Construction and Demolition Debris Generation in the United States, 2015
U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery
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1.0 Introduction

Construction and demolition (C&D) debris includes a variety of materials that may be generated from different sources (e.g., construction, renovation and demolition). The purpose of this document is to explain how U.S. Environmental Protection Agency (EPA) derived its estimate of C&D debris generation in the United States. The estimate included C&D debris generated from the construction, renovation and demolition of buildings, roads and bridges and other structures; and excluded C&D debris generated from land-clearing activity[1] or as a result of natural disasters.

EPA estimated how much C&D debris was generated in the United States by primarily using a materials flow analysis. Materials estimated through the materials flow analysis were concrete, steel, wood products, gypsum wallboard and plaster, brick and clay tile and asphalt shingles. Asphalt concrete generation was estimated using state-reported data for permitted solid waste management facilities as well as industry gathered data on reclaimed asphalt concrete (RAP) accepted by asphalt producers.

By primarily using the materials flow analysis, EPA took the same approach described in the memorandum *Construction and Demolition Debris Generation in the United States, 2014* (U.S. EPA 2016b). The main methodology change presented in this memorandum is the application of a methodology developed by Townsend et al. for estimating the mass of C&D debris materials in end-of-life management pathways in the U.S. (the "CDDPath" methodology), to estimate asphalt concrete generation (Townsend et al. Forthcoming). The estimation methods described in this memorandum, including the new methodology for estimating the generation of C&D asphalt concrete, support estimates published in *Advancing Sustainable Materials Management: 2015 Fact Sheet* (U.S. EPA 2018). In addition to newly published consumption data for 2012 through 2014, the methodology improvement for C&D asphalt also is used in this memorandum to revise and republish the 2012 - 2014 generation estimates priorly published in *Advancing Sustainable Materials Management: Facts and Figures 2013* (U.S. EPA 2015), *Advancing Sustainable Materials Management: 2014 Fact Sheet* (U.S. EPA 2016a) and *Construction and Demolition Debris Generation in the United States, 2014* (U.S. EPA 2016b).

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[1] The materials flow analysis method, the top-down approach that is based on tabulated material consumption data and typical lifespans for material types, does not account for the debris generated in land-clearing activity. A separate methodology was not developed because of limitations associated with the multiple management options for land-clearing debris that are decentralized and not tracked, such as management at the point of generation.

2.0 Construction and Demolition Debris Generation

This section includes a detailed description of the methodology used by EPA to estimate C&D debris generation and results from the analysis. The seven groups of products included in the analysis - concrete, steel, wood products, gypsum wallboard and plaster, brick and clay tile, asphalt shingles and asphalt concrete - represent the major components of the C&D debris stream. C&D debris generated from land-clearing activities or as a result of natural disasters was not included in the estimates.

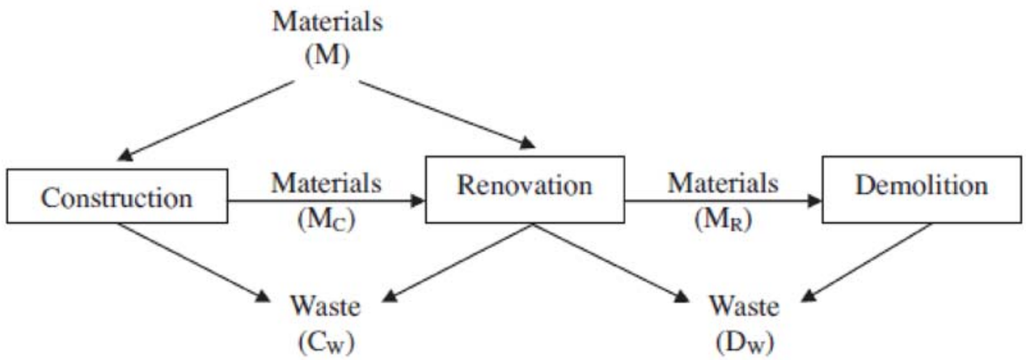
To estimate C&D debris generation for concrete, steel, wood products, gypsum wallboard and plaster, brick and clay tile, and asphalt shingles, EPA chose to use a top-down estimation method developed from a materials flow analysis by Cochran and Townsend (2010). This method is similar to the method EPA uses to calculate waste generation from durable goods in municipal solid waste in its *Advancing Sustainable Materials Management: Facts and Figures* reports. The materials flow method draws on publicly available historical materials-usage (consumption) data from several government and industry organizations, such as the U.S. Geological Survey (USGS) or U.S. Forest Service (USFS). Historical construction-material consumption is tabulated and typical lifespans of material types are assumed. The materials flow analysis estimates when each material has reached its end-of-life (EOL) and is ready for management.

Previously, *Advancing Sustainable Materials Management: Facts and Figures 2013*, *Construction and Demolition Debris Generation in the United States, 2014* and *Advancing Sustainable Materials Management: 2014 Fact Sheet* used a methodology that only included data from the National Asphalt Pavement Association (NAPA) survey, which underestimated asphalt concrete generation as the survey does not extend to state-permitted solid waste management facilities. This year, asphalt concrete generation was estimated using a different method proposed in CDDPath (Townsend et al., Forthcoming). For asphalt concrete, EPA used not only the quantity of asphalt concrete accepted by asphalt mix producers as estimated by NAPA and the U.S. Department of Transportation Federal Highway Administration (FHWA) but also calculated the amount of asphalt concrete managed at state-permitted solid waste management facilities. These data are directly related to total asphalt concrete waste generation, and no assumptions about the lifespan of asphalt concrete were required. The methodology improvement for C&D asphalt concrete supports the estimate of C&D asphalt concrete generation in *Advancing Sustainable Materials Management: 2015 Fact Sheet* and in part shapes this memorandum's updates to the generation estimates in previous publications.

2.1 C&D Debris Generation Methodology

Based on the Cochran and Townsend methodology, EPA derived total C&D debris generation from the sum of waste generated during construction and demolition activities. Figure 1 depicts the flow of materials resulting from construction, renovation and demolition over the lifetime of a building, road, bridge or other structure. Cochran and Townsend define C&D debris generated during construction (C_w) as the portion of purchased construction materials that are not incorporated into the actual structure, such as scraps and surplus materials. New construction and the installation phase of renovation projects both contribute to waste generated during construction. All of the materials (M) are consumed in construction (M_C) or renovation (M_R) becoming part of the structures that will eventually be demolished. Demolition waste (D_w) is the sum of materials removed from a structure during renovation and the materials generated from a structure's final demolition.

Figure 1. Materials Flow Diagram for Construction, Renovation, and Demolition



Source: Cochran and Townsend (2010)

Construction guides, used by builders to estimate the amount of materials to purchase for a construction project, provide the average amount of waste expected during construction for a range of materials. Cochran and Townsend used these guides to estimate the average percentage of materials discarded during construction, shown in Table 1. Equation 1 below shows the calculation of waste during construction for a given year based on annual material consumption and average percentage of material waste during construction.

(1) $C_{w,y} = M_y \times W_c$

where:

$C_{w,y}$ = amount of material waste discarded during construction in year y;

M_y = the amount of a given material consumed in the U.S. in year y; and,

W_c = the percentage of material discarded during new construction or the installation phase of renovation.

Table 1. Percent of Material Discarded During Construction

Material	Percent Discarded
Concrete	3%
Wood Products	5%
Drywall and Plasters	10%
Steel	0%
Brick and Clay Tile	4%
Asphalt Shingles	10%
Asphalt Concrete	0%

Source: DelPico (2004) and Thomas (1991)

Any material incorporated into the actual structure remains until removed during renovation or demolition, at which point it becomes demolition waste.[2] Since C&D debris generated from demolition in a given year was dependent on the lifespan of each construction material, Cochran and Townsend (2010) calculated a range of C&D debris generation from demolition based on the short, typical and long lifespan of the material and source of C&D debris shown in Table 2, resulting in three different values for C&D demolition debris for each year by material and source.

Table 2. Lifespan of Construction Materials by Source (years)

Material	Source	Lifespan		
		Short	Typical	Long
Concrete	Buildings	50	75	100
	Roads & Bridges	23	25	40
	Other Structures	20	30	50
Lumber	Buildings	50	75	100
Railroad Ties	Other Structures	20	35	45
Plywood and Veneers	Buildings	50	75	100
Wood Paneling	Buildings	20	25	30
Drywall and Plasters	Buildings	25	50	75
Steel	Buildings/ Roads & Bridges	50	75	100
Brick	Buildings	50	75	100
Clay Floor & Wall Tile	Buildings	15	20	25
Asphalt Shingles	Buildings	20	25	30
Asphalt Concrete	Buildings	20	25	30

Sources: Zapata and Gambatese (2005), Katz (2004), Park et al. (2003), Scheuer et al. (2003), Junnila and Horvath (2003), Chapman and Izzo (2002), Cross and Parsons (2002), Thormark (2002), Keoleian et al. (2001), Horvath and Hendrickson (1998), Bolt (1997), and Packard (1994), Bolin and Smith (2010) (2013). Additional corroboration with USGS (2010).

Table 3 shows the results for C&D debris generation of brick when using the Cochran and Townsend method for calculating demolition debris. While this method reflects the variability in demolition debris due to the uncertainty in material lifespan, each of the three demolition waste estimates were based on a single data point, i.e., historical consumption data for a single year. Furthermore, to provide a clearer depiction in the variance of the total amount using this method, the overall C&D debris generation was presented as a range. However, a single representative total waste value may be more useful to policymakers. To calculate a single representative total waste value for each material and source in a given year, only one demolition debris estimate must be chosen. However, it is not clear which of the three demolition debris estimates (short, typical, or long) would be the most representative of actual demolition debris generated in a given year.

Table 3 reveals that the demolition debris estimate for bricks calculated with the Cochran and Townsend method using the typical 75-year lifespan for bricks ranged from nearly 20 million short tons in 2000 to less than three million short tons in 2008. Because waste generation during construction remained fairly steady and contributed

[2] Similarly, as in Cochran and Townsend (2010), for a material such as asphalt shingles that reaches its assumed end of life before other materials associated with the same structure, EPA assumed that the material was removed from service through renovation, and it was accounted for in the demolition amount.

less than 10 percent of total C&D debris between 2000 and 2008, demolition debris estimates drove the observed changes. The rapid drop in demolition debris generation between 2004 and 2007 was due to falling consumption of bricks for construction as the Great Depression began in the late 1920s. A strong economy is indicative of high construction activity, and demolition activity to make space for new construction often precedes it. It seems unlikely that in 2007, at the height of the U.S. economy before the recession, demolition waste from bricks would be half of what it was in 2006 and a quarter of what it was in 2005 simply because of low consumption during the Great Depression 75 years ago. The same issues that caused highly variable C&D debris generation using a typical material lifespan can also affect demolition debris estimates using short or long lifespans.

Table 3. U.S. Annual C&D Brick Debris Generation Using Cochran and Townsend's (2010) Method to Calculate Demolition Debris Generation (tons)

Year	Brick Waste During Construction	Demolition Brick			Total C&D Brick Debris		
		Short Life	Typical Life	Long Life	Short Life	Typical Life	Long Life
2000	587,758	12,179,134	19,317,299	14,411,013	12,766,891	19,905,057	14,998,771
2001	568,881	12,756,344	19,163,376	16,258,085	13,325,224	19,732,257	16,826,966
2002	567,509	11,332,559	18,220,600	17,181,621	11,900,068	18,788,109	17,749,131
2003	568,572	11,294,078	16,989,218	17,123,900	11,862,650	17,557,790	17,692,472
2004	637,008	12,929,507	14,699,618	17,508,707	13,566,515	15,336,626	18,145,715
2005	661,298	15,199,867	11,755,846	19,932,990	15,861,165	12,417,145	20,594,288
2006	613,987	15,565,433	6,195,389	20,471,719	16,179,420	6,809,376	21,085,706
2007	523,995	12,814,065	2,693,647	19,971,470	13,338,059	3,217,642	20,495,465
2008	390,968	12,159,893	2,482,004	16,161,883	12,550,861	2,872,971	16,552,851
2009	276,945	14,122,408	2,693,647	20,413,998	14,399,352	2,970,592	20,690,943
2010	259,572	13,352,794	4,386,797	19,086,415	13,612,366	4,646,369	19,345,987
2011	237,394	12,852,545	7,349,809	17,701,110	13,089,939	7,587,203	17,938,504
2012	234,836	13,256,593	8,061,701	18,028,196	13,491,429	8,296,538	18,263,033
2013	203,398	14,257,090	6,791,839	17,162,381	14,460,488	6,995,238	17,365,779
2014	214,422	15,142,146	9,100,680	15,315,309	15,356,567	9,315,101	15,529,730
2015	221,520	15,796,317	7,888,538	14,834,300	16,017,837	8,110,059	15,055,821

Instead of calculating demolition debris generation based on one service life at a time (short, typical, long), EPA calculated an average demolition debris generation for the full range of years within each material's expected lifespan. The demolition debris generation from brick in 2014 was used as an example. The expected lifespan of brick ranged from 50-100 years (Table 2). EPA calculated demolition debris resulting from consumption of bricks for each year in 1914-1964, and then averaged the results. Equation 2 below shows the calculation used to estimate demolition waste for a given year.

(2) $$D_{w,y} = \frac{\sum_{i=(y-l)}^{(y-s)} (M_i - C_{w,i})}{(l-s)+1}$$

where:

y = the given year for which demolition waste generation is calculated;

l = the longest expected lifetime of the material (see Table 2);

s = the shortest expected lifetime of the material (see Table 2);

$D_{w,y}$ = the amount of demolition waste generated from material removed during renovation or demolition in year y;

M_i = the amount of a given material consumed in the U.S. in year i, where i ranges from year y-l to year y-s;

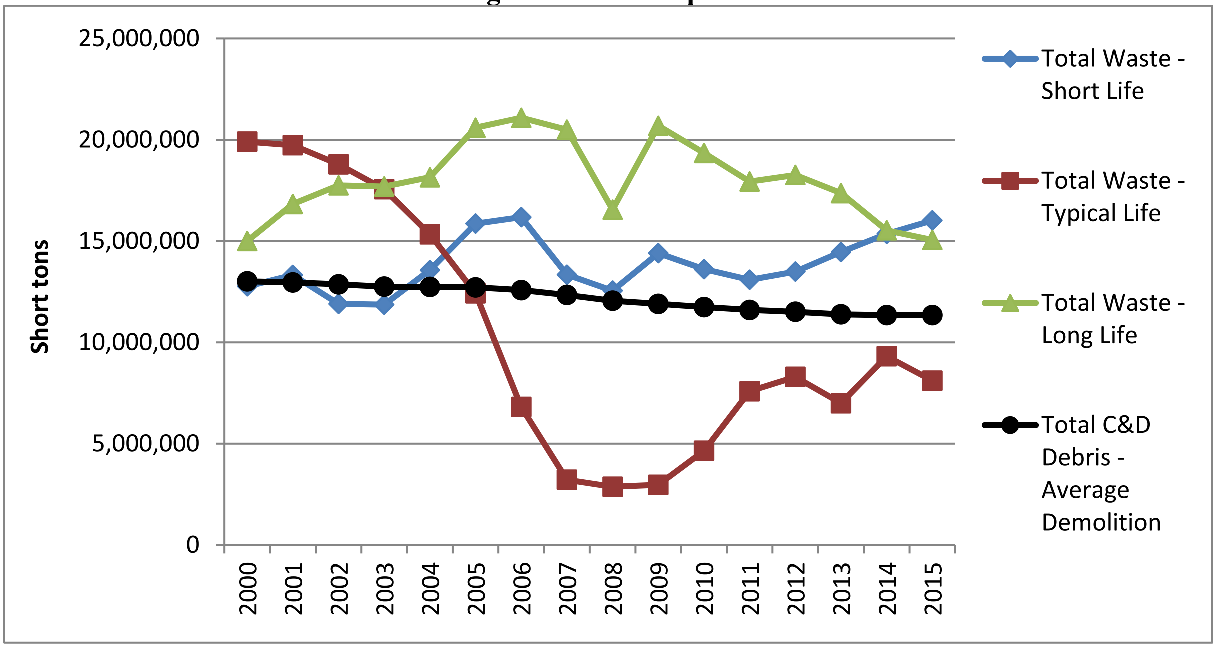
$C_{w,i}$ = the amount of material wasted during construction in year i, where i ranges from year y-l to year y-s.

Table 4 shows waste generated during construction, demolition, and total C&D debris from bricks for 2000-2015 using this averaging method. The total C&D debris estimates using EPA's method were much less susceptible to the influence of a single historical year's construction and consumption activity. Figure 2 shows total C&D brick debris generated between 2000 and 2015 using EPA's method to estimate demolition debris compared to the Cochran and Townsend method.

Table 4. U.S. Annual C&D Debris Generation from Bricks Using Average Demolition Debris Generation over the Range of Material's Useful Life (tons)

Year	Waste Brick During Construction	Demolition Brick	Total C&D Brick Debris
2000	587,758	12,423,599	13,011,357
2001	568,881	12,391,155	12,960,035
2002	567,509	12,294,576	12,862,085
2003	568,572	12,179,134	12,747,706
2004	637,008	12,096,891	12,733,898
2005	661,298	12,051,619	12,712,918
2006	613,987	11,965,981	12,579,968
2007	523,995	11,815,831	12,339,825
2008	390,968	11,662,663	12,053,630
2009	276,945	11,622,673	11,899,617
2010	259,572	11,484,218	11,743,790
2011	237,394	11,361,985	11,599,379
2012	234,836	11,274,838	11,509,674
2013	203,398	11,200,894	11,404,293
2014	214,422	11,161,282	11,375,704
2015	221,520	11,170,714	11,392,234

Figure 2. Comparison of Total C&D Debris Generation for Bricks EPA's Average Demolition Method* and Cochran and Townsend's Short, Typical and Long Material Lifespan method



***Total C&D Debris – Average Demolition estimates shown in Table 4.**

2.2 Historical Consumption Data

The following seven sections describe the historical consumption data used for each construction material, and any assumptions necessary to determine the share of consumption associated with the construction of buildings, roads and other structures.

Concrete

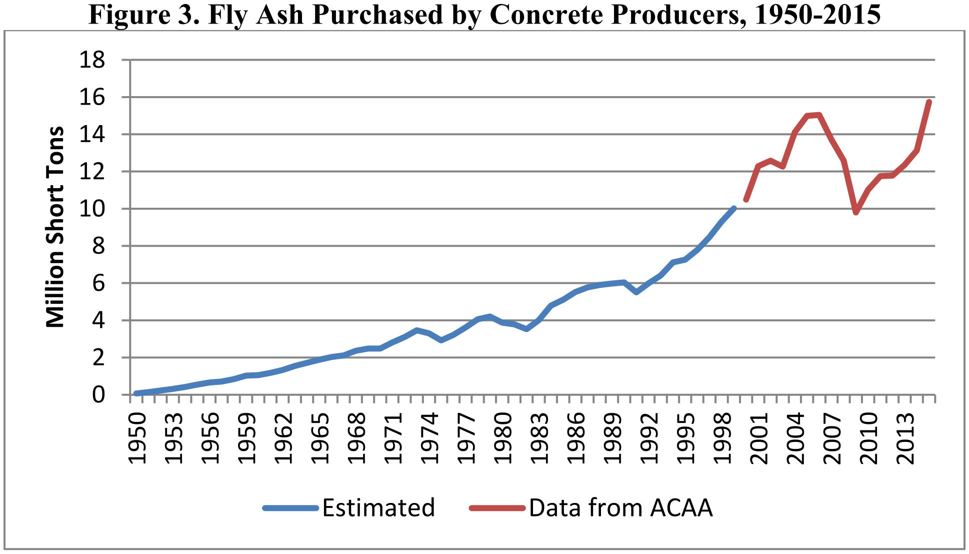
Following the same methodology developed to estimate C&D debris generation in 2014, C&D concrete represents concrete made using either portland cement or a mix of portland cement and fly ash for cementitious material. EPA derived historical concrete consumption largely based on cement consumption data published by the USGS for the years 1900 to 2015 (van Oss, 2017a). The USGS also reports the amount of cement by type, including portland cement for 1975-2014 (USGS, 2005a) (van Oss, 2017b). Since cement consumption statistics by type were not readily available for years prior to 1975, EPA assumed 96 percent of cement was portland cement, based on the data for 1975-2014. For 2015, EPA assumed the same percentage of portland cement as in 2014. In addition to portland cement consumption, EPA also converted fly ash consumption to concrete consumption. EPA used data on fly ash purchased for use in concrete and concrete products published by the American Coal Ash Association for the years 2000 to 2015 (ACAA, 2016).[3]

[3] U.S. cement and concrete producers purchase fly ash from coal-fired power plants to blend with cement. Most fly ash is purchased directly by concrete producers instead of cement producers. USGS historical cement consumption data only include data from cement producers (Thomas, 2007). Therefore, most of the fly ash consumed in concrete will not be captured using the USGS data on its own.

Although the possibility of substituting fly ash for portland cement in concrete has been known since the early 1900s, fly ash was not incorporated into concrete in large quantities until the 1950s (Thomas, 2007). Fly ash may replace portland cement at rates ranging from 15 to 40 percent by mass, depending on the composition of the fly ash and the type of construction in which the fly ash concrete will be used (U.S. EPA, 2014). In 2000, fly ash purchased by concrete producers made up 8.2 percent of total cementitious material input. A stepwise increase of 0.16 percent from zero percent in 1949 to 8 percent in 1999 was used to estimate the amount of fly ash used by concrete producers from 1950 to 1999 (see Figure 3).

EPA converted portland cement and fly ash consumption into estimated concrete consumption using the density of cement and concrete and amount of cement and fly ash used per unit of concrete. Because fly ash is a supplementary cementitious material, it is substituted one to one for portland cement on a mass basis (van Oss, 2016). As cited by Cochran and Townsend (2010), the 2003 American Society for Testing Materials (ASTM) International standard reported an average density of 2,300 kg/m^3 for concrete, and the Portland Cement Association (PCA) gave an average density of 3,150 kg/m^3 for portland cement and a typical concrete composition of 11 percent portland cement by volume. These values translated to 6.64 tons of concrete consumed per ton of portland cement.[4]

Figure 3. Fly Ash Purchased by Concrete Producers, 1950-2015



EPA used the method suggested by Cochran and Townsend (2010) to allocate consumption of concrete across the three sources of concrete C&D debris: buildings, roads and bridges and other structures. PCA estimated that in 2002, 47 percent of portland cement was used in buildings, 33 percent in roads and bridges, and 20 percent in other structures (Townsend and Cochran, 2010). Since this study assumes concrete consumption is directly related to cement consumption, the 2002 percentages for cement were used to calculate concrete consumption by buildings, roads and bridges and other structures in 2002. The following list describes the steps taken to estimate the division of concrete consumption among buildings, roads and bridges and other structures using the ratio from

[4] Although cement and concrete density values do not consider the addition of fly ash, in the absence of a more relevant factor, EPA used the same 6.64 portland cement-to-concrete ratio to convert the fly ash consumption to concrete consumption.

PCA and historical datasets from the U.S. Census Bureau on the annual value of construction put-in-place [5] grouped by type of structure (U.S. Census Bureau, 1975a, 1975b, 2003, 2016, and 2017a). EPA used differences in construction spending between 2002 and a given year in each of the three source categories to adjust the 2002 percentages from PCA to reflect changes in the distribution of concrete consumption between buildings, roads and bridges and other structures over time.

1. Converted all construction put-in-place values into 1996 constant dollars:
    a. 1964-2002 values (U.S. Census Bureau, 2003a): No conversion necessary.
    b. 1915-1963 values (U.S. Census Bureau, 1975a): Converted values presented in 1957-1959 constant dollars by multiplying each value by a factor of 6.39, which was the relative value of a constant 1996 dollar to constant 1957-1959 dollar based on index tables. This value was computed by 1) calculating the ratio of the 1970 index value and 1957-1959 index value using data from series N1 and N30 (U.S. Census Bureau, 1975a); 2) calculating the ratio of the 1996 index value to the 1970 index value in the 1964-2002 historical value of construction put-in-place (U.S. Census Bureau, 2003a and 2003b); and 3) multiplying these two ratios together.
    c. For 2003-2015 values (U.S. Census Bureau, 2008 and 2017a): Converted values presented in current dollars using the annual price indexes of new single-family homes (U.S. Census Bureau, 2017b). The index for each year was calculated by multiplying the current dollar for a given year by the 1996 index value and dividing by the index value of the given year.
2. Calculated construction put-in-place for buildings, roads, and other structures by summation of subcategory values (in constant 1996 dollars).
    a. For 1915-2002, the buildings category included residential and non-residential buildings from private and public construction as well as non-residential farm construction; roads includes publicly constructed highways, roads, and streets; and other structures includes all privately constructed public utilities and all other private structures as well as public construction of military facilities, sewer and water systems, conservation and development, public service enterprises and all other public structures.
    b. For 2003-2015, the buildings category included residential and non-residential lodging, office, commercial, health care, educational, religious, public safety and amusement and recreation categories; roads include the highways and streets category; and other structures include the communication, power, transportation, sewer and waste disposal, water supply, conservation and development and manufacturing categories.
3. Calculated the ratio of spending to tons of concrete (constant 1996 dollars/ ton) consumed for buildings, roads and bridges and other structures in 2002.
    a. Multiplied total concrete consumption in 2002 by PCA's estimated distribution of cement among the three sources in 2002 (47 percent for buildings, 33 percent for roads and bridges and 20 percent for other).

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[5] *Value of construction put-in-place* represents the total dollar value of construction work done in the U.S.

   b. Divided 2002 construction put-in-place values for buildings, roads and bridges and other structures (in constant 1996 dollars) by tons of concrete consumed by each of the three categories.

4. Calculated the percent of concrete use by source for each year using the spending per ton of concrete ratios developed in Step 3.
   a. Divided spending (in constant 1996 dollars) on buildings, roads and bridges, other structures and total construction spending for each year by the corresponding 2002 spending per ton of concrete ratio for each source.
   b. Divided the tons of concrete for each source estimated in Step 4a using 2002 spending ratios by the total tons of concrete for that year derived from construction spending to calculate percent distribution of concrete consumption across buildings, roads and bridges and other structures for the years 1915-2015.
   c. Estimated 1900-1915 concrete consumption distribution for the three sources based on the average distribution for 1915-2015.
5. Calculated the tons of concrete consumed for buildings, roads and bridges and other structures in a given year by multiplying the total tons of concrete consumed in construction (based on USGS cement consumption data) by the percent distribution of concrete use associated with each source (Step 4) for a given year.

The revisions made to 2014 portland cement consumption data published by USGS (2015) resulted in revised concrete generation estimates from those previously published in EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo. The total concrete generation estimate for 2014 in the previously published memo of 375.298 million tons was revised to 375.322 million tons.

Wood Products

The USGS published consumption data from the U.S. Forest Service (USFS) for lumber, wood paneling, and plywood and veneer products available for 1900 to 2013 (USGS, 2016). The USFS *U.S. Forest Products Annual Market Review and Prospects, 2012–2016* report provides data for 2014 and 2015 wood product consumption in units of volume (Howard & Jones, 2016). These preliminary data were converted to a mass basis using conversion factors provided by USFS (Howard & McKeever, 2016; Howard, 2017).

EPA assumed that all wood panels as well as plywood and veneer are used in building applications. For lumber, EPA relied on the study published by the USFS reporting approximately 78 percent of lumber use for construction (Howard, 2007).[6] EPA split that amount between buildings and railroad ties and calculated C&D lumber generation per those two sources. Namely, lumber consumed for construction of buildings was calculated by subtracting the amount of wood used for railroad ties from total lumber used in construction.

Consumption of lumber for railroad ties was based on data for annual rail tie installations from the Rail Tie Association (RTA 2017) (Gauntt, 2012, 2013, 2014, 2015, and 2016) and conversions associated with the use of wood in rail ties. Data were available for the number of ties installed for Class 1 railroads from 1921 through 2015 and for short line and regional railroads from 2011 through 2015. EPA assumed an annual installation rate

[6] The remaining 22 percent of lumber is used in non-construction applications including transport packaging such as pallets and manufacturing wooden consumer goods such as furniture (Howard, 2007).

of six million ties for the years 1900 through 1920 based on the average number of new ties installed from 1921 to 1930. Data for switch and bridge ties included annual board footage for 1995 through 2014.

To calculate the weight of wood consumed annually from the number of ties installed and the board footage of switch and bridge ties, EPA used standard conversion factors. According to the Rail Tie Association, a typical tie is seven inches tall by nine inches wide by 8.5 feet long, which is equivalent to 3.72 cubic feet per tie (RTA 2014). Reported board footage for switch and bridge ties was converted to cubic feet by dividing by 12. EPA used a factor of 20.2 short tons/1000 cubic feet of ties based on USFS volume-to-weight conversion factors for hardwood lumber from USFS (1990).

Construction waste associated with the installation of ties was estimated to be 5 percent of annual consumption; the same rate that was used to estimate the amount of other wood products discarded during construction. To estimate demolition waste, railroad ties were assumed to have a lifespan ranging from 20 to 45 years with an average useful life of 35 years (Bolin and Smith, 2010 and 2013).

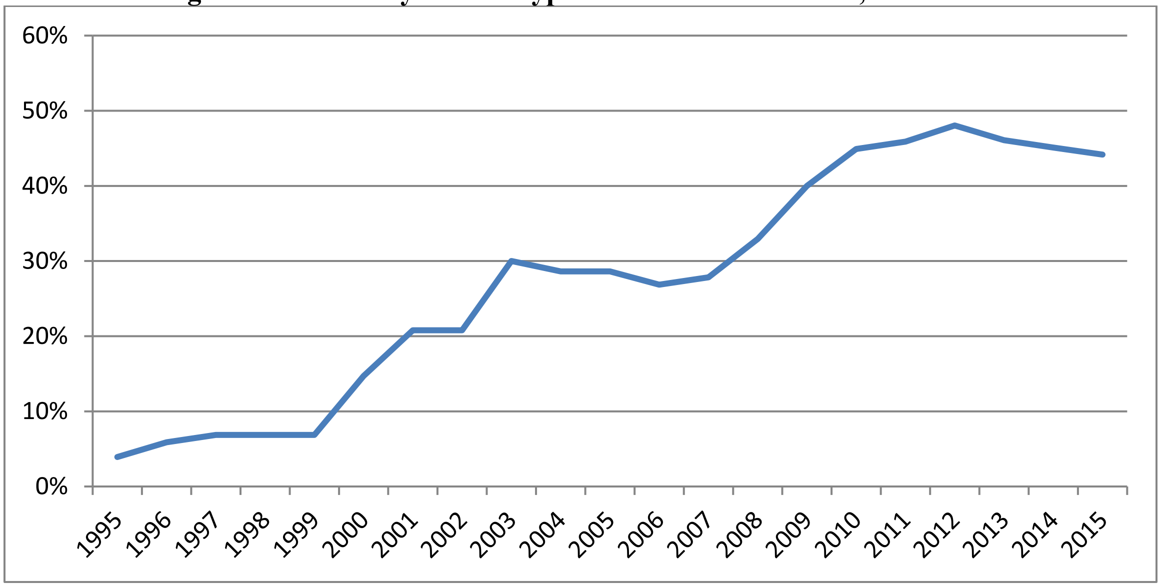
The updated rail tie consumption data from RTA for 2012 through 2014 resulted in slight revisions of generation estimates for lumber from buildings and railroad ties previously published in EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo, but total wood products generation estimates remained the same. In the previously published memo, lumber from buildings was 26.252, 26.380, and 26.572 million tons and railroad ties were 1.412, 1.401, and 1.377 million tons, in 2012-2014, respectively. Using revised data, the lumber from buildings was updated to 26.253, 26.382, and 26.573 million tons and railroad ties were updated to 1.412, 1.400, and 1.376 million tons, in 2012- 2014, respectively.

Gypsum Drywall and Plasters

EPA used USGS historical consumption data for gypsum for 1900 through 2015 (Buckingham et al., 2017) (Crangle, 2017). USGS also published end-use statistics for gypsum, available for 1975-2015, which documented annual consumption of drywall (listed as prefabricated products) and plasters made from calcined gypsum (USGS, 2005b) (Crangle, 2017b). EPA used these data to calculate the percent of gypsum consumed by drywall and plasters for the years 1975-2015. To calculate annual drywall and plaster consumption before 1975, EPA multiplied total apparent gypsum consumed each year in 1900-1974 by 75 percent, the average percent of gypsum used in drywall and plasters during 1975-2012.

Over the last two decades, an increasing amount of gypsum used in construction products has been synthetically produced as a byproduct of emissions control devices at coal-fired power plants. As shown in Figure 4, the Gypsum Association tracks and publishes the amount of synthetic gypsum, also known as flue gas desulphurization (FGD) gypsum, as a percent of total gypsum used in wallboard (Gypsum Association, 2016). As shown in Figure 4, the percent of synthetic gypsum used in wallboard was less than 5 percent in 1995. The short lifespan for drywall and plaster products was estimated to be 25 years (Table 2), which results in 1990 being the most recent consumption data point considered for drywall demolition debris. In 1990, the percent of synthetic gypsum used would have been less than the percent used in 1995. It is, therefore, unlikely that drywall and plaster products made with FGD gypsum represented more than de minimis amounts in the demolition debris generated from 2012- 2015. However, drywall and plaster products made with FGD gypsum did contribute to the construction debris for gypsum drywall and plaster from 2012 - 2015.

Figure 4. Percent Synthetic Gypsum Used in Wallboard, 1995-2015



Updated gypsum consumption data published by USGS for years 2012 through 2014 resulted in revisions of drywall and plaster generation estimates previously published in EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo. The total drywall and plaster generation estimates in the previously published memo were 12.517, 12.832 and 13.591 million tons in 2012-2014, respectively, and were revised to 12.333, 12.724, and 12.702 million tons in 2012-2014, respectively.

Steel

The *Statistical History of the United States: From Colonial Times to the Present* from the U.S. Census Bureau (1975c) provided the amount of structural iron and steel shapes produced for 1900-1970 and USGS published steel consumption data for 1979 through 2014 by end-use, including construction (USGS, 2005c) (Fenton, 2016). Steel consumption for construction for 1971-1978 was estimated by interpolation based on data for 1970 and 1979. EPA estimated 2015 steel consumption for construction using the total apparent steel consumption reported by USGS (DiFrancesco et al., 2017) and the assumption that the percent of steel consumed by construction activities in 2015 remained the same as in 2014 (Fenton, 2016).

Updated 2014 steel consumption data were available from USGS (2017); however, the revision did not result in a change in the previously published 2014 total C&D debris generation estimate for steel in EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo. Note that consumption of steel for construction includes total use in buildings, roads and bridges, and other structures; data were not available to allocate steel use between the three construction categories.

Bricks and Clay Floor and Wall Tile

The U.S. Census Bureau's *Statistical History* (1975d) reported the number of bricks consumed for building construction for the years 1900-1969. EPA used the conversion factor of 499 bricks per short ton, converted from 550 bricks per metric ton as cited in Cochran and Townsend (2010). Total historical consumption by clay type was from USGS data series 140 (Buckingham, Virta, & Flanagan, 2017). For 1970-2014, USGS published clay end-use data, including bricks, for common clay and shale (USGS, 2005d) (Virta, 1975, 2016, and 2017b) and kaolin clay (Virta, 2017c) for 1975-2013. For clay tile, EPA used USGS end-use data for common clay and shale (USGS, 2005d) (Virta, 1975 and 2015c), ball clay (USGS, 2005e) (Virta, 1975 and 2015b) and kaolin clay (Virta, 2015d) available for 1975-2013. For 2015, the USGS Mineral Commodity Summary provides an approximate percentage of common clay and shale used to produce brick and ball clay used to make tiles (Virta, 2016). Consumption of bricks from kaolin clay were not reported separately in the 2014 Minerals Yearbook for clay so were assumed the same in 2014 and 2015 as reported in 2013. Tile from kaolin clay and miscellaneous clay and shale were assumed the same in 2015 as reported in 2014.

Changes in brick and clay tile consumption data published by USGS resulted in revisions in the 2013 and 2014 generation estimates for clay tile and brick that were previously published in EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo. The total brick and clay tile generation estimates in the previously published memo of 12.057 million tons in 2013 and 12.042 million tons in 2014 were revised to 12.076 million tons in 2013 and 12.082 million tons in 2014.

Asphalt Shingles

Since historical data on asphalt shingle consumption were not readily available, EPA first estimated the amount of asphalt shingles consumed in a given year and then used an indicator to estimate changes in asphalt shingle consumption over time. While this method is based on Cochran and Townsend (2010), instead of using asphalt production as the indicator of changes in asphalt shingle consumption, EPA used the sales of roofing granules published by USGS. USGS end-use statistics for 1980-2014 included roofing granules made from construction sand and gravel (USGS, 2005f) (Bolen, 2017), crushed stone (Tepordei, 2006) (Willett, 2017) and silica (USGS, 2005g) (Dolley, 2017). USGS end-use statistics for roofing granules consumed in 2015 were available for silica (Dolley, 2017) and crushed stone (Willet, 2017), but these data were not available for sand and gravel. The quantity of roofing granules from silica in 1980-2015 were used as reported by USGS. However, USGS reported large portions of sand and gravel and crushed stone as "unspecified uses" and only published data every other year between 1980 and 1994. To account for roofing granules included in unspecified uses for these two categories of aggregates, EPA calculated the percent roofing granules of all specified end uses for each year, and multiplied by total apparent consumption for each aggregate (Porter et al., 2017; DiFrancesco, Tepordei, & Willett et al., 2017; Porter and Dolley, 2017). For odd numbered years between 1980 and 1994 where USGS did not calculate roofing granules consumed, EPA estimated consumption by averaging the consumption from the previous and following years. In order to estimate roofing granules from construction sand and gravel in 2015, the ratio of roofing granules to total apparent consumption in 2014 was multiplied by the total apparent consumption in 2015 (Willet, 2017; Porter et al., 2017).

In 2006, the Asphalt Roofing Manufacturers Association (ARMA et al., 2011) reported sales of nearly 149,830,000 squares[7] of roof coverage. Table 1-1 in *Roofing the Right Way* (Bolt, 1997) presented a range of 210-250 pounds per square of roofing coverage. Using the midpoint of 230 pounds per square, EPA converted 2006 shingle sales in squares to tons of shingles sold in 2006. The final step entailed multiplying the weight of shingles sold in 2006 by the ratio of roofing granules consumed in a given year to roofing granules consumed in 2006.

Updated 2013 and 2014 USGS total apparent consumption data for each aggregate and correction of a calculation error resulted in revisions in the 2012 through 2014 generation estimates for asphalt shingles previously published in EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo. The total asphalt

[7] One "square" refers to the amount of shingles required to cover 100 square feet of a roof.

shingles generation estimates in the previously published report were 12.010, 11.629 and 12.699 million tons in 2012-2014, respectively, and were revised to 12.601, 12.280, and 13.043 million tons in 2012-2014, respectively.

Asphalt Concrete

Cochran and Townsend (2010) used a materials flow analysis and USGS end-use statistics on consumption of aggregates used in asphaltic and bituminous aggregates to estimate the generation of asphalt concrete. By contrast, EPA estimated asphalt concrete generation by combining data on reclaimed asphalt pavement (RAP) accepted by asphalt mix producers published by NAPA and FHWA with data for state-permitted solid waste management facilities, such as landfills and mixed C&D debris processing facilities (Townsend et al, Forthcoming; Hansen and Copeland, 2014, 2015, and 2017). This method of estimating C&D asphalt concrete was proposed in the methodology developed for quantifying the mass of C&D debris materials in different end-of-life management pathways in the U.S. (the "CDDPath" methodology) (Townsend et al., Forthcoming). EPA chose this method because the data about the end-of-life management of C&D asphalt concrete are directly related to total asphalt concrete waste generation, and no assumptions about the lifespan of asphalt concrete were required. The data sources for the C&D asphalt managed in state-permitted solid waste management facilities include state reports about the mixed C&D debris amounts and composition in state-permitted facilities, and an industry survey of mixed C&D debris processing facilities (CDRA, 2014).

In CDDPath, the C&D asphalt concrete managed as mixed C&D debris in state-permitted facilities is grouped with glass, organics, plastics, carpet, fines, and cardboard; these materials are in steps below referred to as the group 2 materials. The generation of these materials was not estimated in the *Construction and Demolition Debris Generation in the United States, 2014* report. The group of mixed C&D debris stream's materials whose generation amounts were estimated in the *Construction and Demolition Debris Generation in the United States, 2014* - the mixed C&D stream's concrete, wood, gypsum drywall and plasters, brick and clay tiles, steel, and asphalt shingles – were grouped separately, and are here referred to as the group 1 materials. These groupings were assumed to enable alignment with EPA's *Construction and Demolition Debris Generation in the United States, 2014* report.[8]

Several larger steps in the CDDPath methodology were relevant for calculating the mass amount of C&D asphalt managed in state-permitted solid waste management facilities. In these steps, first the fractional ratios of the C&D materials in the mixed C&D debris stream were calculated, and then the mass amount of the mixed C&D debris landfilled and the mass amount of mixed C&D debris processed for use across the nation were calculated as well, followed by the mass amounts of mixed-stream's C&D asphalt landfilled or processed for use. The number order of the steps below is specific to this memo and does not align with the number order of the steps in CDDPath. Steps in CDDPath encompass additional calculations for source-separated C&D debris materials, and a description of those calculations has here been omitted. Also noteworthy is that the calculation described in the steps below uses references relevant for the 2014 analysis included in CDDPath, such as to the *Construction and*

[8] The mixed-stream's C&D asphalt concrete, glass, organics, plastics, carpet, fines, and cardboard were not part of EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo; the C&D asphalt concrete EPA priorly estimated is the source-separated C&D asphalt concrete managed by asphalt mix producers, and it excludes the C&D asphalt concrete managed in state-permitted solid waste management facilities. Although not part of EPA's *Construction and Demolition Debris Generation in the United States, 2014* memo, glass, organics, plastics, carpet, fines, and cardboard are often managed in state-permitted solid waste management facilities as mixed C&D debris, and the composition data from these facilities include fractions of these materials. The CDDPath included the entirety of the data in these composition studies, but to ensure alignment with the *Construction and Demolition Debris Generation in the United States, 2014* memo, the materials which were outside this publication were regarded in their own distinct steps.

Demolition Debris Generation in the United States, 2014 report. For this 2015 analysis, EPA updated the data sources used in CDDPath to the latest available data:

1. The first CDDPath's step relevant for calculating C&D asphalt concrete managed in state-permitted solid waste management facilities was focused on determining the preliminary composition of the landfilled and processed mixed C&D debris streams and the fractions of different material types in these streams. For example, the ratio of the quantity of asphalt concrete processed for use to the overall quantity of all materials processed for use in the facilities surveyed (CDRA, 2014) was used to estimate the fraction of asphalt concrete in the recovered mixed C&D debris stream.
2. Next, the sum total landfilled C&D wood amount and the sum total processed for use C&D wood amount were calculated based on the landfilling and recycling rates in the state-reported data and the C&D wood generation amount from *Construction and Demolition Debris Generation in the United States, 2014*.
3. Preliminary composition data from the first step above, were normalized to the group of mixed C&D debris stream's materials that were estimated in the *Construction and Demolition Debris Generation in the United States, 2014* - the "group 1" materials. The preliminary sum total amount of the group 1 materials landfilled versus the sum total amount of these materials processed, was calculated using the normalized fraction of C&D wood in the landfilled versus processed streams and the amount of landfilled C&D wood versus the amount of processed C&D wood from the previous step.
4. The preliminary landfilled and processed amounts for each material type in the group 1 were further broken out by applying the normalized fractions to the preliminary C&D debris landfilling or processing sum totals. For each group 1 mixed C&D debris material type, the sum of the landfilled amount and amount processed for use was corrected by setting it to equal the generation calculation in EPA's C&D debris generation analyses, *Construction and Demolition Debris Generation in the United States, 2014.*
5. The final sum amount of all the group 1 materials landfilled and the sum amount of all these materials processed for use were calculated by adding the corrected amounts for each material type from the previous step.
6. The group 2 materials were regarded separately and calculated based on the group 1 materials. The sum amount of the group 2 materials landfilled versus the sum amount processed for use was calculated using the sum amounts for the group 1 materials and the ratio of the preliminary fractions of the group 2 and group 1 materials in the landfilled and processed mixed C&D debris streams from the first step described above.
7. The landfilled and processed preliminary fraction of every group 2 material, including the mixed C&D debris stream's asphalt concrete, was then normalized so that the group 2 materials constituted a 100% of the mixed C&D debris stream's materials. The normalized fractions for C&D asphalt concrete landfilled or processed were then applied to the total estimated mass amount for the group of these materials landfilled or processed for use nationwide by state-permitted solid waste management facilities from the previous step.
8. Finally, the sum of the estimates of asphalt concrete processed nationally as mixed C&D debris and asphalt concrete landfilled nationally as mixed C&D debris from the previous step was added to the amount of RAP accepted in asphalt mix plants published by NAPA and FHWA to obtain the total C&D asphalt generation amount.

Previously, *Advancing Sustainable Materials Management: Facts and Figures 2013*, *Construction and Demolition Debris Generation in the United States, 2014* and the associated *Advancing Sustainable Materials Management: 2014 Fact Sheet* used a methodology that only included data from the NAPA survey, which underestimated asphalt concrete generation as the survey does not extend to state-permitted solid waste management facilities. NAPA's 2013, 2014, and 2015 reports (Hansen and Copeland, 2014, 2015, and 2017) provide annual estimates of the tons of RAP accepted by asphalt mix producers from 2009 to 2015 based on their survey about recycled materials and warm-mix asphalt usage, data from state asphalt pavement associations, and each state's highway apportionment. According to CDDPath, in 2014, asphalt concrete waste sent to state-permitted solid waste management facilities was 6,929,914 million tons, an additional 9.1% more waste than captured by NAPA Survey. Concrete asphalt generation based on NAPA data for 2012 and 2013 were increased by 9.1% to account for C&D asphalt concrete managed by state-permitted solid waste management facilities. The new CDDPath methodology resulted in revised 2012-2014 asphalt concrete estimates compared to those previously published by EPA (U.S. EPA 2016b). The total asphalt concrete generation estimates in the previously published report of 72.020, 76.869, and 76.566 million tons in 2012-2014, respectively, were revised to 77.819, 83.057, and 82.730 million tons in 2012-2014, respectively.

2.3 C&D Debris Generation Results

This section presents results for 2012 through 2015 C&D debris generation estimates. Table 5 displays the amount of C&D debris generated from buildings, roads and bridges and other structures for each material. The "other structures" category included C&D debris from wooden railroad ties and concrete used in communication, power, transportation, sewer and waste disposal, water supply, conservation and development and manufacturing infrastructure. Although results did not vary greatly between the years presented, C&D debris generation rose slightly each consecutive year for all material types except railroad ties, bricks and clay and a small dip in asphalt shingle debris in 2013 and asphalt concrete in 2014.

Methodological improvements for calculating asphalt concrete waste generation resulted in an increase in the asphalt concrete C&D debris generation estimates for 2012 through 2014 previously reported in *Construction and Demolition Debris Generation in the United States, 2014* (U.S. EPA 2016b) by 5.8, 6.2 and 6.2 million short tons for 2012-2014, respectively. Total generation results for 2012, 2013, and 2014 were higher than previously published in large part due to the adjustment in methodology for calculating asphalt concrete generation.

Table 5. C&D Debris Generation by Source (thousand tons)

	Buildings				Roads and Bridges				Other			
	2012	2013	2014	2015	2012	2013	2014	2015	2012	2013	2014	2015
Concrete	78,236	81,054	84,678	88,398	156,259	157,068	157,322	158,386	129,898	131,420	133,323	134,974
Wood Products[1]	36,253	36,773	37,224	37,594					1,412	1,400	1,376	1,356
Drywall and Plasters	12,333	12,724	12,702	13,042								
Steel[2]	4,230	4,282	4,350	4,455								
Brick and Clay Tile	12,180	12,076	12,082	12,147								
Asphalt Shingles	12,601	12,280	13,043	13,525								
Asphalt Concrete					77,819	83,057	82,730	83,900				
Total	155,833	159,189	164,079	169,161	234,078	240,126	240,052	242,286	131,310	132,820	134,699	136,330

1 Wood consumption in buildings also includes some lumber consumed for the construction of other structures. Data were not available to allocate lumber consumption for non-residential and unspecified uses between buildings and other structures except for railroad ties. Since non-residential buildings such as barns, warehouses, and small commercial buildings are assumed to consume a greater amount of lumber than other structures, the amount of lumber for construction remaining after the amount for railroad ties is split out is included in the buildings source category.

2 Steel consumption in buildings also includes steel consumed for the construction of roads and bridges. Data were not available to allocate steel consumption across different sources, but buildings are assumed to consume the largest portion of steel for construction.

Figure 5 illustrates waste generation for 2015 and highlights that roads and bridges contributed significantly more to C&D debris generation in 2015 than buildings and other structures, and concrete made up the largest share of C&D debris generation for all three categories.

Table 6 presents C&D debris generated by activity (i.e. construction and demolition) and total C&D debris for each material. Total C&D debris generation was about 521 million tons in 2012, 532 million tons in 2013, 539 million tons in 2014, and 548 million tons in 2015. As for C&D debris reported by source (Table 5), results categorized by activity were similar across each year. Concrete consumption created much more waste during construction than any other material. However, Figure 6 shows that waste during construction for drywall and plasters contributed a much greater percentage of the overall C&D debris for drywall and plasters than was the case for concrete. As noted in the methodology section for gypsum drywall and plasters, products made with flue gas desulphurization (FGD) gypsum are unlikely to have been on the market long enough to have had much of an impact on demolition debris during 2012 through 2015. However, FGD gypsum found in drywall and plaster products that were generated during construction contributed 8 percent of the 13,042 thousand tons of drywall and plaster C&D debris generated in 2015. Demolition played the largest role in determining C&D debris generation, as demolition debris comprised over 90 percent of total C&D debris generation for all materials except drywall and plasters.

Figure 5. C&D Debris Generated in 2015 by Material and Source

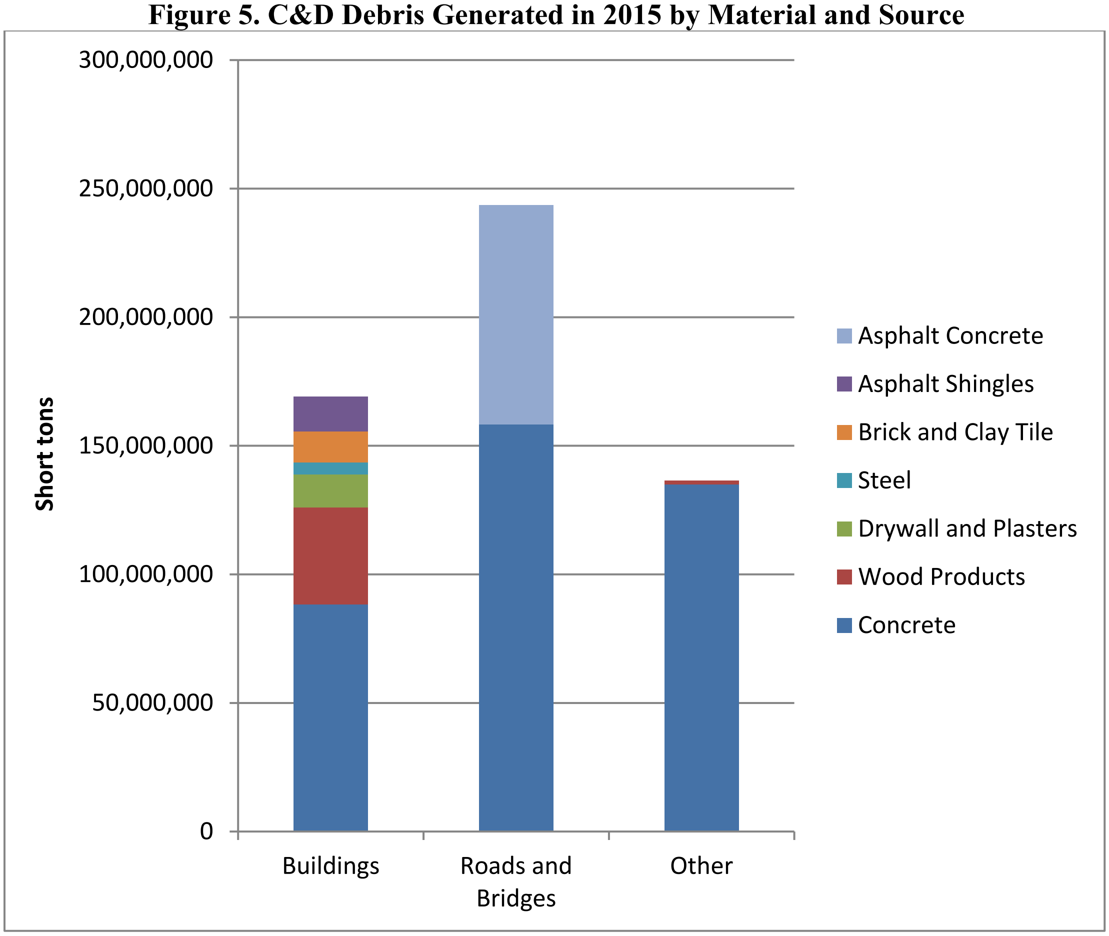
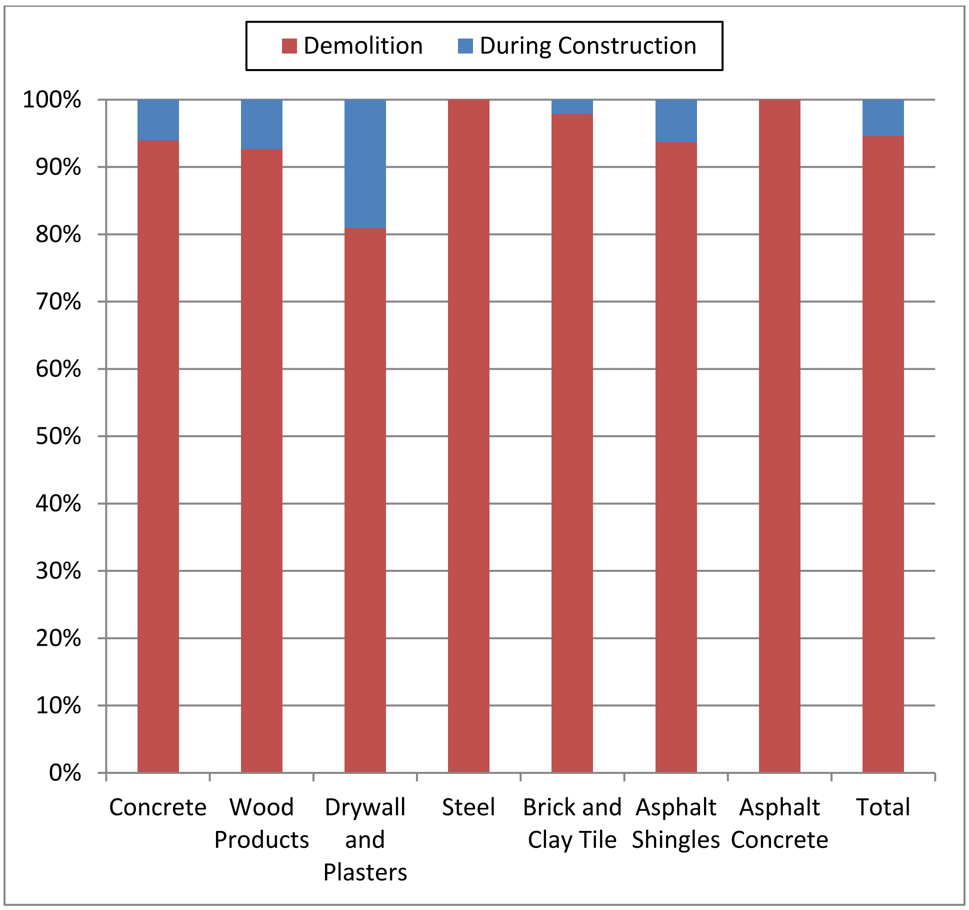


Table 6. C&D Debris Generation by Material and Activity (thousand tons)

	During Construction				Demolition				Total			
	2012	2013	2014	2015	2012	2013	2014	2015	2012	2013	2014	2015
Concrete	19,018	19,939	21,689	23,081	345,376	349,603	353,634	358,677	364,394	369,542	375,322	381,758
Wood Products	2,507	2,691	2,842	2,860	35,158	35,481	35,758	36,090	37,665	38,172	38,600	38,950
Drywall and Plasters	2,697	2,788	2,431	2,490	9,636	9,936	10,271	10,552	12,333	12,724	12,702	13,042
Steel					4,230	4,282	4,350	4,455	4,230	4,282	4,350	4,455
Brick and Clay Tile	265	232	252	258	11,915	11,845	11,830	11,889	12,180	12,076	12,082	12,147
Asphalt Shingles	974	866	498	850	11,627	11,414	12,545	12,675	12,601	12,280	13,043	13,525
Asphalt Concrete					77,819	83,057	82,730	83,904	77,819	83,057	82,730	83,900
Total	25,460	26,516	27,712	29,540	495,760	505,619	511,117	518,242	521,220	532,134	538,829	547,777

Figure 6. Contribution of Construction and Demolition Phases to Total 2015 C&D Debris Generation



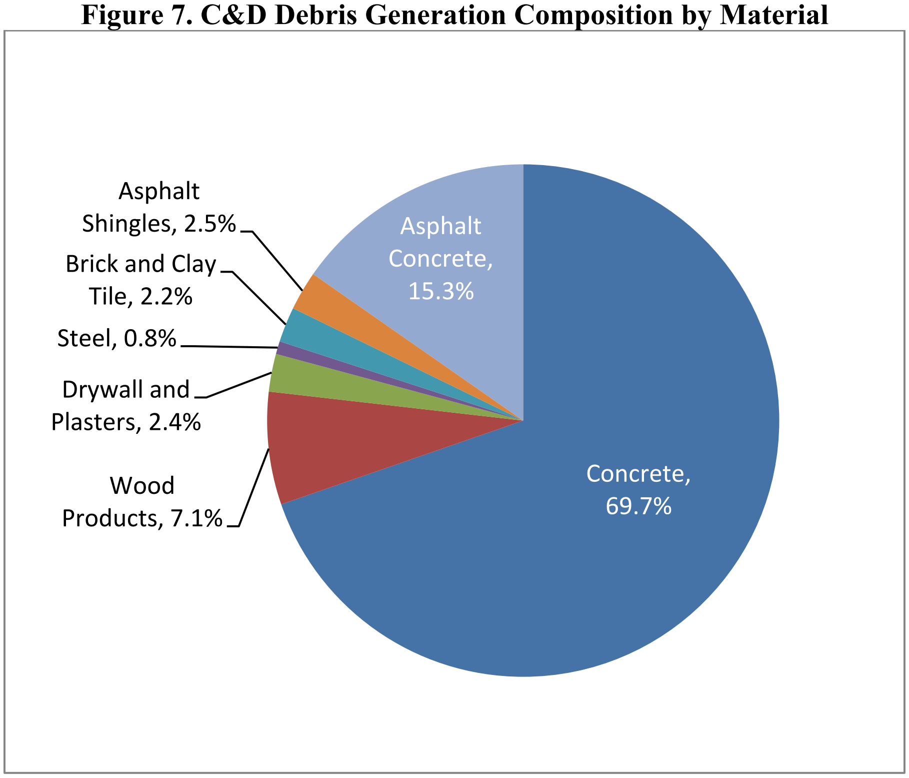
3.0 C&D Debris Generation Composition

The 2015 C&D debris generation composition estimates presented in detail in Table 7 are also depicted in Figure 7. Concrete was the largest portion (69.7 percent), followed by asphalt concrete (15.3 percent). Wood products made up 7 percent and the other products accounted for 8 percent combined.

Table 7. C&D Debris Generation Composition by Material and Source

	Total Generation in 2015	% of Total Generation in 2015
Concrete from Buildings	88,398	16.1%
Concrete from Roads and Bridges	158,386	28.9%
Concrete from Other Structures	134,974	24.6%
Lumber from Buildings	26,687	4.9%
Railroad Ties	1,356	0.2%
Wood Panel Products	8,654	1.6%
Plywood and Veneer	2,253	0.4%
Drywall and Plasters	13,042	2.4%
Steel	4,455	0.8%
Brick	11,392	2.1%
Clay Tile	755	0.1%
Asphalt Shingles	13,525	2.5%
Asphalt Concrete	83,900	15.3%
Total	547,777	100.0%

Figure 7. C&D Debris Generation Composition by Material



4.0 *Conclusions*

The C&D debris generation methodology developed and presented in this memorandum was structured to allow the continuation of the analysis in future years. All historical consumption and distribution data are in place for concrete, steel, wood products, gypsum wallboard and plaster, brick and clay tile, and asphalt shingles. The asphalt concrete generation estimate, based on industry and state-reported data, can be updated using the NAPA survey and estimates from state-permitted solid waste management facilities using the CDDPath method (Forthcoming). It is anticipated that the asphalt industry source will continue to gather and publish the data required for this methodology. Two data points that need updating in future estimates are the Asphalt Roofing Manufacturers Association's asphalt shingle sales data and the Portland Cement Association's estimation of cement consumption by end use. These data points are from 2006 and 2002, respectively. More recent data would improve the methodology assumptions for asphalt shingles and cement end-use markets. Further research is also needed to determine the distribution of steel C&D debris generation across the buildings, roads and bridges and other structures categories.

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