Marketing Survey of Beneficial Use of Waste-to-Energy Bottom Ash for Civil Engineering Applications

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EXECUTIVE SUMMARY

Waste to energy (WTE) facilities combust municipal solid waste (MSW) to dispose of it, produce energy and materials and reduce GHG emissions. Combustion of MSW results in two by-products, waste to energy bottom ash (WTEBA) and fly ash (WTEFA). WTEBA is typically processed for the recovery of ferrous and non-ferrous metals and the remaining ash is sometimes separated into different fractions and, in some cases, it is used as a replacement for natural derived aggregates in civil engineering applications.

In 2016, there were 77 WTE facilities in the US located at 22 states and combusting about 30 million tons of MSW. Assuming that about 20 to 25% by weight of the initial MSW feedstock is WTEBA and 1 to 5% by weight is WTEFA, it was calculated that Florida produced about 1.2-1.45 million-[metric?] tons WTEBA in 2011. Connecticut, Massachusetts, New Jersey, New York, Pennsylvania and Virginia also had high WTEBA availability, with more than 400 thousand metric tons [this seems low] generated in 2011. The other 15 states all generated less than 230 thousand metric tons each, the same year.

Most natural aggregates are derived from crushed stone and sand and gravel, naturally occurring from mineral deposits. The demand for aggregate is much higher than the supply of WTEBA in each state. The amount of crushed stone sold or used in a majority of the 22 states increased from 2011 to 2014. The amount of construction sand and gravel sold or used did not change between 2011 and 2013. Compared with crushed stone, sand and gravel in most of the 22 states was relatively cheaper. So taking the availability of WTEBA into account, the use of WTEBA as a substitute for crushed stone in Virginia, Connecticut, Massachusetts, Florida, Pennsylvania and New York holds promise.

The American Society for Testing and Materials (ASTM) has standard specification for aggregates but it only demonstrates the requirements for grading,

deleterious substances and soundness of produced construction materials. On the contrary, European and British Standards are more detailed in the specifications of the mechanical and physical properties of aggregates for concrete.

Since the demand for crushed stone and construction sand and gravel is much higher than the amount of WTEBA generated, as long as the WTEBA of a facility is proven to be up-to-standard by sampling and testing, WTEBA can be recycled in the form of various construction materials within different areas of the US. Recycling of WTEBA will avoid landfill and also the WTEBA could have value if used for civil construction applications. Also, the recycling of WTEBA instead of landfilling will result in several environmental benefits

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1. Introduction

With the irreversible trend of municipal solid waste (MSW) generation growth, the appropriate management of MSW has become a major environmental issue. WTE facilities dispose MSW by combusting in specially designed power plants equipped with state-of-the-art air emission control equipment to produce energy and materials. Combustion of MSW results in two by products, the WTE bottom ash (WTEBA) and fly ash (WTEFA). WTEBA is typically processed for the recovery of ferrous and non-ferrous metals and the remainder fraction after being separated in different fractions is being used, in some cases, as a replacement of natural derived aggregates in civil engineering applications. The amount of WTEBA that is typically produced amounts to 20 to 25% by weight of the MSW feedstock [1]. Since a large quantity of WTE bottom ash is generated every year, the potential for WTEBA utilization could be large both economically and environmentally.

The aim of this paper is to conduct a marketing survey of beneficial uses of WTEBA for civil engineering applications. In order to do so, the following objectives were evaluated:

- WTE bottom ash availability
- Natural aggregate consumption and pricing information within geographical areas with high concentrations of WTE facilities
- Standard specifications for fine and coarse aggregates

According to the above analysis, it is possible to know the potential applicability and the advantages/disadvantages of ash incorporation into civil engineering products, and also to estimate potential ash use volumes.

2. WTEBA Availability

In 2016, there were 77 WTE facilities in the US combusting about 30 million tons of MSW. These were located at 22 states, among which were Florida (11), New York (10), Minnesota (8), Massachusetts (7), Pennsylvania (6), and Connecticut (5)(ranked in order of availability of facilities). In Florida 21.4% of the total MSW produced (about 5.8 million tons) was combusted for the production of energy and materials in 2011. Connecticut processed 67.1% of the produced MSW by WTE (2.2

million tons). Table 1 shows the amount of MSW that was managed in each state and the amount of MSW that was combusted in WTE plants.

Table 1 MSW Generation and Management in 2011 [2]

State	Number of plants in state	MSW Managed in state (Metric tons)	% of MSW Managed by WTE	MSW Managed by WTE in state (Metric tons)
Alabama	1	5,395,280	3.3	178,044.2
California	3	66,299,346	1.3	861,891.5
Connecticut	6	3,208,768	67.1	2,153,083.3
Florida	11	27,040,919	21.4	5,786,756.7
Hawaii	1	3,884,163	14.1	547,667.0
Indiana	1	6,440,739	10.9	702,040.6
Iowa	1	3,930,863	1.0	39,308.6
Maine	3	1,412,071	33.5	473,043.8
Maryland	3	2,352,939	22.6	531,764.2
Massachusetts	7	7,520,771	42.2	3,173,765.4
Michigan	3	13,780,212	7.2	992,175.3
Minnesota	9	5,710,304	20.1	1,147,771.1
New Hampshire	2	1,144,568	22.0	251,805.0
New Jersey	5	10,861,083	19.6	2,128,772.3
New York	10	17,349,855	21.2	3,678,169.3
North Carolina	1(inactive)	9,137,435	0.0	0.0
Oklahoma	1	4,778,966	4.3	205,495.5
Oregon	1	3,945,093	4.6	181,474.3
Pennsylvania	6	14,135,701	21.8	3,081,582.8
Utah	1	2,535,552	5.0	126,777.6
Virginia	5	15,359,820	13.3	2,042,856.1
Washington	1	8,801,350	3.1	272841.9
Wisconsin	2	5,650,450	1.3	73,455.9
TOTAL	83	240676248	360.9	28,630,542.1

The main by-product from MSW combustion is WTE ash (WTEA), which is composed of WTE Bottom Ash (WTEBA) and Fly Ash (WTEFA). WTEBA accounts for 80% to 90% of the total WTEA. However, the quantities of ash produced are directly related to the combustion technology. WTEBA is normally considered as 20% to 25% by weight of the total MSW combusted and WTEFA about 1 to 5% by weight [1]. Figure 1 presents the WTEBA availability (tons/year) in 22 US states with high concentration of WTE facilities in 2011. Florida had 1.2-1.5 million tons WTEBA available in 2011. Connecticut, Massachusetts, New Jersey, New York, Pennsylvania and Virginia also had high WTEBA availability, more than 400 thousand metric tons in 2011. The other 15 states each generated less than 230 thousand metric tons.

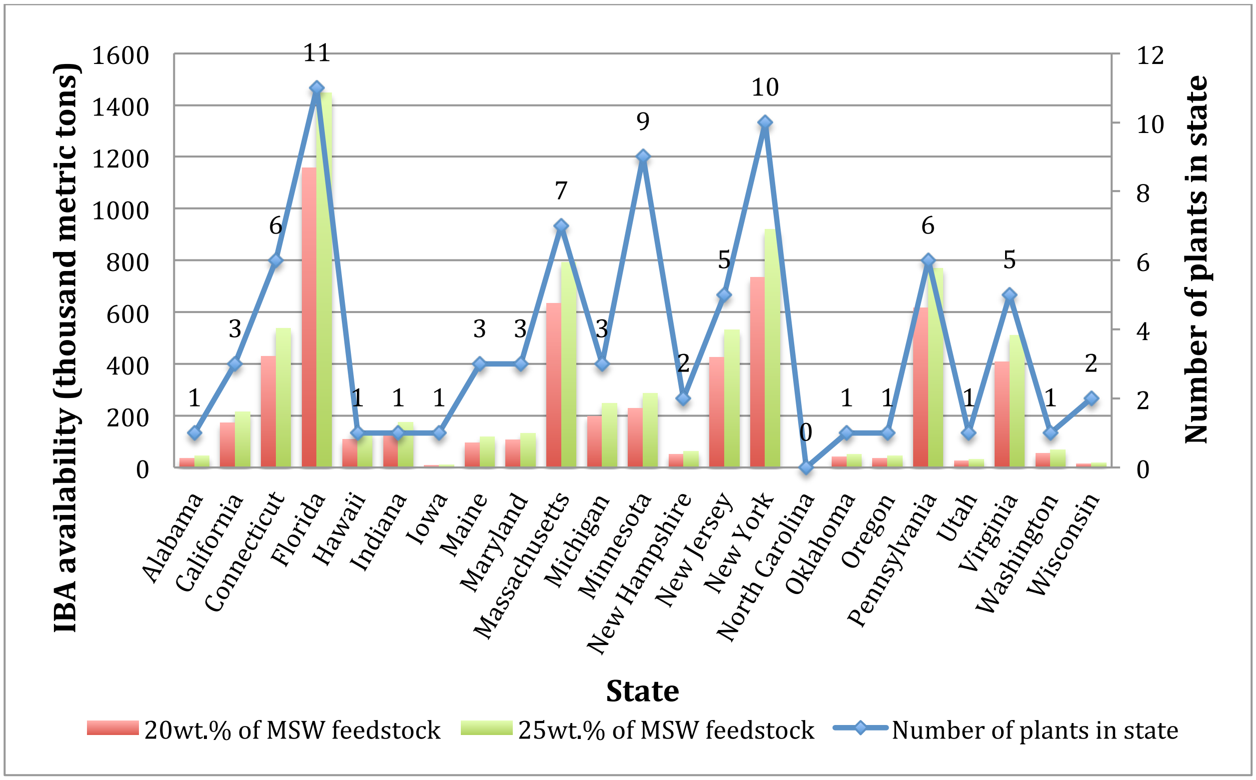

Figure 1 WTEBA Availability in States with WTE facility in 2011

To landfill WTEA, the Toxicity Characteristic Leaching Procedure (TCLP), Method 1311 is conducted to simulate leaching from waste material placed in a landfill into ground water, with the assumption of acidic leaching conditions. Leaching is the mobilization, extraction or washing of soluble constituents from a solid phase by a contacting solvent which is influenced by the solid's chemical composition, the fraction of species available for leaching, the particle morphology, the properties of the solvent, especially the pH or the presence of complex constituents, and the liquid-solid (LS) ratio in the leaching system. There are more than 50 identified leaching tests worldwide. The Leaching Environmental Assessment Framework (LEAF) is a collection of leaching tests, data management tools, and leaching assessment approaches developed to identify detailed characteristic leaching behaviors of a wide range of solid materials (e.g., wastes, soils, construction products, etc.) [3].

The U.S. Environmental Protection Agency (EPA) Office of Resource Conservation and Recovery has initiated the review and validation process for four leaching tests under consideration for inclusion into SW-846: Method 1313 "Liquid-Solid Partitioning as a Function of Extract pH for Constituents in Solid Materials using a Parallel Batch Extraction Procedure" Method 1314 "Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials using an Up-flow Percolation Column Procedure" Method 1315 "Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials using a Semi-dynamic Tank Leaching Procedure" Method 1316 "Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials using a Parallel Batch Extraction Procedure" These protocols are derived from published leaching methods contained in the LEAF [4]. These four tests are environmental leaching assessment for the evaluation of disposal, beneficial use, treatment effectiveness and site remediation options.

3. Natural Aggregates Consumption and Pricing Information

Most natural aggregates are derived from crushed stone and sand and gravel, present in natural mineral deposits [5].

3.1 Crushed Stone

3.1.1 Consumption

As shown in figure 2, all of the 22 states mentioned before had crushed stone sold or used more than 3 million metric tons in both 2011 and 2014, which obviously exceeds the amount of available WTEBA within each state in 2011. It means the demand of aggregate is much higher than the supply of WTEBA in each state. Furthermore, Florida, as the state with the highest WTEBA availability, also had the second highest consumption of 57.2 million tons in 2014. Among the states with high WTEBA availability, Pennsylvania, Virginia and New York respectively had the first, fourth and sixth highest demand for crushed stone. Indiana, Oklahoma and Alabama also had a high consumption of crushed stone in 2014. So, they all have a promising market for WTEBA recycled as a replacement of crushed stone, especially those had both high supply and demand, namely Florida, and Pennsylvania.

As for the changes in demand from 2011 to 2014, there were 5 states decreasing (Maine, Pennsylvania, Virginia, Washington and Wisconsin) and 1 unchanged (Iowa). The changes were within 4,200 thousand metric tons except for Florida and Pennsylvania respectively increased 16,500 and decreased 6,800 thousand metric tons, which are relatively big changes. The amount of crushed stone sold or used in a majority of states increased from 2011 to 2014.

3.1.2 Pricing Information

The unit value ranges between $6 and $19 in 22 states in 2014. The average price is $9.65 in 2011 and $10.15 in 2014 [6]. And the difference between 2011 and 2014 is not obvious in most of the states. It was most expensive at Hawaii ($19.12/18.9), Virginia ($14.6/15.3), Connecticut ($13.9/15.6), Massachusetts ($11.9/13.8), Florida ($12.7/11.9), Washington ($10.3/13.4), Minnesota ($12.1/11.6), Pennsylvania ($10.8/11.6) and New York ($11.1/11.1). So taking the availability of WTEBA into account, the use of WTEBA as a substitute for crushed stone is most promising in Virginia, Connecticut, Massachusetts, Florida, Pennsylvania and New York. In conclusion, thoroughly considering supply and demand, Florida, Pennsylvania, Virginia and New York should be first focused on to develop the market.

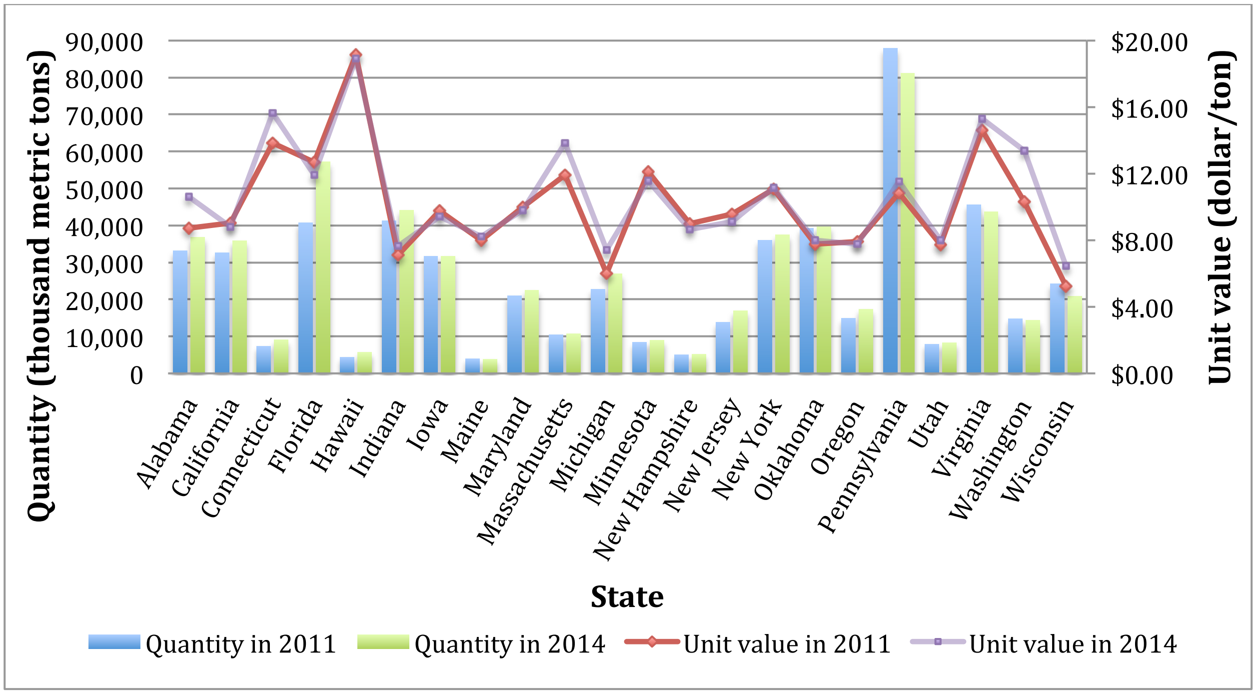

Figure 2 Crushed Stone Sold or Used in States with WTE facility in 2011 and 2014

3.1.3 Civil engineering applications

Crushed stone is a traditional basic construction material used as both coarse aggregate and fine aggregate. As coarse aggregate (+1½ inch), it can be used as macadam, riprap and jetty stone and if graded, then concrete aggregate, bituminous aggregate and railroad ballast. In terms of fine aggregate (- ⅜ inch), it can be used as stone sand and bituminous mix or seal. Also, it can be used for graded road base or subbase, unpaved road surfacing, terrazzo and exposed aggregate or fill or waste as coarse and fine aggregates. Figure 3 shows different usage of crushed stone in the US in 2011 and 2014. Construction uses account for 37.4% and 35.3% of the total uses in 2011 and 2014 respectively, which equaled 433,740 and 441,422 thousand metric tons in each year [6]. Unspecified uses are accounted for 52.2% of the total in 2011 and 53.4% of the total in 2014. The WTE plants in 22 states generated 5,726 to 7,157 thousand tons WTEBA in 2011. It's of great possibility that all of these WTEBA could be able to use as various construction materials within different area of US according to their quantity and quality.

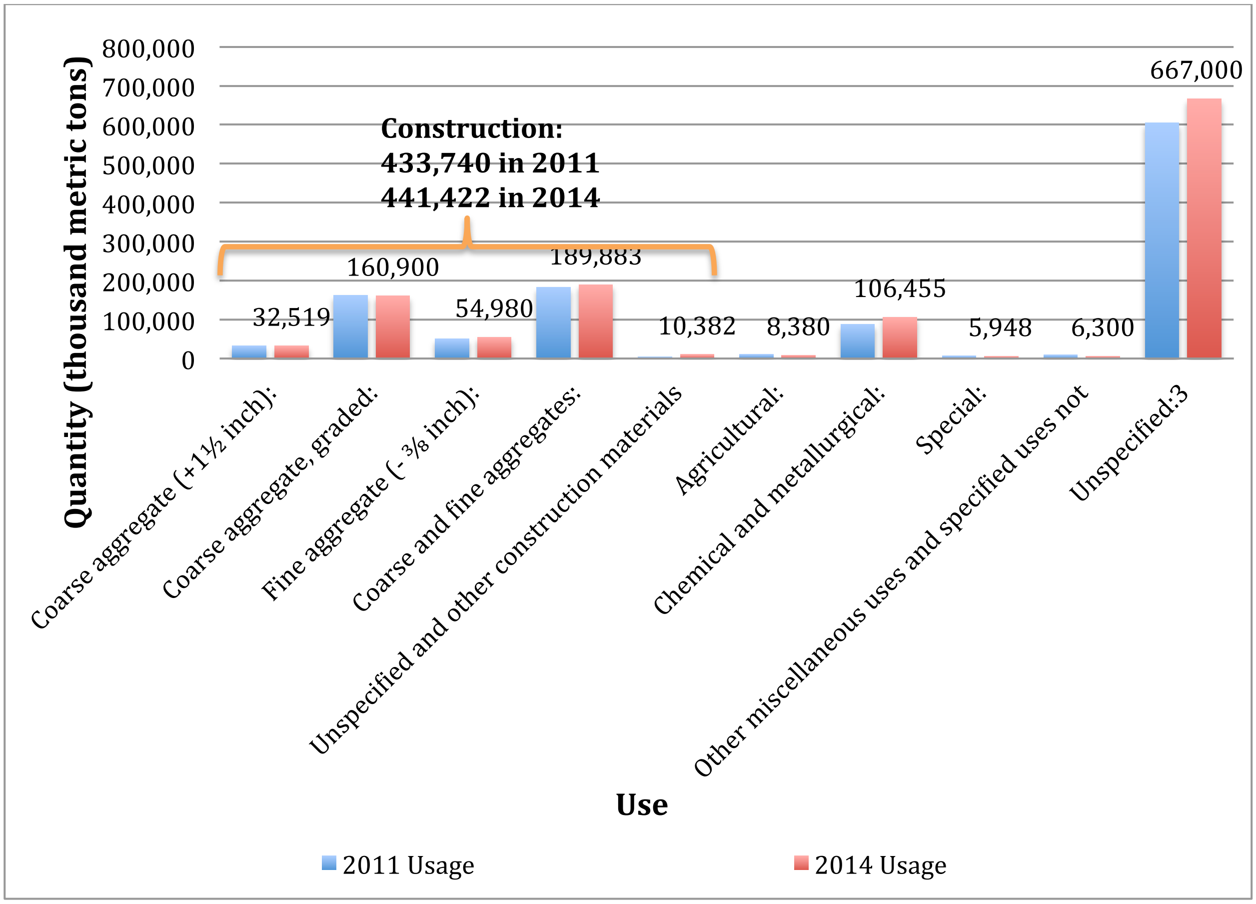

Figure 3 Different Usages of Crushed Stone in US in 2011 and 2014

3.2 Construction Sand and Gravel

3.2.1 Consumption

Construction sand and gravel is one of the earliest materials used by humans for dwellings and later for outdoor areas such as paths, roadways, and other construction. Sand and gravel is very accessible and is widely used throughout the United States and the world. However, it became less available owing to resource constraint or economic conditions in some locales. As shown in Figure 4, except for Hawaii all of the states had more than 4 million metric tons of construction sand and gravel sold or used in 2011 and 2013. 14 out of the 22 states consumed more than 10 million metric tons in both 2011 and 2013 and 7 states consumed more than 20 million metric tons. These quantities exceed the supply of WTEBA in each state, including Hawaii, which only consumed a quantity of 962 thousand metric tons in 2011 and 679 thousand metric tons in 2013.

As for the changes in consumption from 2011 to 2013, 11 states reported a decrease and 1 was unchanged (New Jersey). The amount of construction sand and gravel sold or used did not significantly change between 2011 and 2013.

3.2.2 Pricing Information

Compared with crushed stone, sand and gravel in most of the 22 states was less expensive. The unit values ranged between $4.9 and $15.7 in 2011 and between $4.6 and $18.9 in 2013. The average price was 8.24 in 2011 and 7.62 in 2013. It was most expensive in Hawaii ($7.5/18.8), Maryland ($11.9/11.6), Virginia ($11.6/11.2), California ($11.0/10.1), Connecticut ($9.8/9.5), Massachusetts ($10.1/9.2), Pennsylvania ($9.0/9.0), and New York ($8.5/8.8). Therefore, these states have a more promising market for WTEBA recycling as a replacement of sand and gravel, especially for those had a high availability of WTEBA including Connecticut, Massachusetts, New York, Pennsylvania and Virginia.

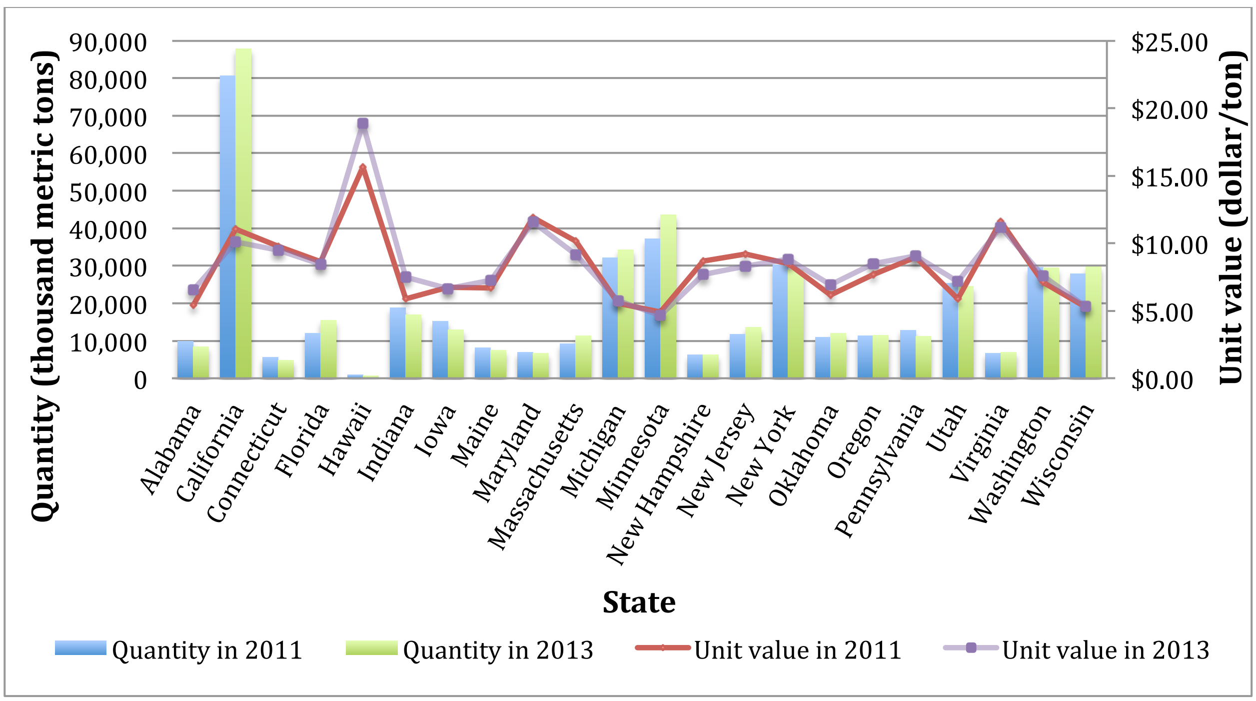

Figure 4 Construction Sand and Gravel Sold or Used in States with WTE facility in 2011 and 2013

4. Standard Specifications for Fine and Coarse Aggregates

Fine aggregates generally consist of natural sand or crushed stone with most particles smaller than 5 mm (0.2 in.). Coarse aggregates consist of one or a combination of gravels or crushed stone with particles predominantly larger than 5 mm (0.2 in.) and generally between 9.5 mm and 37.5 mm (3/8 in. and 11/2 in.) [6]. The important characteristics of aggregates for concrete are listed in Table 2 and most are discussed in the following sections.

Table 2 Characteristics and Tests of Aggregate [8]

Characteristic	Significance	Test designation*	Requirement or item reported
Resistance to abrasion and degradation	Index of aggregate quality; wear resistance of floors and pavements	ASTM C 131 (AASHTO T 96) ASTM C 535 ASTM C 779	Maximum percentage of weight loss. Depth of wear and time
Resistance to freezing and thawing	Surface scaling, roughness, loss of section, and aesthetics	ASTM C 666 (AASHTO T 161) ASTM C 682 AASHTO T 103	Maximum number of cycles or period of frost immunity; durability factor
Resistance to disintegration by sulfates	Soundness against weathering action	ASTM C 88 (AASHTO T 104)	Weight loss, particles exhibiting distress
Particle shape and surface texture	Workability of fresh concrete	ASTM C 295 ASTM D 3398	Maximum percentage of flat and elongated particles
Grading	Workability of fresh concrete; economy	ASTM C 117 (AASHTO T 11) ASTM C 136 (AASHTO T 27)	Minimum and maximum percentage passing standard sieves
Fine aggregate degradation	Index of aggregate quality; Resistance to degradation during mixing	ASTM C 1137	Change in grading
Uncompacted void content of fine aggregate	Workability of fresh concrete	ASTM C 1252 (AASHTO T 304)	Uncompacted voids and specific gravity values
Bulk density (unit weight)	Mix design calculations; classification	ASTM C 29 (AASHTO T 19)	Compact weight and loose weight
Relative density (specific gravity)	Mix design calculations	ASTM C 127 (AASHTO T 85) fine aggregate ASTM C 128 (AASHTO T 84) coarse aggregate	—
Absorption and surface moisture	Control of concrete quality (water-cement ratio)	ASTM C 70 ASTM C 127 (AASHTO T 85) ASTM C 128 (AASHTO T 84) ASTM C 566 (AASHTO T 255)	—
Compressive and flexural strength	Acceptability of fine aggregate failing other tests	ASTM C 39 (AASHTO T 22) ASTM C 78 (AASHTO T 97)	Strength to exceed 95% of strength achieved with purified sand
Definitions of constituents	Clear understanding and communication	ASTM C 125 ASTM C 294	—
Aggregate constituents	Determine amount of deleterious and organic materials	ASTM C 40 (AASHTO T 21) ASTM C 87 (AASHTO T 71) ASTM C 117 (AASHTO T 11) ASTM C 123 (AASHTO T 113) ASTM C 142 (AASHTO T 112) ASTM C 295	Maximum percentage allowed of individual constituents
Resistance to alkali reactivity and volume change	Soundness against volume change	ASTM C 227 ASTM C 289 ASTM C 295 ASTM C 342 ASTM C 586 ASTM C 1260 (AASHTO T 303) ASTM C 1293	Maximum length change, constituents and amount of silica, and alkalinity

*The majority of the tests and characteristics listed are referenced in ASTM (American Society for Testing and Materials) C 33 or AASHTO (American Association of State Highway and Transportation Officials) M 6/M 80

4.1 Grading

The aggregates are usually washed and graded at the pit or plant. The aim of grading is to distribute particle-size by using wire-mesh sieves with square openings. The grading and grading limits are usually expressed as the percentage (by mass) of material passing each sieve [8]. Table 2 shows these limits for coarse aggregate. Fine aggregate, when tested by means of laboratory sieves, shall conform to the requirements of Table 3.

Table 2 Grading Requirements for Coarse Aggregates [9,10]

Size Number	Nominal Size (Sieves with Square Openings)	Amounts Finer than Each Laboratory Sieve (Square-Openings), Mass Percent													
		100 mm (4 in.)	90 mm (3½ in.)	75 mm (3 in.)	63 mm (2½ in.)	50 mm (2 in.)	37.5 mm (1½ in.)	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (⅜ in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	300 µm (No.50)
1	90 to 37.5 mm (3½ to 1½ in.)	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...	...
2	63 to 37.5 mm (2½ to 1½ in.)	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...	...
3	50 to 25.0 mm (2 to 1 in.)	...	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...
357	50 to 4.75 mm (2 in. to No. 4)	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	...	0 to 5	...	...	...
4	37.5 to 19.0 mm (1½ to ¾ in.)	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...	...
467	37.5 to 4.75 mm (1½ in. to No. 4)	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...	...
5	25.0 to 12.5 mm (1 to ½ in.)	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...	...
56	25.0 to 9.5 mm (1 to ⅜ in.)	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...	...
57	25.0 to 4.75 mm (1 in. to No. 4)	...	...	...	...	...	100	95 to 100	...	25 to 60	...	0 to 10	0 to 5	...	...
6	19.0 to 9.5 mm (¾ to ⅜ in.)	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...	...
67	19.0 to 4.75 mm (¾ in. to No. 4)	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...	...
7	12.5 to 4.75 mm (½ in. to No. 4)	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...	...
8	9.5 to 2.36 mm (⅜ in. to No. 8)	...	...	...	...	...	...	...	...	100	85 to 100	10 to 30	0 to 10	0 to 5	...
89	9.5 to 1.18 mm (⅜ in. to No. 16)	...	...	...	...	...	...	...	...	100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5
9[A]	4.75 to 1.18 mm (No. 4 to No. 16)	...	...	...	...	...	...	...	...	...	100	85 to 100	10 to 40	0 to 10	0 to 5

Table 3 Grading Requirements for Fine Aggregate [9,11]

Sieve	Mass, % Passing
9.5 mm (3/8 in.)	100
4.75 mm (No.4)	95 to 100
2.36 mm (No.16)	80 to 100
1.18 mm (No.16)	50 to 85
600 µm (No.30)	25 to 60

300 μm (No.50)	10 to 30
150 μm (No.100)	2 to 10

4.2 Deleterious Substances

Aggregates must conform to certain standards for optimum engineering use. Coarse aggregates shall conform to the limits given in Table 5 for the class specified, when Table 4 clarifies the typical uses for aggregate conforming to the requirements for the various classes. The amount of deleterious substances within fine aggregates shall not exceed the following limits in Table 6.

Table 4 Typical Uses for Aggregate Conforming to the Requirements for the Various Classes [9,12]

Typical Uses (Suggested)	Weathering Exposure	Class of Aggregate
Architectural concrete, bridge decks, other uses where surface disfigurement due to popouts, etc., is objectionable	Severe	A
	Moderate	B
	Negligible	C
Concrete pavements, base courses, sidewalks where a moderate number of popouts can be tolerated	Severe	B
	Moderate	C
	Negligible	D
Concealed concrete not exposed to the weather: footings, structural members to be covered by a facing material, interior floors, etc.	—	E

Table 5 Limits for Deleterious Substances and Physical Property Requirements of Coarse Aggregate for Concrete [9,12]

Class Designation	Maximum Allowable%						
	Clay Lumps and Friable Particle	Chert (Less Than 2.40 sp gr SSD)	Sum of Clay Lumps, Friable Particles, and Chert (Less than 2.40 sp gr SSD)	Material Finer Than 75-μm (No.200) Sieve	Coal and Lignite	Abrasion	Sodium Sulfate Soundness (5 Cycles)
A	2.0	3.0	3.0	1.0	0.5	50	12

B	3.0	3.0	5.0	1.0	0.5	50	12
C	5.0	5.0	7.0	1.0	0.5	50	12
D	5.0	8.0	10.0	1.0	0.5	50	12
E	10.0	—	—	1.0	1.0	50	—

Table 6 Deleterious Substances Limits of Fine Aggregate [9,11]

	Class A, Max Mass, %	Class B, Max Mass, %
Clay lumps and friable particles	3.0	3.0
Coal and lignite	0.25	1.0
Material finer than 75-μm (No. 200) sieve: a. In concrete subject to surface abrasion not more than	2.0	4.0
b. All other classes of concrete, not more than	3.0	5.0
Other deleterious substances (such as shale, alkali, mica, coated grains, and soft and flaky particles)	Note 6	Note 6

Both fine and coarse aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalis in the cement in an amount sufficient to cause excessive expansion of mortar or concrete, except that if such materials are present in injurious amounts, use of the fine or coarse aggregate is not prohibited when used with a cement containing less than 0.60 % alkalis calculated as sodium oxide equivalent (Na_2O + 0.658K_2O), if there is a satisfactory service record evaluation, or with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction.

4.3 Others

The American Society for Testing and Materials (ASTM) has standard specifications for aggregates but it only demonstrates the requirements for grading, deleterious substances and soundness. It does not have any limitation on particle shape or surface texture. However, ASTM C 1252 describes an indirect test method for particle shape of fine aggregate, and ASTM D 4791 for coarse aggregate. These methods primarily are utilized in asphaltic concrete specifications, and no limitations are under consideration for fine or coarse aggregate particle shape within the ASTM C 33 specification, which is about standard specification for concrete aggregates.

For most aggregates used in concrete, the physical properties include bulk density, relative density (specific gravity) absorption and grading. ASTM C 33 is silent with regard to requirements for these properties. However, ASTM C 29 provides methods to determine bulk density and void content. Standard test methods for relative density (specific gravity) and absorption are introduced in ASTM C 127 for fine aggregate and 128 for coarse aggregate.

Compared to American standards, European and British Standards have more detailed descriptions of the mechanical and physical properties for aggregates.

5. Conclusions

WTEBA is a granular material containing lithophilic elements, intermingled with ferrous and non-ferrous metals and other incombustibles. After being processed for the recovery of ferrous and non-ferrous metals, WTEBA can conform to the requirements stated above by being separated in different fractions so that it can be used as a replacement for natural derived aggregates and further used for civil engineering applications.

Also, the demand for crushed stone and construction sand and gravel is much more than the amount of WTEBA generation in 2011. So as long as the WTEBA in each WTE facility is proven to be up-to-standard by sampling (AASHTO T 2) and testing, which includes Sieve Analysis and Fineness Modulus (T 27), Clay Lumps and Friable Particles (T 112), Lightweight Pieces in Aggregate (T 113), etc. WTEBA can be recycled in the form of various construction materials within different area of the US.

Recycling of WTEBA will avoid landfill and also the WTEBA could have value if used for civil construction applications. Also, the recycling of WTEBA instead of landfilling will result in several environmental benefits. However, the beneficial use of WTEBA depends on the material's properties, which in turn depend directly on the composition of feed waste and, to a lesser extent, on the type of combustor and combustion conditions [13].

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