

kali content and using fly ash as a replacement for some of the cement.

Figure 2 shows available expansion data for concrete in which residue was used as aggregate. The expansion test results were obtained on concrete bars 8.9x8.9x29.2 cm (3.5x3.5x11.5 in) that were continuously moist cured at 21°C (70°F). As Johnston (3) points out, this approach is preferable to the standard mortar bar test (ASTM C 227) because it more readily identifies such variables as cement content and coarse-aggregate component.

It is interesting to note that significant expansions occur at an early age and then continue slowly over longer periods of time (Figure 2). This is similar to results obtained by Phillips and Cahn (4) in their investigation of the use of refuse glass in concrete block. The presence of additional fly ash in mix B reduces expansion by apparently dissipating the alkalis with the additional surface area available for reaction.

### CONCRETE MASONRY BLOCK

The use of residue as aggregate in concrete block was investigated. The results are compared below with ASTM C 90 specifications (1 MPa = 145 lbf/in<sup>2</sup>; 1 kg/m<sup>3</sup> = 0.062 lb/ft<sup>3</sup>):

Property	ASTM C90 Hollow Load-Bearing Units, Grade N	Blocks Made with Incinerator Residue
Compressive strength of individual units using gross area (MPa)	5.5	> 5.5
Medium weight classification (kg/m <sup>3</sup> )	1682-2002	1728
Maximum water absorption (kg/m <sup>3</sup> )	240	232
Moisture content		
Percentage of total	35	35
Associated percentage of linear shrinkage	< 0.03	> 0.3

The grading of the residue was altered to conform to that used locally in lightweight block. The blocks were fabricated in a manually operated single-block machine. Although they are not directly comparable with data for machine-manufactured units that are steam cured at low pressure, the data indicate a potential use for residue

in this area. The possibility of alkali-glass reaction is also of concern in this case. Figure 3 shows the expansion characteristics of two blocks. Block 1 was water-cured at 21°C (70°F) after 24 h of exposure to a laboratory environment (~24°C and 50 percent relative humidity). After 24 h of exposure to laboratory air, block 2 was cured in water at a temperature of 82°C (182°F) for 24 h to simulate low-pressure steam curing. The block was then cured in water at 21°C. The increased initial expansion associated with block 2 is to be expected. The subsequent lack of expansion may be especially significant. The fact that these data are based on single blocks and do not include kiln curing must be kept in mind.

### CONCLUSIONS

On the basis of tests carried out to date, the following conclusions appear to be warranted:

1. Incinerator residue can potentially be used as aggregate in PCC. Strengths of 27.6 MPa (4000 lbf/in<sup>2</sup>) have been attained. The problem of alkali-aggregate expansion exists, but initial test data indicate that it can be controlled.
2. Incinerator residue can potentially be used as aggregate in masonry block. A medium-weight block that meets ASTM C 90 specifications has been manufactured in a manually operated block machine.

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# Composition and Characteristics of Municipal Incinerator Residues

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The basic physical and chemical composition of municipal incinerator residues and their essential engineering properties are discussed. The analytic methods used in characterizing samples of incinerator residue from various sources are also discussed. Some unique characteristics of incinerator residue are identified, and the significance of these characteristics relative to the potential use of residue as construction material is outlined. A means for classifying the residues from municipal-scale incinerator operations is recommended.

Billions of dollars are spent each year on the collection and disposal of municipal solid waste in the United States. Although 90 percent of all solid waste is currently disposed of in landfills, incineration is the principal means of solid waste disposal in many U. S. metropolitan areas. The primary advantage of incineration is that it reduces the volume of incoming solid waste by as much as 80-90 percent, thereby extending

existing landfill space, which is often scarce in densely populated areas. Furthermore, combustion of solid waste provides municipalities with an opportunity to convert such waste into a needed source of energy.

Despite such advantages, incineration produces a residue after burning that usually represents 20-30 percent by weight of the original refuse and must be disposed of in an environmentally acceptable manner. Currently, there are approximately 140 municipal incinerator plants in operation in the United States, primarily in the Northeast. It has been estimated that these plants produce a combined total of 4.5 million Mg (5 million tons) of incinerator residue annually (1).

Incinerator residue is potentially useful in a number of construction-related applications. It is necessary, however, to know something about the material and its essential properties before considering its possible utilization. This paper discusses the physical and chemical characteristics of different incinerator residues and offers a system for classifying residues from different sources.

#### CLASSIFICATION OF INCINERATOR RESIDUES

Incinerator residue is a heterogeneous material derived from the combustion of municipal refuse. Essentially, municipal refuse consists of a combustible fraction (including paper, wood, food wastes, textiles, and yard wastes) and a noncombustible fraction (including metals, glass, bricks, ceramics, and rocks). Although the composition and moisture content of refuse vary during different times of the year and in different parts of the country, the combustible fraction ordinarily comprises 60-80 percent by weight of the refuse. The table below gives published data on the nationwide average composition of municipal refuse (2):

Component	Percentage by Dry Weight
Paper	51.6
Food wastes	19.3
Metals	10.2
Glass	9.9
Wood	3.0
Textiles	2.7
Leather and rubber	1.9
Plastics	1.4
Total	100.0

These data assume a material free of "yard waste" and "miscellaneous" components (yard waste includes leaves, grass, and branches, and miscellaneous includes bricks, rocks, and dirt). These two fractions are highly variable and can constitute up to one-third of refuse at certain times.

The proper combustion of solid waste in a municipal incinerator plant is influenced by three basic factors: time, temperature, and turbulence. For satisfactory burning to occur, the refuse might be exposed for a sufficient amount of time to temperatures in the range of 871°C-982°C (1600°F-1800°F). Generally, the greater the agitation of the refuse is during burning, the more complete is the "degree of burnout".

Degree of burnout—the ratio of the incinerated refuse to the combustible fraction of the refuse—is directly related to the design of the incinerator furnace and the feed grates but can also be affected by differences in plant operational philosophies. In general, continuous-fed incinerators produce a better burnout than batch-fed incinerators. In addition, incinerators that have grates that agitate the refuse during the

burning cycle can be expected to produce a higher degree of burnout than incinerators with grates that provide little or no agitation.

For practical purposes, municipal incinerator residues can be broadly classified into three main categories on the basis of degree of burnout:

1. Well-burned—Well-burned residues come from continuous-fed incinerators that provide a high degree of grate agitation. Residues of this type are usually produced at plants that have rotary kilns, reciprocating grates, or rocking grates. Well-burned residue should constitute approximately 10 percent by volume and from 20 to 30 percent by weight of the refuse input (3).

2. Intermediately burned—Intermediately burned residue is produced by continuous-fed incinerators with traveling grates, which do not mechanically agitate or break down the burning refuse to any great extent. These residues generally represent approximately 20 percent by volume and from 25 to 35 percent by weight of the incoming refuse (3).

3. Poorly burned—Poorly burned residues are by-products from batch-fed incinerators or from poorly operated continuous-fed incinerators, especially plants with traveling grates. Variations in burning time in such plants significantly affect the burnout and result in a substantial amount of unburned or partially burned combustible material. Typically, poorly burned residue will be from 30 to 40 percent of the original volume and weight of the refuse (3).

Since incineration is used by cities to reduce the overall volume of solid waste for disposal, quality control of the resultant residue is of little importance in the operation of most incinerator plants. Therefore, the basic design of the furnace and the grates should not be the only criterion used to classify a source of incinerator residue. The manner in which the plant is operated should also be considered.

In addition to conventional incineration, pyrolysis is also being used in the thermal reduction of municipal solid waste (although very few municipal-scale plants are operational at this time). Pyrolysis is a process by which heat is applied, in the absence of excess air, at temperatures that range from 500° to 1000°C (932°F-1832°F). This results in the chemical decomposition of organic substances. In addition to oil and gaseous fuel by-products, the process produces a char residue. The residues from pyrolysis processes are, in most cases, extremely well burned, uniformly graded, glassy materials that represent approximately 5-10 percent by volume and 10-20 percent by weight of the original solid waste (4). Pyrolysis residue should be considered a special residue classification.

Because classification of incinerator residues according to degree of burnout depends largely on visual inspection and the judgment of the observer, a more definitive means of assigning a residue classification is needed for practical use. Recommended criteria for quantitatively classifying incinerator residue are given below:

Classification	Loss on Ignition (%)	Color of Organic Test Solution
Well burned	<5	Lighter than standard
Intermediately burned	5-10	Same as standard
Poorly burned	>10	Darker than standard

Since there is a unique similarity among the residues from pyrolysis operations, these criteria are not appli-

cable to materials produced by pyrolysis. In classifying pyrolysis residue, it is necessary only to identify that the source of the residue was a pyrolysis process.

The two parameters used as classification criteria for incinerator residues are loss on ignition and the presence of organic impurities. Since these parameters are indicative of the relative content of carbonaceous and organic matter in the residue, they can readily be related to the degree of residue burnout, which is the basis for the classification system.

Loss on ignition is tested in accordance with a test method developed and reported by the U. S. Environmental Protection Agency (5). This procedure involves fine grinding a representative sample of the residue, selecting a 50-g sample for testing, subjecting the sample to 1-h exposure in a muffle furnace at 950°C (1742°F), and computing the loss in weight of the sample. The loss-on-ignition value is directly related to the percentage of combustible material contained in the sample. Because of the comparatively small sample size, it is recommended that a series of tests be performed so that a truly representative value is obtained.

The test for organic impurities in sands for concrete (ASTM C 40) is simple to perform. It consists of adding a 3 percent NaOH solution to a sample of material in a standard glass container, shaking, and allowing it to stand for 24 h, after which the color of the supernatant liquor in the bottle is compared with that of a standard reference color solution. If the supernatant liquor is darker, the material is considered to have a comparatively high organic content.

Classification of incinerator residues is extremely important in identifying the potential use of the material. The classification system described here is based on normal operating conditions at the incinerator plant. At the same time, it is recognized that significant variations in operating conditions over an extended period of time could result in a change in classification for a particular source of residue.

#### SAMPLING INCINERATOR RESIDUE

The collection of representative samples of incinerator residue is essential for proper characterization of the material from a specific source. Since different plants use different burning techniques and discharge methods, sampling procedures are extremely important in order to ensure that representative samples are obtained. It is recommended that approximately 1.8 Mg (2 tons) of residue be collected at a specific incinerator site over a relatively short time period (from 30 min to several hours) of normal plant operation. Samples should be collected in 208-L (55-gal) drums, and maximum particle size should be limited to objects 152.4 mm (6 in) in diameter. Samples can be obtained directly from the residue discharge chute, where possible, or loaded from stockpiles by a front-end loader. Samples can probably be obtained most conveniently from stockpiles.

#### ANALYSIS OF INCINERATOR RESIDUES

A recently completed study on the use of incinerator residue in highway construction, performed for the Federal Highway Administration (FHWA) by Valley Forge Laboratories (7), involved the analysis of residues from seven different sources, each of which represented a type of incinerator (including pyrolysis) in terms of grate design and anticipated type of residue. The findings of characterization studies performed on these samples are discussed below and are

compared with data from a 1968 study by the U. S. Bureau of Mines (6) in which 0.9-Mg (1-ton) or larger samples of residues were obtained from seven incinerator plants and analyzed.

#### Basic Engineering Properties

Incinerator residue, as it is discharged directly from the plant, is a soaking-wet mixture of glass, metals, ash, minerals, and partially burned combustible matter. Its moisture content is highly variable and depends on the degree of burnout, the method of quenching, and the age of the residue. The moisture content of incinerator residues can range from as low as 15 percent, for well-burned residue that has been stockpiled for some time, to 60 percent or higher, for freshly quenched residue that has not been well burned. It is well known that stockpiling reduces the moisture content of fresh residue over time. In the studies already noted, the average moisture content of samples of incinerator residue was found to be approximately 30 percent but that of stockpiled, drained samples to average about 20 percent. The natural moisture content of pyrolysis residues is extremely low, usually from 1 to 2 percent, because these materials, after the separation of ferrous metal and carbon, are essentially glassy slags with very low porosity.

The unit weight of incinerator residues is directly related to the composition of the residue and the extent of burnout. As burnout improves, the unit weight of the residue increases. Samples of incinerator residue were first dried to constant weight at 105°C (220°F) and then screened to a 76.2-mm (3-in) maximum size. Dry unit weight was determined by compacting the samples in a 152.4-mm (6-in) diameter container. The procedures used were a modification of the test method outlined in ASTM C 29. Dry rodded unit weights were found to range from less than 800 kg/m<sup>3</sup> (50 lb/ft<sup>3</sup>) for poorly burned residue to more than 1280 kg/m<sup>3</sup> (80 lb/ft<sup>3</sup>) for well-burned material. The unit weight of the glassy fraction of pyrolysis residues is considerably higher than that of incinerator residues, usually ranging from 1600 to 1920 kg/m<sup>3</sup> (100-120 lb/ft<sup>3</sup>).

Initial determinations of particle-size distribution for "as-received" incinerator residues involved the removal of oversize material by means of a 76.2-mm screen. Regardless of the degree of burnout, all residues sampled were found to be essentially well-graded materials with particle sizes that ranged from the 76.2-mm upper limit to a nominal amount passing the 0.075-mm (no. 200) screen. In general, residues from rotary-kiln incinerators are likely to be more finely graded than grate-type incinerator residues because of the constant tumbling action in the kiln, which results in more degradation of residue particles. Pyrolysis residues are, by comparison, much more finely graded than incinerator residues. Pyrolysis residues, as received from the plant, will not normally contain particles larger than 12.7 mm (0.5 in), and the majority of particle sizes were in the 4.76-mm (no. 4) to 0.42-mm (no. 40) range. Figure 1 shows the normally expected particle-size distribution of as-received incinerator and pyrolysis residues. The maximum particle size of the incinerator residues is 76.2 mm.

To more realistically evaluate incinerator residue for potential applications in highway construction, a maximum particle size of 38.1 mm (1.5 in) was selected as the upper limit for material used as structural fill or in base-course applications. Samples of various sources of incinerator residue were oven dried and passed through a 38.1-mm screen. Several sieve analyses were performed on samples from each basic type

of residue. Despite the inherent variability of residues from different sources, the results of the sieve analyses of screened residues were, for the most part, comparable. Figure 2 shows the range of particle-size distribution observed for various sources of incinerator

residues with a maximum size of 38.1 mm.

Physical Characterization

The physical composition of incinerator residues is

Figure 1. Particle-size distribution of as-received incinerator residues.

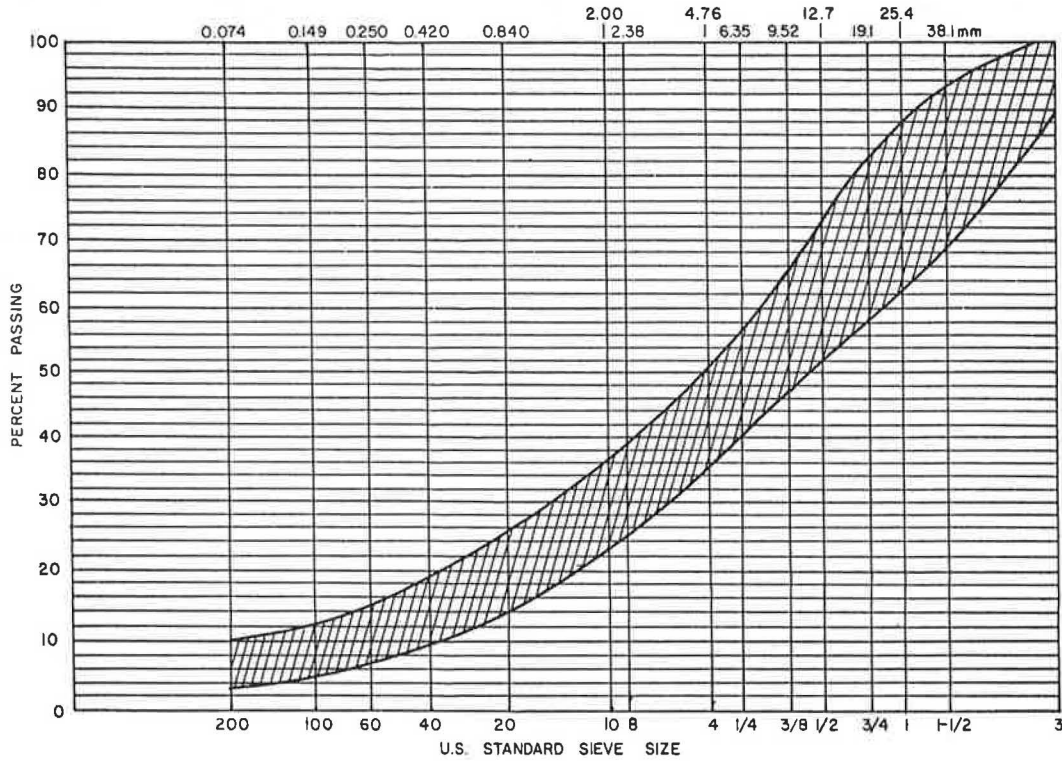
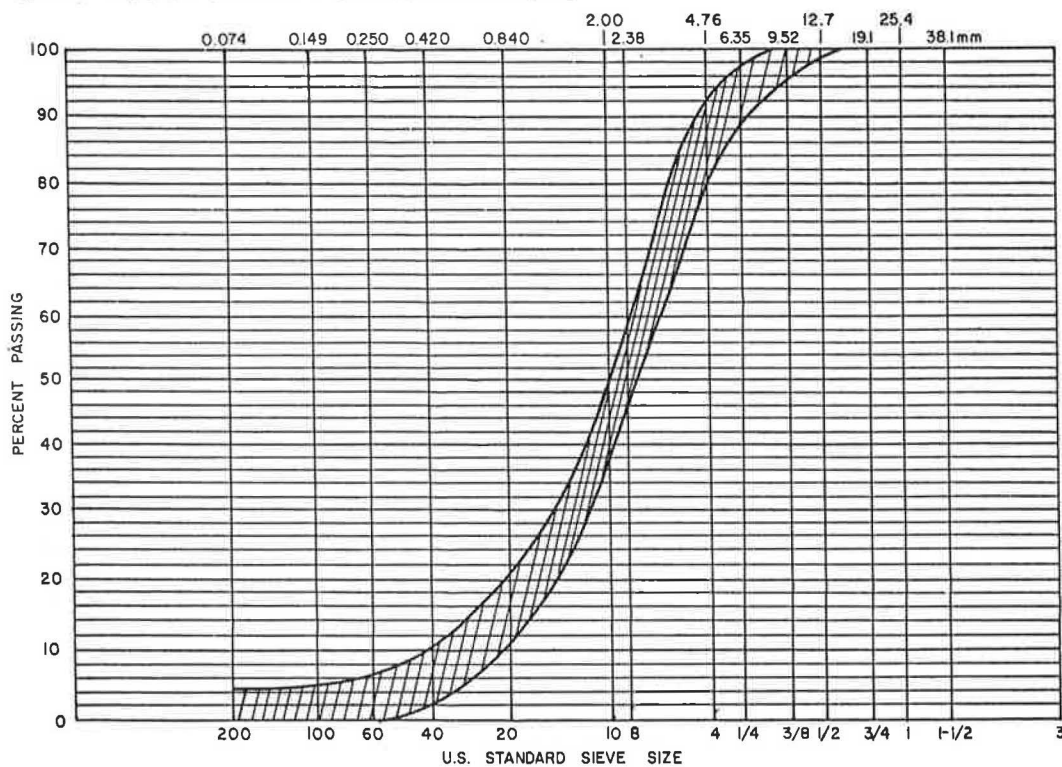


Figure 2. Particle-size distribution of graded incinerator residues.





significant because of the heterogeneity of these materials. Fluctuations in composition influence the engineering properties and behavior of residues and are thus a factor in determining the overall suitability of different residue sources in some form of highway construction use.

In extensive laboratory studies performed for FHWA by Valley Forge Laboratories, the principal components of municipal incinerator residues have been identified as glass, ferrous metal, nonferrous metal, minerals and ash, and combustible and organic matter. The components of as-received residue samples were identified by first separating each of the samples into individual sieve fractions or cuts, as follows:

Size Fraction	Sieve Cut	Sieve Size (mm)	
		Passing	Retained
Coarse	1	76.2	25.4
	2	25.4	12.7
	3	12.7	6.35
	4	6.35	2.00
Fine	5	2.00	0.420
	6	0.420	0.074
	7	0.074	

Hand sorting and visual inspection were used to identify the principal components of the coarse fractions. For the fine cuts, visual identification proved to be extremely difficult, even under a microscope, because of the uniform color and appearance of the fine-size particles [ $<2$  mm ( $<$ no. 10)]. The composition of the fine cuts was therefore determined chemically.

Ignition in a Leco induction furnace was used to determine the carbon content in the finer fractions. The carbon content was then used to estimate the amount of unburned combustibles, assuming an average of 86 percent fixed carbon in typical organic compounds. The iron content of the fine sieve fractions was determined by volumetric chemical analysis by using the Zimmerman-Reinhardt method with  $\text{KMnO}_4$  titration. The iron identified in the finer cuts was assumed to be iron oxide.

The glass content in the fine cuts was estimated from the silicon content obtained with gravimetric chemical analysis. Standard wet silicate analysis of the solution of sodium carbonate fusion with the sample material was used. Since glass is approximately 70 percent silica and silicon makes up approximately 47 percent of silica, the silicon content was converted to percentage glass by multiplying the percentage of silicon by 3.062.

Various chemical methods were used to identify the principal nonferrous metal components in the finer fractions. Standard gravimetric analysis was used to determine the total alumina ( $\text{Al}_2\text{O}_3$ ), including that present in glass and ceramics. It is unlikely that much, if any, free aluminum is present in the fine cuts since it would be easily oxidized. Atomic absorption analysis was used to identify the copper content. Other nonferrous metals are normally found in trace amounts. The identification of these trace elements will be discussed as part of the chemical composition of incinerator residues.

The overall physical characterization of each residue sample was determined by multiplying the percentage of each component in any sieve fraction by the weight distribution of that sieve fraction relative to the entire sample and then summing each of the products. Samples that represented the same residue classification were grouped together and averaged for reporting. Table 1 gives the physical composition of the as-

received incinerator residue samples evaluated by Valley Forge Laboratories and also the data for average residue composition developed in 1968 by the U. S. Bureau of Mines.

The data given in Table 1 show that the average composition of incinerator residues reported by the two studies is basically in agreement, although the percentage of ferrous metal reported by Valley Forge Laboratories was considerably lower than that reported by the Bureau of Mines. This is because the maximum particle size of residue samples evaluated by Valley Forge Laboratories was 76.2 mm (3 in), whereas the Bureau of Mines exercised no size control of residue samples. The fact that most material larger than 76.2 mm is ferrous metal accounts for the apparent difference in the data.

Although the average composition of residue samples appears to be consistent between the two studies, closer inspection of Table 1 shows a significant variation in composition among residues of different classifications. Most obvious is the wide range of combustible and organic matter, which can constitute between 25 and 30 percent by weight of a poorly burned residue. The amount of minerals and ash also varies according to the degree of burnout and is highest in the well-burned residues. The deviations in composition are much less pronounced for the other component materials. In fact, the amount of nonferrous metal was found to be almost the same in all residue samples. The average physical composition of as-received incinerator residues, as determined by Valley Forge Laboratories, is shown in Figure 3.

Residues from pyrolysis processes are quite different from municipal incinerator residues. The physical composition of the "glassy aggregate" fraction of residue obtained from the Landgard pyrolysis system in Baltimore was as follows:

Component	Percentage by Weight
Glass	65
Mineral matter	28
Ferrous metal	3
Nonferrous metal	2
Carbon	2
Total	100

The composition of this material is probably representative of most sources of pyrolysis residue in which the carbon char and ferrous metal components have first been separated, as was the case here. Figure 4 shows the composition of this sample of pyrolysis residue. Although the residue is well burned, the combined carbon and ferrous components are nearly equal in weight to the glassy fraction.

#### Chemical Composition

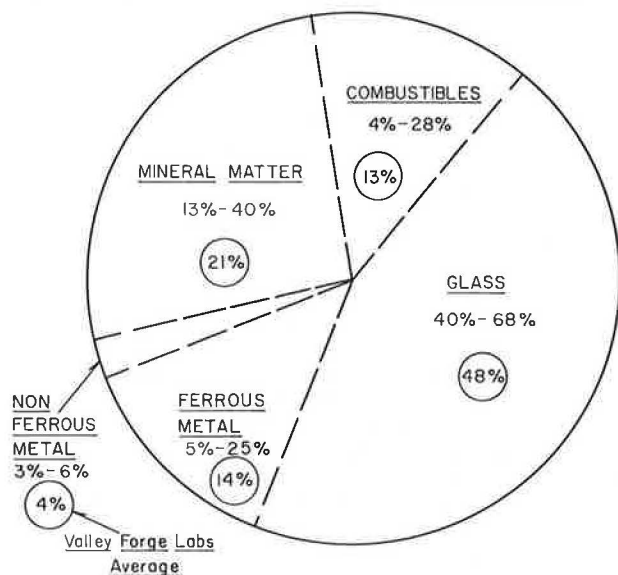
The chemical composition of incinerator residues is determined by the characteristics of the incoming refuse, which fluctuate according to geography and season and the extent to which the refuse is burned at the plant. The most variable component in the basic chemistry of incinerator residues is its carbon content. The amount of carbon in incinerator residue can vary widely depending on the degree of burnout. To determine reasonably accurate figures for the chemical composition of residues from different sources, it was decided to compare the analyses of the carbon-free fractions of residues evaluated in previous studies.

In a study of high-temperature incineration, Bortz and Pincus (8) cited the chemical analysis of organic-

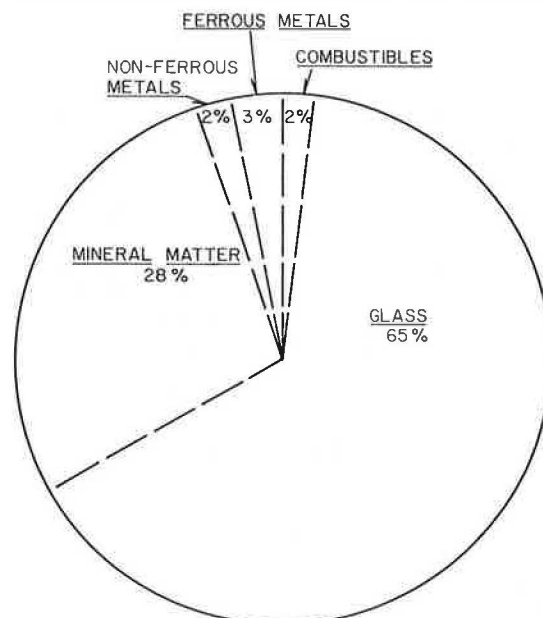
**Table 1. Physical composition of municipal incinerator residues.**

Component	Percentage by Weight				
	Valley Forge Laboratories				
	Well Burned	Intermediately Burned	Poorly Burned	Average	Bureau of Mines
Glass	39.9	51.5	45.7	48.0	44.0
Mineral matter	39.5	17.5	13.1	21.0	17.6
Ferrous metal	13.8	16.0	8.7	14.2	28.0
Nonferrous metal	3.3	4.3	4.3	4.1	1.4
Combustible and organic matter	3.5	10.7	28.2	12.7	9.0
Total	100.0	100.0	100.0	100.0	100.0

**Figure 3. Physical composition of municipal incinerator residues.**



**Figure 4. Physical composition of Landgard pyrolysis residue.**



**Table 2. Chemical analysis of carbon-free incinerator residue.**

Compound	Percentage by Weight				
	Hartford	Brockton	Pittsburgh	St. Louis	Average
SiO	61.9	62.4	60.0	54.88	59.8
Al <sub>2</sub> O <sub>3</sub>	13.6	7.6	8.0	9.87	9.8
Fe <sub>2</sub> O <sub>3</sub>	3.7	5.2 <sup>a</sup>	4.0	3.42	4.0
TiO <sub>2</sub>	-	0.7	-	1.25	1.0
CaO	6.6	14.2	17.0	9.93	11.9
MgO	2.0	3.3	5.0	1.66	3.0
BaO	0.2	-	-	-	-
ZnO	1.7	-	-	-	0.4
PbO	0.5	-	-	-	0.1
CuO	0.4	-	-	-	0.1
MnO	-	0.2	1.0	-	0.3
Na <sub>2</sub> O	9.4 <sup>b</sup>	3.8 <sup>b</sup>	3.0 <sup>b</sup>	6.19	6.1
K <sub>2</sub> O	-	-	-	1.99	0.5
SO <sub>3</sub>	-	-	-	3.66	0.9
P <sub>2</sub> OS	-	0.7	-	1.33	0.5
Other	-	1.9	2.0	5.82 <sup>c</sup>	1.6
Total	100.0	100.0	100.0	100.0	100.0

<sup>a</sup>Percentage expressed as FeO.

<sup>b</sup>Percentage includes both Na<sub>2</sub>O and K<sub>2</sub>O.

<sup>c</sup>Includes 2.79 percent reported as ash.

free incinerator residues from three sources. Residues from high-temperature furnaces in Hartford, Connecticut; Brockton, Massachusetts; and Pittsburgh, Pennsylvania, were analyzed. The findings, which are given in Table 2, are considered to be closely representative of well-burned residues. Also included in Table 2 is an analysis of carbon-free residue from

an installation in St. Louis (9). An average chemical composition of carbon-free incinerator residue, based on the analyses of these four sources, is also given in Table 2.

In addition to the data given in Table 2, further chemical analyses of residues from different sources have been reported by Lilje (10), Schoenberger and Purdom (11), and others. Gony and Cossais (12) have documented the chemical composition of residues from French incinerators. All of these analyses are essentially in agreement with the average chemical composition presented in this paper.

As data given in Table 2 show, the principal component of carbon-free incinerator residue is silica, which constitutes approximately 60 percent by weight of the residue. Oxides of calcium and aluminum make up approximately 22 percent and sodium, potassium, and iron oxides 10 percent. Magnesium and titanium oxides constitute 4 percent by weight of incinerator residue. The remaining 4 percent consists of sulfates and metallic oxides of copper, lead, zinc, manganese, phosphorus, and other trace elements.

Individual sources of residue may vary somewhat from this average composition. But such differences should not be significant, and the relation between principal components should be essentially the same. Although carbonaceous material is not accounted for in Table 2, allowance must be made for the amount of carbonaceous material contained in residue. The most

**Table 3. Summary of results of aggregate acceptance tests for incinerator residues.**

Test	ASTM Test Method	Type of Residue			
		Well Burned	Intermediately Burned	Poorly Burned	Pyrolysis
Specific gravity <sup>a</sup>	D 2041	2.53	2.43	2.27	3.18
Moisture content <sup>b</sup> (%)	D 698	12-18	14-20	16-24	
Dry density <sup>b</sup> (kg/m <sup>3</sup> )	D 698	1532-1774	1452-1693.5	1210-1452	
Los Angeles abrasion loss <sup>c</sup> (%)	C 131	37.1	36.6	36.4	40
Sodium sulfate soundness loss (%)	C 88				
Fine <sup>d</sup>		10.3	11.8	27.6	5.2
Coarse <sup>e</sup>		15.6	14.2	11.3	8.0

Note: 1 kg/m<sup>3</sup> = 0.062 lb/ft<sup>3</sup>.

<sup>a</sup>Average specific gravity was determined by using a modified dry-back procedure.

<sup>b</sup>Optimum moisture content and maximum dry density were determined by using separate samples of material to develop each point on the moisture density curve.

<sup>c</sup>Different charge weights were used according to residue gradations. Allowable value ranges from 40 to 50 percent, depending on use of aggregate (AASHTO specifications).

<sup>d</sup>Allowable value ranges from 10 to 15 percent, depending on use of aggregate (AASHTO specifications).

<sup>e</sup>Allowable value is 12 percent (AASHTO specifications).

practical way of measuring the amount of combustible and organic matter in incinerator residue is the loss-on-ignition test. Loss-on-ignition values from 2 to more than 15 percent can be expected. The chemical composition of a particular source of residue must, therefore, be adjusted to include the presence of carbon in the analysis.

Some analytic work has also been performed to identify the concentration of trace elements in residues that are potentially detrimental to the environment. Since leaching potential is a function of surface area and water solubility, an analysis was made of the fine fractions of residue samples from various types of incinerators to determine trace-element concentrations. Results of these tests show that, with the exception of zinc, the presence of trace elements in the finer-size fractions of incinerator residues is consistently low for each basic type of residue. This is particularly true for arsenic, cadmium, and selenium, of which concentrations less than 0.005 percent were generally noted. Furthermore, incinerator residues, and in particular the fine sieve fractions, were shown to be slightly basic, a condition that is more desirable from the standpoint of leaching than is acidity.

The combustion of municipal solid waste by pyrolysis produces gaseous fuel, tar and oils, and a char residue. The residue from the Landgard pyrolysis system in Baltimore is subjected to several levels of processing before its final use as aggregate in bituminous pavement. First, the lightweight carbon and ash fraction is separated by flotation. Ferrous metal is then reclaimed by magnetic separation. The remainder of the residue, approximately 60 percent by weight, is referred to as glassy aggregate (13). Although no chemical analysis is presented for the glassy fraction of pyrolysis residue, in all probability the material is highly siliceous with a substantial percentage of alumina. Information on the presence of trace elements in the glassy portion of the residue is not available. However, because of its slaglike structure, the material does not appear to have high potential for leaching.

### Results of Aggregate Acceptance Tests

Standard soil and aggregate acceptance tests were performed to evaluate the potential of different sources of residue for applications in highway construction. Because of the heterogeneous nature of these materials and their tendency to absorb moisture, difficulties were encountered during some of these tests.

The procedures normally used in ASTM C 127 and

C 128 for determination of specific gravity and absorption for conventional aggregate materials were not suitable for testing incinerator residues. Dry-back procedures similar to those described in ASTM D 2041 (Rice method) were adapted for determining the bulk specific gravity of incinerator residue samples. Because of variations in the composition of the material itself and the comparatively high percentage of lightweight particles present, a larger-size pycnometer was used in the test together with a proportionately increased sample size in order to ensure better reproducibility of test results. Although bulk specific gravities were found to vary somewhat for different samples from the same residue source, average values of specific gravity were found to increase as the degree of burnout improved.

The normal relation between moisture and density was not consistently applicable to the testing of incinerator residues. Sieve analyses performed before and after compaction clearly show that considerable particle degradation occurs when the same sample of residue is used throughout the entire moisture-density test. To counteract this, separate samples of residue should be used in determining individual moisture-density values in the test.

Besides particle degradation, the absorption and nonuniform distribution of moisture throughout the sample also contribute to the problem of determining the moisture-density relation of incinerator residues. For these reasons, small variations in dry density often occur over a wide range of moisture content values. It was ultimately concluded that a fully reliable value for the optimum moisture content of incinerator residue could not be determined solely on the basis of maximum dry density without some exercise in judgment by the operator of the test (14). Nevertheless, it is possible to attain a high degree of compaction with incinerator residue in the field despite fluctuations of moisture content in the material.

A number of other physical tests were performed on samples of incinerator residues. The most significant of these tests were the Los Angeles abrasion resistance and sodium sulfate soundness tests. Although all residue samples tested exhibited satisfactory abrasion loss, most specimens did not fully satisfy soundness criteria.

Table 3 summarizes the results of the physical tests performed on as-received samples of various types of incinerator residues. This table also includes results from tests performed on samples of pyrolysis residue. Because of the unusual behavior of incinerator residue, caution is advised in the use of data from standard test methods as evaluative criteria for determining the ap-

plicability of a particular source of residue for use in highway construction. Since the glassy fraction of pyrolysis residues is similar to a sandy slag, this material is more suited to the use of standard test methods than residues from conventional incinerator plants.

#### SUMMARY

Although residues from the municipal incineration of solid waste are heterogeneous materials, their physical composition and basic physical properties do fall within generally predictable limits. These characteristics are related to the degree of burnout of the residue, which can be determined to a great extent by the basic design of the incinerator plant. The degree of burnout is used as the basis for classifying residues in three categories and considering residues from pyrolysis operations as a special classification.

Well-burned and intermediately burned materials are considered acceptable for some type of use in highway construction. Poorly burned residues should not be used as received in any type of application but should be stockpiled for at least six months. Other residue materials, except pyrolysis residues, should be aged for at least one to two months after leaving the plant to reduce moisture content to an acceptable level prior to their use.

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