.0 mm NMAS | | 9.5 mm NMAS | | 19.0 mm NMAS | | 9.5 mm NMAS | | 19.0 mm NMAS | | 9.5 mm NMAS | | 19.0 mm NMAS | |
| | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% | Opt. $P_b$ | Opt. $P_b$ + 0.5% |
| Infrared | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| Standard | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x |

## RESULTS AND DISCUSSION

### Calibration Factor for Aggregate Loss

Correction factors for aggregate loss ($C_f$) were determined for each mixture/furnace combination. The correction factor for each mixture was determined by burning three samples at optimum asphalt content and averaging the difference between the total loss and the known asphalt content. The results are summarized in Table 5 and the complete results are shown in Appendix A, Tables A1 and A2. Generally, it appears that the correction factor was slightly smaller for the infrared furnace as compared to the standard furnace. This does not match the findings of Williams and Hall (*6*) for Arkansas aggregates. However, they used the most aggressive burn profile (Option 2) for the Infrared furnace. Troxler recommends the default burn profile for most materials (*7*).

**Table 5. Correction Factors for Aggregate Loss**

| Mixture | Aggregate Correction Factor, % | |
|---|---|---|
| | **Standard Furnace** | **Infrared Furnace** |
| 9.5 mm NMAS Granite | 0.07 | 0.01 |
| 9.5 mm NMAS Crushed Gravel | 0.11 | 0.03 |
| 9.5 mm NMAS Limestone | 0.24 | 0.14 |
| 9.5 mm NMAS Dolomite | 0.66 | 0.51 |
| 19.0 mm NMAS Granite | -0.03 | -0.13 |
| 19.0 mm NMAS Crushed Gravel | -0.02 | 0.04 |
| 19.0 mm NMAS Limestone | 0.19 | 0.16 |
| 19.0 mm NMAS Dolomite | 0.55 | 0.40 |

The option 1 burn profile is less aggressive and is designed for soft aggregates. The option 2 burn profile is more aggressive. It is designed for mixes for which a clean burn might otherwise not be obtained, such as some Superpave mixes and many base (large aggregate/samples size) mixes. Troxler does not define what parameter(s) (air flow or temperature) are changed by the setting.

Analysis of Variance (ANOVA) was performed to statistically analyze the difference in correction factors. ANOVA is used to determine the factors that significantly affect a given response. The aggregate correction factor was used as the response variable; furnace type (two levels), aggregate type (four levels) and NMAS (two levels) were the effects (factors). AASHTO T308 specifies averaging the difference between the measured and optimum asphalt content from two samples to determine the correction factors. Thus, to have true replicates for the ANOVA, at least four samples would have needed to be tested. However, using the individual samples as replicates is still indicative of whether the correction factors are different for the two furnaces. The differences in optimum asphalt content were accounted for by using aggregate type and NMAS as factors. The analysis was conducted with Minitab statistical software using the balanced model (8). The results of the analysis are shown in Table 6. Furnace type, aggregate type and NMAS are all significant factors. The significance of both aggregate type and NMAS were expected since different aggregates are known to have different correction factors and NMAS accounts for the difference in optimum asphalt content within aggregate type. However, the analysis also indicated a significant difference between the correction factors determined by the two types of furnaces. Practically, the differences for all but the 9.5 mm NMAS limestone and both dolomite mixtures are less than 0.1 percent. None of the interactions were significant. This indicates that if a contractor and agency were using different brands of furnaces, a separate correction factor should be determined for each brand. Since only one unit of each brand was evaluated in this study, it is impossible to tell if the correction factor could be shared within a brand of ignition furnace.

**Table 6. Analysis of Variance on Aggregate Correction Factor Versus Furnace Type, Aggregate Type and NMAS**

| Factor | Degrees of Freedom | $F$-Statistic | P-Value | Significance[1] |
|---|---|---|---|---|
| Furnace Type | 1 | 9.83 | 0.004 | Yes |
| Aggregate Type | 3 | 92.06 | 0.000 | Yes |
| NMAS | 1 | 8.84 | 0.006 | Yes |
| Furnace * Aggregate | 3 | 1.19 | 0.330 | No |
| Furnace * NMAS | 1 | 0.92 | 0.345 | No |
| Aggregate * NMAS | 3 | 0.87 | 0.466 | No |
| Furnace * Aggregate * NMAS | 3 | 0.66 | 0.582 | No |
| Error | 32 | | | |
| Total | 47 | | | |

[1] Significant at the 5 percent significance level

**Accuracy and Variability of Measured Asphalt Contents**

The aggregate correction factors, determined at optimum asphalt content, were then used to evaluate the accuracy and repeatability of the measured asphalt contents for the two furnaces. Six samples of each mix were prepared at optimum plus 0.5 percent asphalt. Three samples were tested in each furnace using the correction factors determined at optimum asphalt content. The results are summarized in Table 7.

When evaluating a new piece of equipment, both the accuracy and the variability of the measurements made with the device must be considered. The accuracy of the asphalt contents is measured by the bias, or difference between the measured and true asphalt content of the samples. Variability is measured by the standard deviation (square-root of variance) of the test

**Table 7. Summary of Measured Asphalt Contents, Bias and Standard Deviations by Furnace**

| Aggregate | NMAS | Actual PB | Measured $P_b$ 1 | Measured $P_b$ 2 | Measured $P_b$ 3 | Bias (Measured - Actual) 1 | Bias (Measured - Actual) 2 | Bias (Measured - Actual) 3 | Avg. Bias | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|---|
| Standard Furnace | | | | | | | | | | |
| Dolomite | 9.5 | 5.0 | 5.05 | 4.51 | 5.07 | 0.05 | -0.49 | 0.07 | -0.12 | 0.3177 |
| Dolomite | 19 | 4.3 | 4.24 | 4.22 | 4.24 | -0.06 | -0.08 | -0.06 | -0.07 | 0.0115 |
| Granite | 9.5 | 5.8 | 5.84 | 5.75 | 5.74 | 0.04 | -0.05 | -0.06 | -0.02 | 0.0551 |
| Granite | 19 | 4.7 | 4.78 | 4.77 | 4.73 | 0.08 | 0.07 | 0.03 | 0.06 | 0.0265 |
| Gravel | 9.5 | 5.2 | 5.14 | 5.15 | 5.22 | -0.06 | -0.05 | 0.02 | -0.03 | 0.0436 |
| Gravel | 19 | 4.7 | 4.76 | 4.81 | 4.70 | 0.06 | 0.11 | 0.00 | 0.06 | 0.0551 |
| Limestone | 9.5 | 4.2 | 4.17 | 4.09 | 4.17 | -0.03 | -0.11 | -0.03 | -0.06 | 0.0462 |
| Limestone | 19 | 4.2 | 4.15 | 4.21 | 4.09 | -0.05 | 0.01 | -0.11 | -0.05 | 0.0600 |
| | | | | | | | | Avg. | -0.0292 | 0.0770 |
| Infrared Furnace | | | | | | | | | | |
| Dolomite | 9.5 | 5.0 | 4.98 | 4.95 | 4.97 | -0.02 | -0.05 | -0.03 | -0.03 | 0.0153 |
| Dolomite | 19 | 4.3 | 4.29 | 4.30 | 4.27 | -0.01 | 0.00 | -0.03 | -0.01 | 0.0153 |
| Granite | 9.5 | 5.8 | 5.78 | 5.77 | 5.70 | -0.02 | -0.03 | -0.10 | -0.05 | 0.0436 |
| Granite | 19 | 4.7 | 4.77 | 4.83 | 4.72 | 0.07 | 0.13 | 0.02 | 0.07 | 0.0551 |
| Gravel | 9.5 | 5.2 | 5.19 | 5.22 | 4.93 | -0.01 | 0.02 | -0.27 | -0.08 | 0.1595 |
| Gravel | 19 | 4.7 | 4.68 | 4.70 | 4.50 | -0.02 | 0.00 | -0.20 | -0.07 | 0.1102 |
| Limestone | 9.5 | 4.2 | 4.06 | 4.15 | 4.14 | -0.14 | -0.05 | -0.06 | -0.08 | 0.0493 |
| Limestone | 19 | 4.2 | 4.02 | 4.16 | 4.02 | -0.18 | -0.04 | -0.18 | -0.13 | 0.0808 |
| | | | | | | | | Avg. | -0.0479 | 0.0661 |

results. The standard deviation determined from a single furnace is not sufficient to determine the within-lab variability or repeatability of the device.

The average bias (-0.0479) for the infrared furnace was greater than the average bias for the standard furnace (-0.0292). To further evaluate the differences in the biases between the two furnaces, an ANOVA was performed using bias as the response variable; furnace type (2 levels), aggregate type (4 levels) and NMAS (2 levels) were the effects. The results are shown in Table 8. The analysis indicates that furnace type, aggregate type, NMAS and the interactions are not significant factors. This means that for a properly calibrated furnace, neither the type (or brand) of furnace, the aggregate type or the NMAS of the mixture affects the accuracy of the results. The pooled standard deviation for the infrared furnace (0.066) is slightly less than the pooled standard deviation for the standard furnace (0.077). To further compare the variability of the measurements from the two furnaces, an $F$-test was performed to compare the variances of the two furnaces. To normalize the results for the different asphalt contents of the mixtures, the $F$-test was performed on the bias between measured and actual asphalt content. The critical $F$-value is 2.02. and the calculated $F$-value was 1.69; thus, at the 5 percent significance level, the variances produced by the standard and infrared furnaces are equal with a P-value of 0.216. The three highlighted cells in Table 6 exceed the 95 percent confidence limit for the bias values. Though these readings have a significant effect on the average bias and pooled standard deviations, with 48 test samples, that number of outliers is expected.

**Table 8. Analysis of Variance on Bias of Asphalt Content Measurements Versus Furnace Type, Aggregate Type and NMAS**

| Factor | Degrees of Freedom | $F$-Statistic | P-Value | Significance[1] |
|---|---|---|---|---|
| Furnace Type | 1 | 0.50 | 0.486 | Yes |
| Aggregate Type | 3 | 1.95 | 0.141 | Yes |
| NMAS | 1 | 2.07 | 0.160 | Yes |
| Furnace * Aggregate | 3 | 1.19 | 0.246 | No |
| Furnace * NMAS | 1 | 0.29 | 0.596 | No |
| Aggregate * NMAS | 3 | 0.75 | 0.528 | No |
| Furnace * Aggregate * NMAS | 3 | 0.18 | 0.909 | No |
| Error | 32 | | | |
| Total | 47 | | | |

[1] Significant at the 5 percent significance level

## Measured Gradation

The aggregate from each source was fractionated and then recombined to meet the target gradations shown in Table 1. Thus, all of the gradations for both the 9.5 mm and 19.0 mm mixes should be the same. The complete gradation results for both the calibration and the optimum plus 0.5 percent asphalt samples are shown in the Appendix, Tables A1 to A4. Unfortunately, due to the presence of adherent fines (Table 2), the gradations were not identical for each mix of a given NMAS. Critical sieves for control of HMA tend to be near the NMAS, the 4.75 mm (No. 4) or the 2.36 mm (No. 8) sieves and the 0.075 mm (No. 200 sieve). The average percent passing for the critical sieves for each NMAS/aggregate combination are shown in Figures 1 and 2 for the 9.5 mm (3/8 in) and 19.0 mm (3/4 in) NMAS, respectively. The error bars shown in the graphs represent the range of observations (minimum and maximum). The variability in the

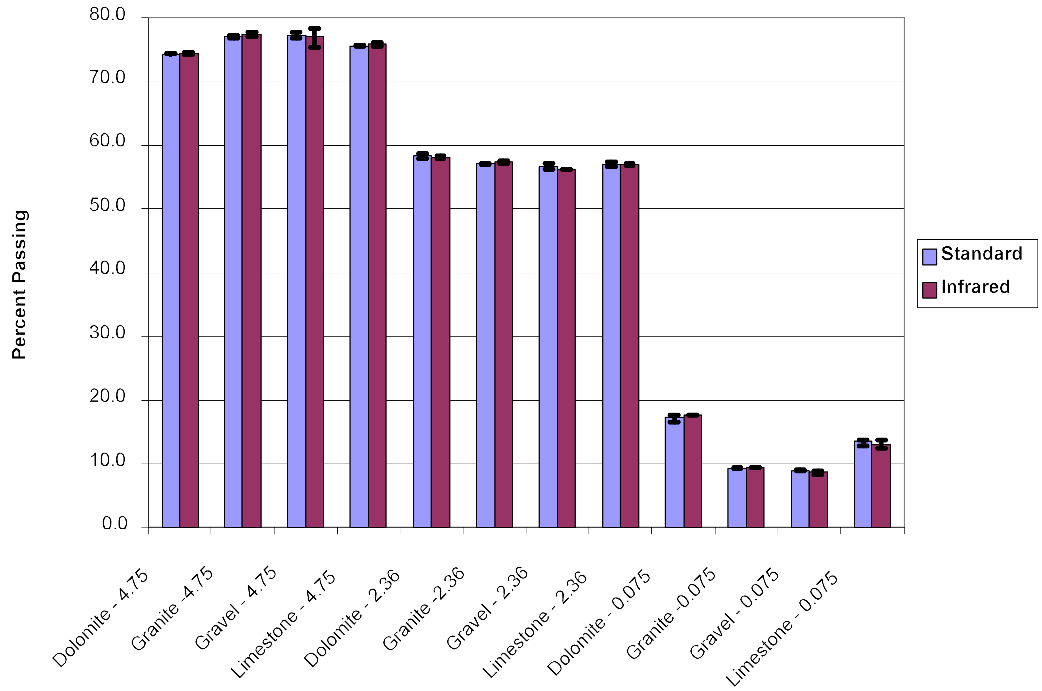


**Figure 1. Summary of Recovered Gradations for 9.5 mm NMAS Mixes**

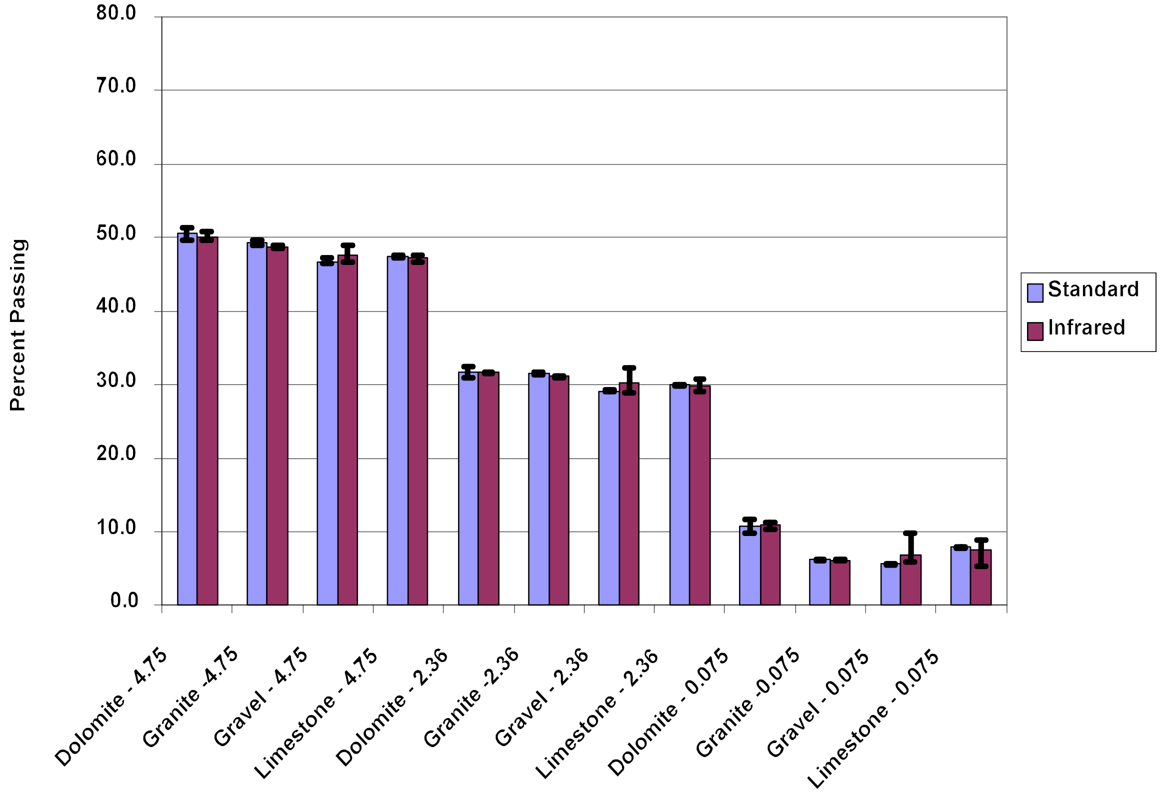


**Figure 2. Summary of Recovered Gradations for 19.0 mm NMAS Mixes**

gradations of the 19.0 mm (3/4 in) NMAS mixes (Figure 2) appears to be larger than the variability of the 9.5 mm (3/8 in) NMAS mixes (Figure 1). Overall, the data indicates consistent sample production (except for the adherent fines) and little effect of recovery using either type of ignition furnace.

ANOVA was used to statistically evaluate whether one furnace produced consistently more or less breakdown of the aggregate. In addition to furnace type, aggregate type and NMAS were used as factors for the response of the percent passing a given sieve size. Though aggregate breakdown is generally believed to be independent of asphalt content, any effect of asphalt content on the measured gradation would have been accounted for by aggregate type and NMAS. The ANOVA results for both NMAS are shown in Table 9. For Table 9, NMAS was eliminated as a factor, since the analysis was run separately for each NMAS. The results in Table 9 indicate that aggregate type significantly affects the measured percent passing the NMAS. This appears to result from adherent fines, particularly for the limestone and dolomite aggregate types, producing consistently finer gradations. Furnace type was not a significant factor. This indicates that neither furnace type produced significantly more or less aggregate breakdown at the NMAS.

**Table 9. ANOVA of Percent Passing Nominal Maximum Aggregate Size**

| Source | DF | 19.0 mm | | | 9.5 mm | | |
|---|---|---|---|---|---|---|---|
| | | *F*-Stat | P-Value | Sig.[1] | *F*-Stat | P-Value | Sig.[1] |
| Aggregate | 3 | 3.99 | 0.01 | Y | 22.61 | 0.00 | Y |
| Furnace | 1 | 0.15 | 0.70 | N | 0.40 | 0.53 | N |
| Agg.*Furnace | 1 | 1.82 | 0.16 | N | 0.27 | 0.85 | N |
| Error | 40 | | | | | | |
| Total | 47 | | | | | | |

[1] Significant at the 5 percent significance level

The ANOVA results for the 4.75 mm, 2.36 mm and 0.075 mm sieves are shown in Table 10. Nominal maximum aggregate size produces the largest *F*-statistic, as expected, since different design gradations were targeted for each NMAS.

Aggregate type and the interaction between NMAS and aggregate type are both significant due to the effect of adherent fines. Furnace type is not a significant factor for any of the key sieve sizes. This indicates that for the aggregates tested, furnace type does not significantly affect aggregate breakdown and the resulting gradation of the recovered aggregate.

**Table 10. ANOVA of Percent Passing Key Sieves**

| Source | DF | 4.75 mm | | | 2.36 mm | | | 0.075 mm | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *F*-Stat | P-Value | Sig.[1] | *F*-Stat | P-Value | Sig.[1] | *F*-Stat | P-Value | Sig.[1] |
| Aggregate | 3 | 33.33 | 0.00 | Y | 88.25 | 0.00 | Y | 545.4 | 0.00 | Y |
| NMAS | 1 | 55000 | 0.00 | Y | 65000 | 0.00 | Y | 1057.7 | 0.00 | Y |
| Furnace | 1 | 0.00 | 0.99 | N | 0.08 | 0.78 | N | 1.66 | 0.202 | N |
| Agg. * NMAS | 3 | 136.89 | 0.00 | Y | 6.94 | 0.00 | Y | 41.12 | 0.00 | Y |
| NMAS * Furnace | 3 | 0.07 | 0.98 | N | 0.51 | 0.68 | N | 1.31 | 0.28 | N |
| Agg. * Furnace | 1 | 0.05 | 0.82 | N | 0.92 | 0.34 | N | 1.50 | 0.22 | N |
| Agg. * NMAS * Furnace | 3 | 0.52 | 0.67 | N | 0.74 | 0.53 | N | 0.93 | 0.43 | N |
| Error | 80 | | | | | | | | | |
| Total | 95 | | | | | | | | | |

[1] Significant at the 5 percent significance level

## CONCLUSIONS

The infrared furnace produced similar results as compared to the standard furnace when evaluated for correction factor due to aggregate loss, accuracy and variability of asphalt content determinations and aggregate degradation.

As expected, each mix produced a unique correction factor for aggregate loss. The correction factors for aggregate loss were not significantly different for the two types of furnaces. However, the correction factors for the infrared furnace were generally smaller than those for the standard furnace.

Examination of the bias, or difference between the measured and actual asphalt contents of laboratory prepared samples, evaluated the accuracy of the two types of furnaces. The biases for the infrared and standard furnaces were not significantly different. However, the bias for the standard furnace was generally smaller. Mix type was not a significant factor in the calculated biases for either furnace. This indicates that both furnaces, properly calibrated, can produce similarly accurate results regardless of the mix tested.

The standard deviation of the biases for each mix/furnace combination was used to evaluate the variability of the results. The variabilities of the infrared and standard furnace were not statistically different. However, variability of the infrared furnace's results was slightly less than the standard furnace's results. The variability data is insufficient to compare the precision statements of the two types of furnaces.

A comparison of the recovered aggregate gradations from both furnaces indicated no significant difference in the degree of aggregate degradation during the ignition test. The comparison was performed on the NMAS, 4.75 mm, 2.36 mm and 0.075 mm sieves.

## RECOMMENDATIONS

A round robin should be conducted to confirm that the precision of the infrared furnace is similar to the precision of the standard furnace.

## ACKNOWLEDGMENTS

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# Appendix A

**Table A1. Standard Furnace Calibration Results**

| Aggregate | NMAS | Actual $P_b$, % | Loss, % | Correction Factor, % | Percent Passing Standard Sieve Size, mm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 25.0 | 19.0 | 12.5 | 9.5 | 4.75 | 2.36 | 1.18 | 0.600 | 0.300 | 0.150 | 0.075 |
| Dolomite | 9.5 | 4.5 | 5.23 | 0.73 | 100.0 | 100.0 | 100.0 | 96.5 | 74.2 | 58.1 | 45.4 | 34.9 | 28.1 | 23.0 | 17.6 |
| Dolomite | 9.5 | 4.5 | 5.07 | 0.57 | 100.0 | 100.0 | 100.0 | 96.0 | 74.4 | 58.2 | 45.2 | 35.2 | 28.3 | 23.2 | 17.9 |
| Dolomite | 9.5 | 4.5 | 5.19 | 0.69 | 100.0 | 100.0 | 100.0 | 96.3 | 74.6 | 58.1 | 45.2 | 34.8 | 28.0 | 22.7 | 17.4 |
| Granite | 9.5 | 5.3 | 5.45 | 0.15 | 100.0 | 100.0 | 100.0 | 96.6 | 77.6 | 57.0 | 43.5 | 31.3 | 21.8 | 14.0 | 9.2 |
| Granite | 9.5 | 5.3 | 5.27 | -0.03 | 100.0 | 100.0 | 100.0 | 96.9 | 76.8 | 57.0 | 43.5 | 31.3 | 21.8 | 13.9 | 9.2 |
| Granite | 9.5 | 5.3 | 5.39 | 0.09 | 100.0 | 100.0 | 100.0 | 97.9 | 77.2 | 57.5 | 44.1 | 31.9 | 22.2 | 14.3 | 9.5 |
| Gravel | 9.5 | 4.7 | 4.88 | 0.18 | 100.0 | 100.0 | 100.0 | 96.6 | 77.0 | 56.2 | 44.1 | 32.7 | 21.5 | 13.0 | 9.0 |
| Gravel | 9.5 | 4.7 | 4.84 | 0.14 | 100.0 | 100.0 | 100.0 | 97.0 | 77.2 | 56.4 | 43.9 | 33.0 | 22.1 | 13.9 | 10.0 |
| Gravel | 9.5 | 4.7 | 4.72 | 0.02 | 100.0 | 100.0 | 100.0 | 97.6 | 77.6 | 56.6 | 44.3 | 33.2 | 21.8 | 13.0 | 9.0 |
| Limestone | 9.5 | 3.7 | 4.02 | 0.32 | 100.0 | 100.0 | 100.0 | 96.3 | 75.7 | 57.2 | 43.4 | 32.2 | 24.6 | 18.4 | 13.4 |
| Limestone | 9.5 | 3.7 | 3.92 | 0.22 | 100.0 | 100.0 | 100.0 | 96.8 | 75.7 | 57.0 | 43.5 | 32.2 | 24.5 | 18.4 | 13.7 |
| Limestone | 9.5 | 3.7 | 3.89 | 0.19 | 100.0 | 100.0 | 100.0 | 96.4 | 75.8 | 57.3 | 43.6 | 32.1 | 24.3 | 17.9 | 13.2 |
| Dolomite | 19 | 3.8 | 4.46 | 0.66 | 100.0 | 95.0 | 88.5 | 70.7 | 50.8 | 31.2 | 22.1 | 18.0 | 15.7 | 14.2 | 10.2 |
| Dolomite | 19 | 3.8 | 4.33 | 0.53 | 100.0 | 95.5 | 81.7 | 70.1 | 49.8 | 30.8 | 21.2 | 16.8 | 14.5 | 13.0 | 9.2 |
| Dolomite | 19 | 3.8 | 4.25 | 0.45 | 100.0 | 96.4 | 82.3 | 71.4 | 50.1 | 32.0 | 22.5 | 18.3 | 16.3 | 14.9 | 10.8 |
| Granite | 19 | 4.2 | 4.15 | -0.05 | 100.0 | 95.0 | 85.4 | 73.9 | 46.1 | 28.9 | 20.5 | 15.1 | 11.4 | 9.2 | 5.4 |
| Granite | 19 | 4.2 | 4.17 | -0.03 | 100.0 | 95.0 | 84.5 | 73.9 | 46.5 | 29.4 | 21.2 | 15.7 | 11.9 | 9.7 | 5.9 |
| Granite | 19 | 4.2 | 4.2 | 0 | 100.0 | 95.6 | 83.7 | 73.3 | 49.0 | 31.0 | 21.7 | 15.4 | 13.1 | 10.6 | 6.3 |
| Gravel | 19 | 4.2 | 4.21 | 0.01 | 100.0 | 95.0 | 85.4 | 73.9 | 46.1 | 28.9 | 20.5 | 15.1 | 11.4 | 9.2 | 5.4 |
| Gravel | 19 | 4.2 | 4.22 | 0.02 | 100.0 | 95.0 | 84.5 | 73.9 | 46.5 | 29.4 | 21.2 | 15.7 | 11.9 | 9.7 | 5.9 |
| Gravel | 19 | 4.2 | 4.11 | -0.09 | 100.0 | 95.5 | 83.6 | 73.0 | 47.2 | 29.4 | 21.2 | 15.7 | 12.0 | 9.8 | 6.0 |
| Limestone | 19 | 3.7 | 3.94 | 0.24 | 100.0 | 95.0 | 81.5 | 69.9 | 47.3 | 29.9 | 20.2 | 15.7 | 13.4 | 11.7 | 8.2 |
| Limestone | 19 | 3.7 | 3.71 | 0.01 | 100.0 | 94.9 | 81.3 | 70.7 | 46.9 | 29.7 | 20.3 | 15.9 | 13.5 | 11.9 | 8.3 |
| Limestone | 19 | 3.7 | 4.01 | 0.31 | 100.0 | 94.4 | 82.1 | 70.0 | 47.0 | 30.3 | 20.6 | 16.1 | 13.6 | 11.8 | 8.3 |

**Table A2. Infrared Furnace Calibration Results**

| Aggregate | NMAS | Actual $P_b$, % | Loss, % | Correction Factor, % | Percent Passing Standard Sieve Size, mm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 25.0 | 19.0 | 12.5 | 9.5 | 4.75 | 2.36 | 1.18 | 0.600 | 0.300 | 0.150 | 0.075 |
| Dolomite | 9.5 | 4.5 | 4.92 | 0.42 | 100.0 | 100.0 | 100.0 | 96.5 | 74.4 | 58.0 | 45.1 | 35.0 | 28.4 | 23.0 | 17.9 |
| Dolomite | 9.5 | 4.5 | 5.09 | 0.59 | 100.0 | 100.0 | 100.0 | 96.0 | 74.2 | 58.0 | 44.6 | 34.2 | 27.3 | 21.9 | 16.4 |
| Dolomite | 9.5 | 4.5 | 5.01 | 0.51 | 100.0 | 100.0 | 100.0 | 96.3 | 74.4 | 58.5 | 45.1 | 34.7 | 27.9 | 22.8 | 17.3 |
| Granite | 9.5 | 5.3 | 5.28 | -0.02 | 100.0 | 100.0 | 100.0 | 97.9 | 76.7 | 57.0 | 43.5 | 31.2 | 21.5 | 13.8 | 9.1 |
| Granite | 9.5 | 5.3 | 5.29 | -0.01 | 100.0 | 100.0 | 100.0 | 97.2 | 76.5 | 57.2 | 43.8 | 31.6 | 21.9 | 14.2 | 9.4 |
| Granite | 9.5 | 5.3 | 5.35 | 0.05 | 100.0 | 100.0 | 100.0 | 96.1 | 76.6 | 57.3 | 44.0 | 31.8 | 22.1 | 14.3 | 9.4 |
| Gravel | 9.5 | 4.7 | 4.72 | 0.02 | 100.0 | 100.0 | 100.0 | 97.6 | 76.8 | 56.4 | 43.9 | 32.9 | 21.5 | 12.8 | 8.8 |
| Gravel | 9.5 | 4.7 | 4.72 | 0.02 | 100.0 | 100.0 | 100.0 | 97.3 | 77.2 | 56.3 | 44.0 | 32.5 | 21.3 | 12.9 | 8.8 |
| Gravel | 9.5 | 4.7 | 4.72 | 0.02 | 100.0 | 100.0 | 100.0 | 97.3 | 77.2 | 56.2 | 43.3 | 32.6 | 21.4 | 13.1 | 9.2 |
| Limestone | 9.5 | 3.7 | 3.83 | 0.13 | 100.0 | 100.0 | 100.0 | 96.3 | 75.8 | 57.3 | 43.5 | 32.0 | 24.1 | 18.1 | 13.1 |
| Limestone | 9.5 | 3.7 | 3.78 | 0.08 | 100.0 | 100.0 | 100.0 | 96.3 | 75.7 | 56.9 | 43.2 | 31.8 | 24.0 | 18.0 | 13.2 |
| Limestone | 9.5 | 3.7 | 3.9 | 0.2 | 100.0 | 100.0 | 100.0 | 96.5 | 75.5 | 57.1 | 43.4 | 32.1 | 24.3 | 18.2 | 13.4 |
| Dolomite | 19 | 3.8 | 4.2 | 0.4 | 100.0 | 96.1 | 82.3 | 72.3 | 50.9 | 32.3 | 22.7 | 18.3 | 16.0 | 14.5 | 10.4 |
| Dolomite | 19 | 3.8 | 4.2 | 0.4 | 100.0 | 95.1 | 82.0 | 71.2 | 51.0 | 31.8 | 22.3 | 18.1 | 15.9 | 14.4 | 10.3 |
| Dolomite | 19 | 3.8 | 4.19 | 0.39 | 100.0 | 94.7 | 81.7 | 71.1 | 50.5 | 31.6 | 22.1 | 17.7 | 15.6 | 14.1 | 10.4 |
| Granite | 19 | 4.2 | 4.14 | -0.06 | 100.0 | 94.5 | 83.2 | 75.1 | 48.6 | 30.7 | 21.4 | 16.3 | 12.9 | 10.4 | 6.1 |
| Granite | 19 | 4.2 | 3.88 | -0.32 | 100.0 | 96.7 | 82.8 | 75.0 | 48.3 | 30.3 | 21.0 | 15.9 | 12.8 | 10.4 | 6.1 |
| Granite | 19 | 4.2 | 4.19 | -0.01 | 100.0 | 95.0 | 81.9 | 74.3 | 48.4 | 30.3 | 21.0 | 15.9 | 12.6 | 10.2 | 5.8 |
| Gravel | 19 | 4.2 | 4.31 | 0.11 | 100.0 | 95.0 | 84.1 | 72.6 | 46.4 | 29.4 | 21.0 | 15.9 | 11.9 | 9.7 | 6.2 |
| Gravel | 19 | 4.2 | 4.2 | 0 | 100.0 | 95.0 | 84.9 | 71.6 | 46.7 | 29.5 | 21.2 | 15.9 | 11.8 | 9.7 | 6.3 |
| Gravel | 19 | 4.2 | 4.2 | 0 | 100.0 | 95.0 | 84.9 | 71.9 | 46.7 | 29.4 | 20.8 | 16.1 | 11.9 | 9.7 | 6.2 |
| Limestone | 19 | 3.7 | 3.77 | 0.07 | 100.0 | 94.9 | 81.7 | 70.2 | 47.0 | 29.8 | 20.2 | 15.8 | 13.5 | 11.9 | 8.5 |
| Limestone | 19 | 3.7 | 4 | 0.3 | 100.0 | 95.9 | 81.8 | 70.9 | 48.3 | 31.2 | 21.5 | 16.7 | 14.2 | 12.4 | 8.7 |
| Limestone | 19 | 3.7 | 3.81 | 0.11 | 100.0 | 95.3 | 80.6 | 70.9 | 48.0 | 30.3 | 20.7 | 16.1 | 13.6 | 11.7 | 8.1 |

**Table A3. Standard Furnace Results for Optimum + 0.5 Percent Asphalt**

| Aggregate | NMAS | Actual $P_b$, % | Loss, % | Cor. Factor, % | Measured $P_b$, % | Difference, % | Percent Passing Standard Sieve Size, mm 25.0 | 19.0 | 12.5 | 9.5 | 4.75 | 2.36 | 1.18 | 0.600 | 0.300 | 0.150 | 0.075 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dolomite | 9.5 | 5 | 5.85 | 0.66 | 5.05 | 0.05 | 100.0 | 100.0 | 100.0 | 96.5 | 74.3 | 58.1 | 44.9 | 34.7 | 27.7 | 22.6 | 17.7 |
| Dolomite | 9.5 | 5 | 5.30 | 0.66 | 4.51 | -0.49 | 100.0 | 100.0 | 100.0 | 96.8 | 74.3 | 58.7 | 45.8 | 35.2 | 28.1 | 23.0 | 17.7 |
| Dolomite | 9.5 | 5 | 5.87 | 0.66 | 5.07 | 0.07 | 100.0 | 100.0 | 100.0 | 96.5 | 74.3 | 58.0 | 44.7 | 33.9 | 26.7 | 21.6 | 16.5 |
| Granite | 9.5 | 5.8 | 6.03 | 0.07 | 5.84 | 0.04 | 100.0 | 100.0 | 100.0 | 97.8 | 76.9 | 57.2 | 43.9 | 31.7 | 21.9 | 14.0 | 9.4 |
| Granite | 9.5 | 5.8 | 5.96 | 0.07 | 5.75 | -0.05 | 100.0 | 100.0 | 100.0 | 96.9 | 76.8 | 56.9 | 43.5 | 31.4 | 21.7 | 13.9 | 9.3 |
| Granite | 9.5 | 5.8 | 5.94 | 0.07 | 5.74 | -0.06 | 100.0 | 100.0 | 100.0 | 97.5 | 77.2 | 57.1 | 43.7 | 31.5 | 21.8 | 14.0 | 9.3 |
| Gravel | 9.5 | 5.2 | 5.39 | 0.11 | 5.14 | -0.06 | 100.0 | 100.0 | 100.0 | 97.2 | 76.8 | 56.2 | 43.4 | 32.6 | 21.3 | 12.8 | 8.8 |
| Gravel | 9.5 | 5.2 | 5.40 | 0.11 | 5.15 | -0.05 | 100.0 | 100.0 | 100.0 | 97.1 | 77.3 | 57.2 | 44.0 | 33.1 | 21.6 | 12.8 | 8.8 |
| Gravel | 9.5 | 5.2 | 5.48 | 0.11 | 5.22 | 0.02 | 100.0 | 100.0 | 100.0 | 97.3 | 77.8 | 56.7 | 44.0 | 32.9 | 21.7 | 13.1 | 9.0 |
| Limestone | 9.5 | 4.2 | 4.55 | 0.24 | 4.17 | -0.03 | 100.0 | 100.0 | 100.0 | 96.8 | 75.5 | 56.6 | 43.0 | 31.7 | 23.9 | 18.0 | 12.9 |
| Limestone | 9.5 | 4.2 | 4.47 | 0.24 | 4.09 | -0.11 | 100.0 | 100.0 | 100.0 | 96.6 | 75.6 | 57.3 | 43.7 | 32.5 | 24.9 | 19.2 | 13.8 |
| Limestone | 9.5 | 4.2 | 4.55 | 0.24 | 4.17 | -0.03 | 100.0 | 100.0 | 100.0 | 96.7 | 75.7 | 57.3 | 43.5 | 32.1 | 24.7 | 18.3 | 13.7 |
| Dolomite | 19 | 4.3 | 4.91 | 0.55 | 4.24 | -0.06 | 100.0 | 95.1 | 82.2 | 70.8 | 49.6 | 31.0 | 21.8 | 17.4 | 15.1 | 13.7 | 9.9 |
| Dolomite | 19 | 4.3 | 4.92 | 0.55 | 4.22 | -0.08 | 100.0 | 96.9 | 81.8 | 70.6 | 50.9 | 31.9 | 22.4 | 18.1 | 15.9 | 14.4 | 10.7 |
| Dolomite | 19 | 4.3 | 4.92 | 0.55 | 4.24 | -0.06 | 100.0 | 95.4 | 81.9 | 70.8 | 51.4 | 32.5 | 23.1 | 18.9 | 16.7 | 15.4 | 11.6 |
| Granite | 19 | 4.7 | 4.84 | -0.03 | 4.78 | 0.08 | 100.0 | 95.6 | 86.7 | 74.0 | 49.7 | 31.8 | 22.8 | 17.1 | 13.6 | 10.9 | 6.3 |
| Granite | 19 | 4.7 | 4.89 | -0.03 | 4.77 | 0.07 | 100.0 | 95.4 | 82.8 | 74.9 | 49.5 | 31.5 | 22.0 | 16.5 | 13.1 | 10.6 | 6.2 |
| Granite | 19 | 4.7 | 4.82 | -0.03 | 4.73 | 0.03 | 100.0 | 95.6 | 85.3 | 75.9 | 49.0 | 31.3 | 22.1 | 16.4 | 13.0 | 10.4 | 6.1 |
| Gravel | 19 | 4.7 | 4.89 | -0.02 | 4.76 | 0.06 | 100.0 | 95.5 | 84.5 | 74.2 | 47.3 | 29.1 | 22.0 | 15.1 | 11.7 | 9.6 | 5.5 |
| Gravel | 19 | 4.7 | 4.90 | -0.02 | 4.81 | 0.11 | 100.0 | 95.1 | 84.0 | 73.8 | 46.5 | 29.3 | 22.1 | 15.0 | 11.7 | 9.5 | 5.7 |
| Gravel | 19 | 4.7 | 4.82 | -0.02 | 4.70 | 0.00 | 100.0 | 94.9 | 84.5 | 74.3 | 46.6 | 29.1 | 22.1 | 14.9 | 11.7 | 9.5 | 5.7 |
| Limestone | 19 | 4.2 | 4.48 | 0.19 | 4.15 | -0.05 | 100.0 | 94.4 | 80.6 | 70.1 | 47.2 | 30.1 | 20.4 | 15.8 | 13.4 | 11.7 | 8.0 |
| Limestone | 19 | 4.2 | 4.51 | 0.19 | 4.21 | 0.01 | 100.0 | 93.7 | 80.2 | 70.4 | 47.2 | 29.8 | 20.2 | 15.7 | 13.3 | 11.6 | 7.8 |
| Limestone | 19 | 4.2 | 4.42 | 0.19 | 4.09 | -0.11 | 100.0 | 95.3 | 82.9 | 71.1 | 47.6 | 30.0 | 20.4 | 16.0 | 13.6 | 11.9 | 8.0 |

**Table A4. Infrared Furnace Results for Optimum + 0.5 Percent Asphalt**

| Aggregate | NMAS | Actual $P_b$, % | Loss, % | Cor. Factor, % | Measured $P_b$, % | Difference, % | Percent Passing Standard Sieve Size, mm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 25.0 | 19.0 | 12.5 | 9.5 | 4.75 | 2.36 | 1.18 | 0.600 | 0.300 | 0.150 | 0.075 |
| Dolomite | 9.5 | 5 | 5.49 | 0.51 | 4.98 | -0.02 | 100.0 | 100.0 | 100.0 | 95.9 | 74.5 | 58.3 | 45.2 | 35.1 | 28.0 | 22.9 | 17.6 |
| Dolomite | 9.5 | 5 | 5.46 | 0.51 | 4.95 | -0.05 | 100.0 | 100.0 | 100.0 | 96.3 | 74.2 | 58.0 | 45.2 | 34.7 | 28.0 | 22.9 | 17.6 |
| Dolomite | 9.5 | 5 | 5.48 | 0.51 | 4.97 | -0.03 | 100.0 | 100.0 | 100.0 | 96.3 | 74.4 | 58.2 | 45.2 | 34.8 | 28.0 | 22.9 | 17.6 |
| Granite | 9.5 | 5.8 | 5.79 | 0.01 | 5.78 | -0.02 | 100.0 | 100.0 | 100.0 | 98.1 | 77.4 | 57.6 | 44.0 | 31.9 | 22.2 | 14.2 | 9.4 |
| Granite | 9.5 | 5.8 | 5.78 | 0.01 | 5.77 | -0.03 | 100.0 | 100.0 | 100.0 | 97.8 | 77.7 | 57.1 | 43.9 | 31.8 | 22.1 | 14.2 | 9.4 |
| Granite | 9.5 | 5.8 | 5.71 | 0.01 | 5.70 | -0.10 | 100.0 | 100.0 | 100.0 | 97.2 | 77.1 | 57.3 | 43.6 | 31.4 | 21.8 | 14.2 | 9.5 |
| Gravel | 9.5 | 5.2 | 5.22 | 0.03 | 5.19 | -0.01 | 100.0 | 100.0 | 100.0 | 96.9 | 78.4 | 56.2 | 43.3 | 32.9 | 21.6 | 13.0 | 8.9 |
| Gravel | 9.5 | 5.2 | 5.25 | 0.03 | 5.22 | 0.02 | 100.0 | 100.0 | 100.0 | 97.5 | 77.4 | 56.3 | 44.4 | 32.4 | 21.2 | 12.5 | 8.4 |
| Gravel | 9.5 | 5.2 | 4.96 | 0.03 | 4.93 | -0.27 | 100.0 | 100.0 | 100.0 | 96.2 | 75.3 | 56.2 | 43.0 | 32.8 | 21.6 | 13.0 | 8.9 |
| Limestone | 9.5 | 4.2 | 4.20 | 0.14 | 4.06 | -0.14 | 100.0 | 100.0 | 100.0 | 95.9 | 75.6 | 57.1 | 43.1 | 31.7 | 24.0 | 18.0 | 13.0 |
| Limestone | 9.5 | 4.2 | 4.29 | 0.14 | 4.15 | -0.05 | 100.0 | 100.0 | 100.0 | 96.1 | 76.0 | 57.2 | 43.5 | 32.5 | 24.9 | 18.9 | 13.8 |
| Limestone | 9.5 | 4.2 | 4.28 | 0.14 | 4.14 | -0.06 | 100.0 | 100.0 | 100.0 | 97.2 | 75.8 | 56.7 | 43.0 | 31.5 | 23.7 | 17.1 | 12.4 |
| Dolomite | 19 | 4.3 | 4.69 | 0.40 | 4.29 | -0.01 | 100.0 | 92.7 | 80.2 | 72.3 | 49.8 | 31.8 | 22.6 | 18.4 | 16.2 | 15.0 | 11.3 |
| Dolomite | 19 | 4.3 | 4.70 | 0.40 | 4.30 | 0.00 | 100.0 | 95.3 | 82.2 | 71.3 | 50.9 | 31.8 | 22.7 | 18.4 | 16.4 | 15.2 | 11.4 |
| Dolomite | 19 | 4.3 | 4.67 | 0.40 | 4.27 | -0.03 | 100.0 | 95.5 | 81.5 | 71.2 | 49.7 | 31.6 | 22.1 | 17.7 | 15.6 | 14.1 | 10.4 |
| Granite | 19 | 4.7 | 4.64 | -0.13 | 4.77 | 0.07 | 100.0 | 96.0 | 85.0 | 74.0 | 49.0 | 31.1 | 21.8 | 16.4 | 13.1 | 10.6 | 6.2 |
| Granite | 19 | 4.7 | 4.70 | -0.13 | 4.83 | 0.13 | 100.0 | 95.7 | 82.1 | 74.1 | 48.7 | 31.1 | 22.1 | 16.6 | 13.1 | 10.6 | 6.2 |
| Granite | 19 | 4.7 | 4.59 | -0.13 | 4.72 | 0.02 | 100.0 | 95.1 | 82.1 | 74.0 | 48.6 | 31.0 | 22.0 | 16.6 | 13.0 | 10.4 | 6.1 |
| Gravel | 19 | 4.7 | 4.72 | 0.04 | 4.68 | -0.02 | 100.0 | 94.9 | 85.1 | 72.5 | 47.1 | 29.0 | 22.1 | 14.8 | 11.5 | 9.3 | 5.4 |
| Gravel | 19 | 4.7 | 4.74 | 0.04 | 4.70 | 0.00 | 100.0 | 94.8 | 85.3 | 74.2 | 46.6 | 29.2 | 22.0 | 14.9 | 11.6 | 9.4 | 5.3 |
| Gravel | 19 | 4.7 | 4.54 | 0.04 | 4.50 | -0.20 | 100.0 | 95.2 | 86.6 | 75.7 | 48.9 | 32.2 | 25.3 | 18.6 | 15.6 | 13.5 | 9.9 |
| Limestone | 19 | 4.2 | 4.18 | 0.16 | 4.02 | -0.18 | 100.0 | 95.3 | 80.7 | 71.0 | 47.6 | 30.7 | 21.0 | 16.6 | 14.1 | 12.6 | 8.9 |
| Limestone | 19 | 4.2 | 4.32 | 0.16 | 4.16 | -0.04 | 100.0 | 94.5 | 81.5 | 71.9 | 46.7 | 29.1 | 18.9 | 14.0 | 11.5 | 9.7 | 5.9 |
| Limestone | 19 | 4.2 | 4.18 | 0.16 | 4.02 | -0.18 | 100.0 | 95.3 | 82.9 | 71.1 | 47.6 | 30.0 | 20.4 | 16.0 | 13.6 | 11.9 | 8.0 |