Crushed Cement Concrete Substitution for Construction Aggregates—A Materials Flow Analysis

By Thomas Kelly

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ABSTRACT

An analysis of the substitution of crushed cement concrete for natural construction aggregates is performed by using a materials flow diagram that tracks all material flows into and out of the cement concrete portion of the products made with cement concrete: highways, roads, and buildings. Crushed cement concrete is only one of the materials flowing into these products, and the amount of crushed cement concrete substituted influences the amount of other materials in the flow. Factors such as availability and transportation costs, as well as physical properties that can affect stability and finishability, influence whether crushed cement concrete or construction aggregates should be used or predominate for a particular end use.

INTRODUCTION

The substitution of crushed cement concrete for natural aggregates can be investigated effectively by applying a materials flow analysis. The amounts of substitution in each end use can be explained by examining the factors that direct the flow of crushed cement concrete into its end uses, that is, the physical-chemical properties of crushed cement concrete, its availability, and transportation costs.

Construction aggregates are natural mineral and rock materials used by the construction industry in portland cement concrete, bituminous concrete pavement, road base, construction fill, railroad ballast, riprap for waterway construction, landscaping, and other construction uses. They are used as an inexpensive component in portland cement concrete, road base, and fill materials where they take up space (bulk) while providing the compressive strength necessary in the final product. In bituminous concrete pavement, construction aggregates provide resistance to creep at elevated temperatures, as well as bulk. In portland cement or bituminous concrete pavements, construction aggregates must have the surface properties to allow the physical and chemical bonds which hold these products together. The physical properties required of construction aggregates for their various uses are bulk, weight, durability, compressive strength, porosity, permeability, inert chemistry, uniformity of composition, and special features such as shape, color, and texture. The natural sources of construction aggregates are crushed stone and sand and gravel. Crushed cement concrete that substitutes for natural aggregates must have a similar combination of physical properties required by the end use to compete effectively.

IMPORTANCE OF CONSTRUCTION AGGREGATES TO THE U.S. ECONOMY

Crushed stone is, by weight, the major raw material used by the construction industry, and sand and gravel aggregate is the second most used material. Together their use is an indicator of the economic well-being of the Nation, because of their close connection to the construction products, highways, roads, and buildings. Figure 1 (an area chart) shows the U.S. consumption of these commodities from 1900 to 1995 with a projection of trends in future consumption from the year 1995 to 2020 (Tepordei, 1997, p. 2).

Figure 1 indicates that the consumption of natural aggregates has increased over the years, with a rapid rise in consumption occurring between the years 1945 and 1965. The construction of the interstate highway system and the postwar construction boom were the primary causes for this rise. During the years 1965–1995 two noticeable changes in consumption occurred. The consumption of natural aggregates decreased in slope, and three large dips in consumption are visible. The dips in aggregate consumption reach a low point during the recession years 1975, 1982, and 1991. These dips indicate that consumption of natural aggregates is tied to economic growth in general and growth in the construction industry in particular. Figure 1 projects the consumption of both crushed stone and sand and gravel to increase until the year 2020. These projections assume that crushed stone consumption will increase at a greater rate than that of sand and gravel.

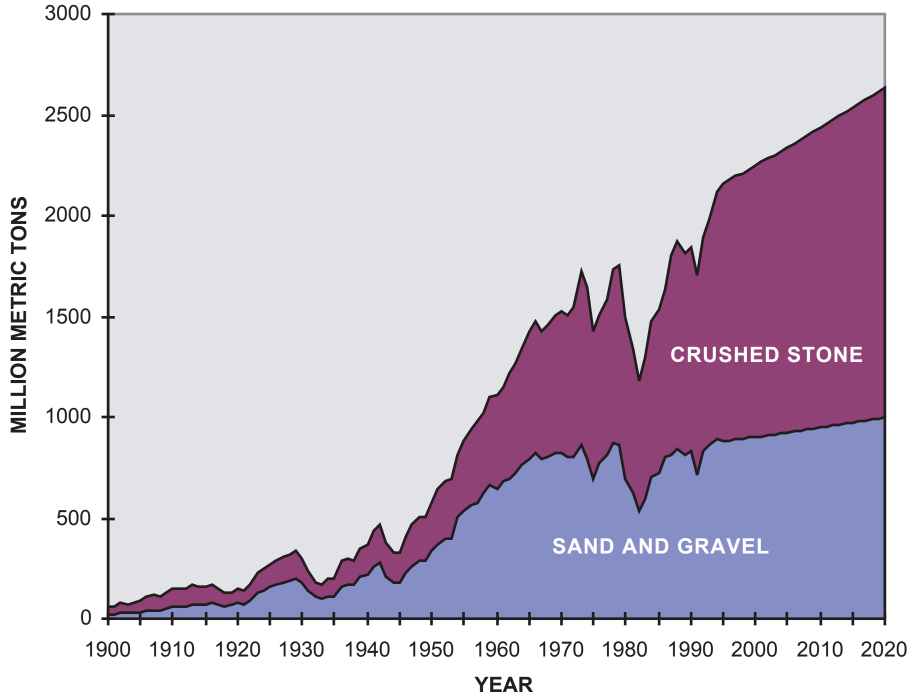

Figure 1. Natural aggregate consumption in the United States (historical and projected). From Tepordei (1997, p. 2).

Another method of illustrating these diverging trends in both materials' consumption is to linearly graph and project the consumption of both sand and gravel and crushed stone. A line graph of consumption from the years 1965 to 1995 (fig. 2), indicates that crushed stone consumption surpassed sand and gravel consumption in 1974, traded places back and forth until 1977, and then increased in consumption relative to sand and gravel until 1995.

A study published by S.B. Bhagwat of the Illinois State Geological Survey stated that the increased use of crushed stone in Illinois can be explained by two factors: the increased use of limestone and dolomite for pollution control in coal-burning power plants, and the change in quality specifications for construction aggregate materials during the past two decades (Bhagwat, 1997, p. 2). William Langer, Natural Aggregate Resource Geologist, U.S. Geological Survey, stated that another factor influencing this trend towards increased reliance on crushed stone is greater competition from other land uses for areas underlain with sand and gravel. Linear projections of these trends graphed on a *national* basis, figure 2, highlight the diverging consumption of crushed stone and sand and gravel. This is an important consideration because the substitution of crushed cement concrete for natural aggregates occurs for end uses more often fulfilled by the use of crushed stone than sand and gravel.

THE FUTURE OF CRUSHED CEMENT CONCRETE SUBSTITUTION

The markets for construction aggregates are largely dependent on population density, because populated areas require more highways, roads, and buildings than do sparsely populated areas (McCarl, 1994, p. 289). This has created a paradoxical situation, whereby the physical placement of construction products may diminish the availability of natural aggregate resources because potential sites of future resources are being used for present construction. Construction aggregates are a high-volume, low-unit-value commodity, making transportation cost a determining factor in competing sources of natural aggregates. Thus location of resource is an important factor for a substitute material such as crushed cement concrete. The use of crushed cement concrete is helping to resolve the problem of diminishing resource availability for two reasons: the populated regions of the country are also the location of an "urban deposit" of concrete (Wilburn and Goonan, 1998, p. 12), and the location of the resource, waste concrete from construction demolition, is near the site of new construction, lowering the transportation cost.

Currently, the annual amount of substitution of crushed cement concrete for construction aggregates is approximately 4.8 percent according to a Spring 1998 phone survey

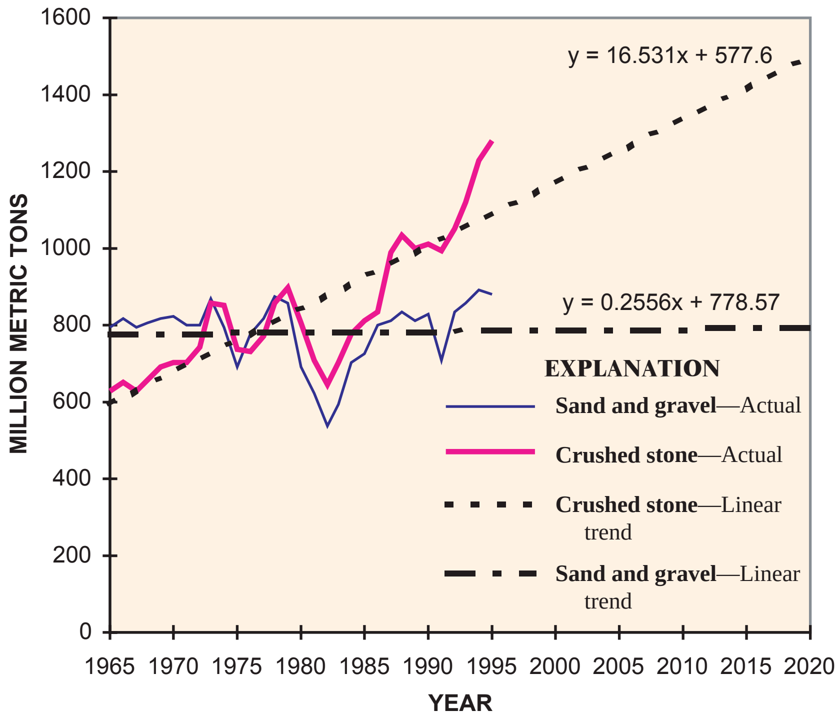

Figure 2. Projections of U.S. consumption of crushed stone and sand and gravel.

done by the Portland Cement Association. Approximately 95 million t (metric tons) of crushed cement concrete substitutes for construction aggregates, which are consumed at approximately 2 billion t per year. But the use of crushed cement concrete is rapidly increasing. More than half of the 81 companies contacted for the phone survey reported an increase in amount of recycled concrete from 1996 to 1997. Natural aggregate producers, who represent only part of crushed cement concrete producers, increased their production of recycled concrete by 37 percent between 1995 and 1996 (Bolen and Tepordei, 1996, tables 16 and 22). Several factors presented herein show why this substitution should continue to increase. A method of tracking this increase is to analyze the flow of construction aggregates through the materials flow cycle.

THE MATERIALS FLOW CYCLE

The materials flow cycle is illustrated in figure 3. Materials are extracted from the earth in a crude form, refined, and purified, so that they can be manufactured into products. At the end of a product's lifetime, the materials are either discarded or recycled. At every step of a material's lifecycle there are potential material losses. These losses may occur through the discard of wastes or through dissipative losses of material into the environment. The mineral commodity specialists of the former U.S. Bureau of Mines (now with the U.S. Geological Survey) tracked the lifecycle of 12 commodities through the material cycle. A generic representation of the materials flow concept, illustrated in figure 4, was used for the 12 studies (Kostick, 1996, p. 220).

In tracking a commodity's lifecycle each study also considered the flow of that commodity through the U.S. economy. Waste and dissipative losses, recycling, exports, and imports were tracked to give a thorough picture of the commodity's flow. The studies provided an understanding of the resource production, manufacturing processes, and consumption for these commodities, and also provided a framework for analyzing a material substitution.

MATERIAL SUBSTITUTIONS FOR MORE THAN A SINGLE COMMODITY

Material substitution occurs when an alternate material is substituted for a traditional material in a product. Substitution often involves more than one commodity, because most products are a combination of several minerals, metals, or plastics. Thus the substitution process must be analyzed at the product level to be understood. Examples of recent substitutions include the material changes in motor oil cans and construction framing studs: plastics have replaced metal and paper in oil cans; steel studs require an alternative form of insulation—foam panels—to produce an exterior residential house wall, a product traditionally insulated with fiberglass. An analysis of material substitution should include flows of

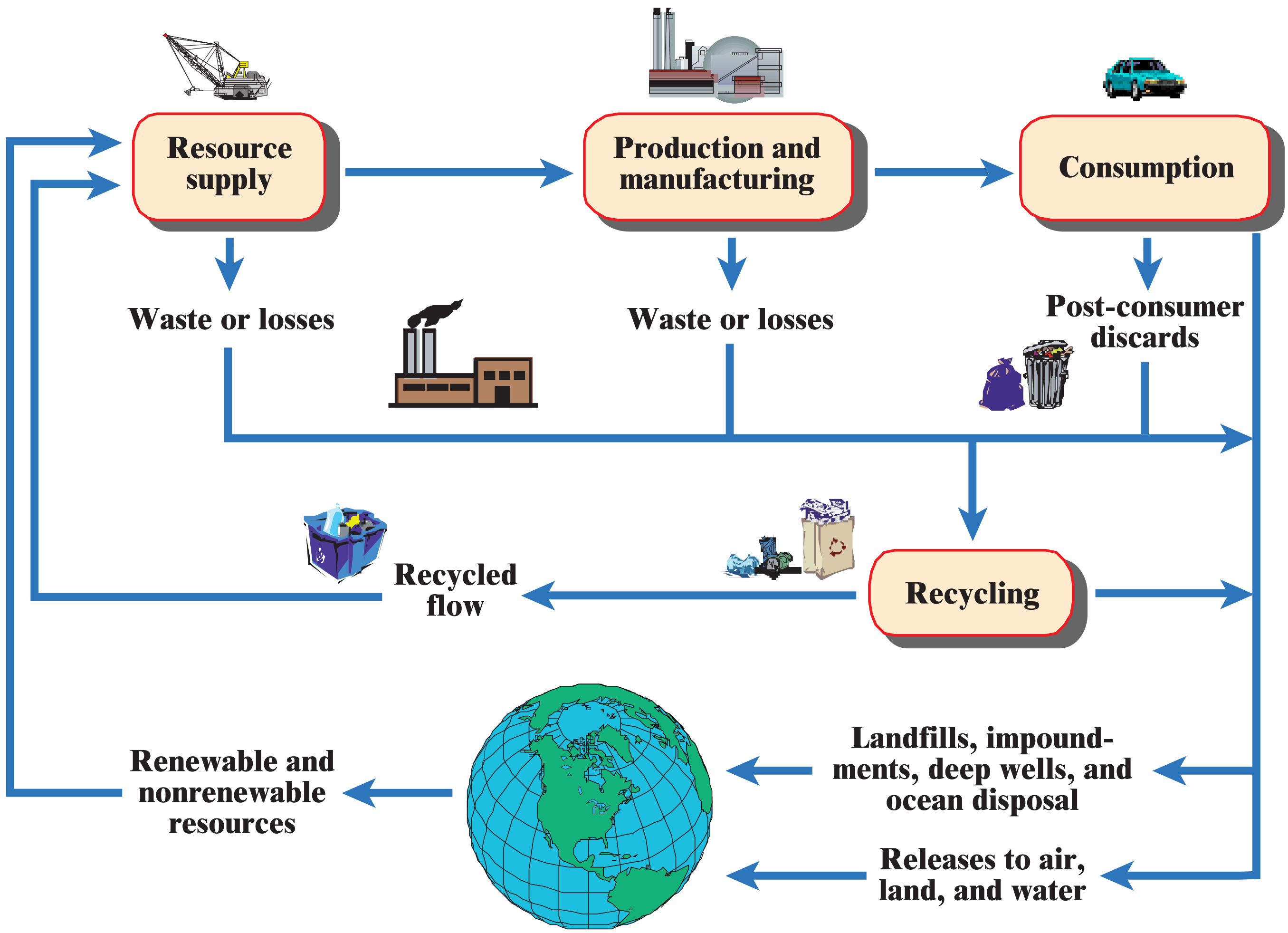

Figure 3. The materials flow cycle.

all materials into a product, because use of an alternative material may require changes in quantity or types of other materials in the product. Material substitutions may also affect post-consumption flows of the materials to recycling or disposal, because material changes upstream may change the type or quantity of materials released downstream at the end of a product's lifecycle.

A product may contain several end uses for the same material. For example, construction aggregates are used in a loose form as base material for a road and in a bound form for the bituminous or cement concrete pavement at the surface of a road. At the point of substitution, in the product, the flows of all materials to each end use should be given a flow direction and quantity in order to analyze the effect that the current amount of substitution has on the U.S. economy. For crushed cement concrete consumption the relevant economic issues are waste reduction, increased longevity of our natural aggregate resources, environmental impact, and conservation of energy resources.

THE END USES FOR CRUSHED CEMENT CONCRETE

Substitution of crushed cement concrete for construction aggregates occurs for several end uses. The majority of these end uses are part of the products: highways, roads, and buildings. Figure 5 illustrates these end uses and quantifies the percentages flowing to each end use.

Uses of crushed cement concrete illustrated in figure 5 are all substitutions for construction aggregates derived from sand and gravel and crushed stone. Subbase is the aggregate material used for the bottom 25–36 cm in highway construction. Bituminous concrete is the pavement layer of highways that uses approximately 4.5–6 percent by weight asphalt binder mixed with 95.5–94 percent aggregate material for the road surface. Cement concrete is the combination of portland cement, water, and 60–75 percent aggregate used for highway and building construction. General fill is aggregate used to provide drainage for building foundations, leach fields, or

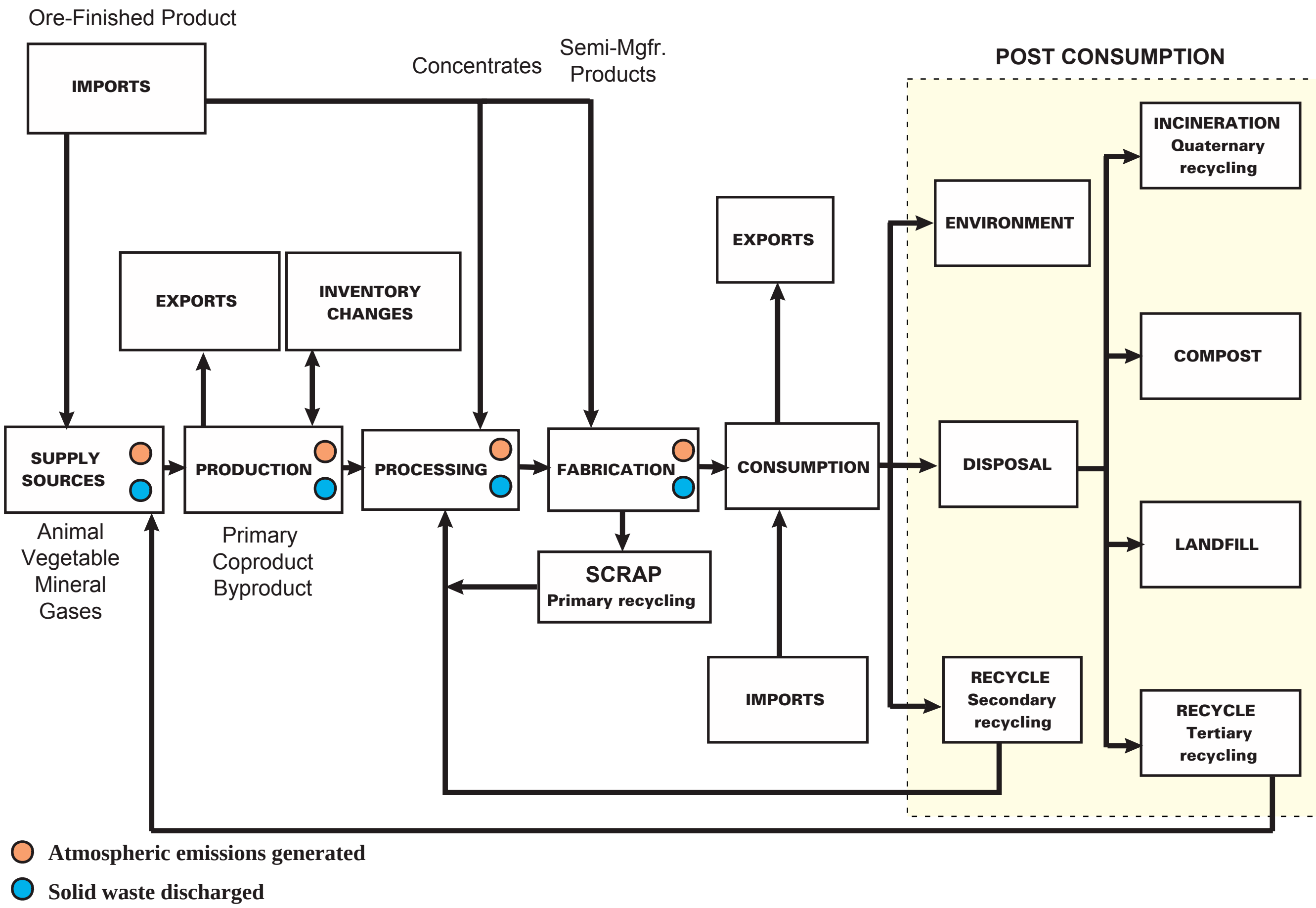

Figure 4. Generic material flow concept for minerals and materials. From Kostick, 1996.

as pipe bedding. Riprap is large chunks of aggregate used for shore protection along rivers or harbors and other areas where erosion damage is possible. The "other" category includes end uses such as landscape rock and railroad ballast. The breakout in figure 5 is not inclusive of all the end uses for construction aggregates, because crushed cement concrete is not capable of replacing all end uses for construction aggregates. Furthermore, these uses are only part of the materials in roads, highways, and buildings; these products require other materials besides aggregates for their production such as steel and cement.

THE MATERIALS FLOW DIAGRAM FOR SUBSTITUTION

Figure 6 represents the flow of materials involved in the substitution of crushed cement concrete for construction aggregates. This flow diagram is analogous to the generic materials flow diagram, figure 4, in that it tracks the flow of materials through the material cycle. The figure represents data or estimates for 1996. (See the appendix for a discussion of this issue.) Figure 6 represents the flow of all materials involved in the use of construction aggregates for highways, roads, and buildings, not just the flow of a single commodity. The inclusion of all materials is necessary because the analysis is done from the perspective of a substitution process. As previously mentioned, the substitution of an alternative material for a traditional material should be analyzed at the product level, because of the possible changes in material flows into and out of a product when a substitution occurs.

This materials flow diagram is designed to investigate the substitution process of crushed cement concrete for construction aggregates in two products, "highways and roads" and "buildings." Therefore, those uses of construction aggregates for which crushed cement concrete will not substitute are eliminated. For example, crushed limestone used to produce cement cannot be replaced with crushed cement concrete, so this flow is not included on the diagram and this amount of crushed stone is not included in the crushed stone commodity flow. Maintaining this exclusive consideration of only those materials involved in the substitution establishes a quantitative relationship between the amount of materials flowing into and out of the products. The substitution process is quantified so that the amount of material that can be replaced, construction aggregates used in highways, roads, and buildings, can be compared to the amount of material available for substitution, crushed cement concrete.

The construction aggregates used this year will, of course, not be available for recycling as crushed cement concrete for many years. To indicate the time dependency of the data, ovals and rectangles are used. All of the data flowing into or out of the ovals (processes) span a year's time, whereas the data flowing into and out of a rectangle (stock) span more than a year's time. By subtracting the known inflows from a known outflow, an unknown inflow may be estimated in a process oval, or by subtracting known split flows from a total flow, an unknown split flow may be calculated. (Split flows occur downstream of a total commodity or recycled flow.) It is necessary that all flows except one into or out of an oval are known in order to do a material balance on a process oval. This condition is met for the ovals "concrete mix" and "hot asphalt mix" but not for "roofing manufacturing." Material balances were performed on the "concrete mix" and "hot asphalt mix" ovals to calculate the amounts of crushed stone flowing into each process, and the total of these two flows was subtracted from the construction aggregate flow to calculate crushed stone used for "road base and others." The ability to calculate unknown flows is one example of the usefulness of this materials flow diagram.

Commodity flows are indicated with heavy black arrows which split into individual flows, thin black arrows, that lead to end uses in the products. Smaller downstream flows from the products are indicated with thin black arrows also, and recycling flows are indicated with dashed arrows. Recycling flows can also split into smaller quantity flows so that they can be directed to the particular end use for which they substitute. The details of the calculations performed and data sources used in order to produce this materials flow diagram are included in the appendix.

Some lumping of end uses was done to simplify the flow diagram, figure 6. The categories subbase, general fill, riprap, and other in figure 5 are combined into a category called "road base and others." This lumping of categories is illustrated in figure 7 (p. 8). This lumped flow is directed into the product or stock, "highways and roads" on the flow diagram for several reasons. It is impossible to indicate to which product some of the end uses flow because the data are unavailable. For example, construction fill is not always associated with roads or highways. Buildings also use some aggregate for construction fill, and some construction fill, such as pipe bedding, may not be accurately associated with either "highways and roads" or "buildings." However, the amount of flow to "highways and roads" as road base material is so much greater than the flows to the other end uses, "bituminous concrete" and "cement concrete," that less error is introduced by associating all small categories with "highways and roads."

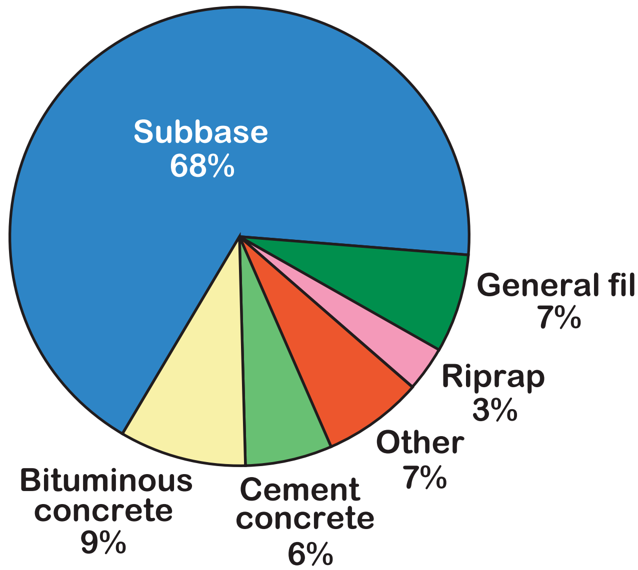

Figure 5. End uses of crushed cement concrete. From "C&D Debris Recycling," September/October 1997. Used with permission.

Moreover, the physical properties required for road base and the other small categories are more alike than the physical properties required of the other two categories, "bituminous concrete" and "cement concrete."

The amounts of crushed cement concrete flowing to these three end uses shown in figure 7 are compared to the amounts of construction aggregates flowing to these same end uses in figure 8.

The construction aggregates that flow to these end uses are those reported for sand and gravel and crushed stone in the U.S. Geological Survey (USGS) Minerals Yearbook (Bolen and Tepordei, 1997, table 1). The percentage amount of crushed cement concrete that flows to these end uses is reported in a joint survey taken by Vanderbilt University and C&D Debris Recycling, an industry association magazine. Combining these percentage flows with the estimate of total crushed cement concrete recycled from the previously mentioned Portland Cement Association phone survey gives the amount flowing to each end use in figure 8. Comparison of the total flow quantities of construction aggregates versus crushed cement concrete indicates that substitution occurred at approximately 4.8 percent per year for 1997, (94.8/1,960=.048). Also noticeable is that 85 percent of the crushed cement concrete flows to the end use, "road base and others," versus 57 percent of the construction aggregates. This can be explained partially by availability of crushed cement concrete and transportation costs. However, the physical properties of crushed cement concrete such as its absorption and specific gravity also contribute to this preferred direction of flow.

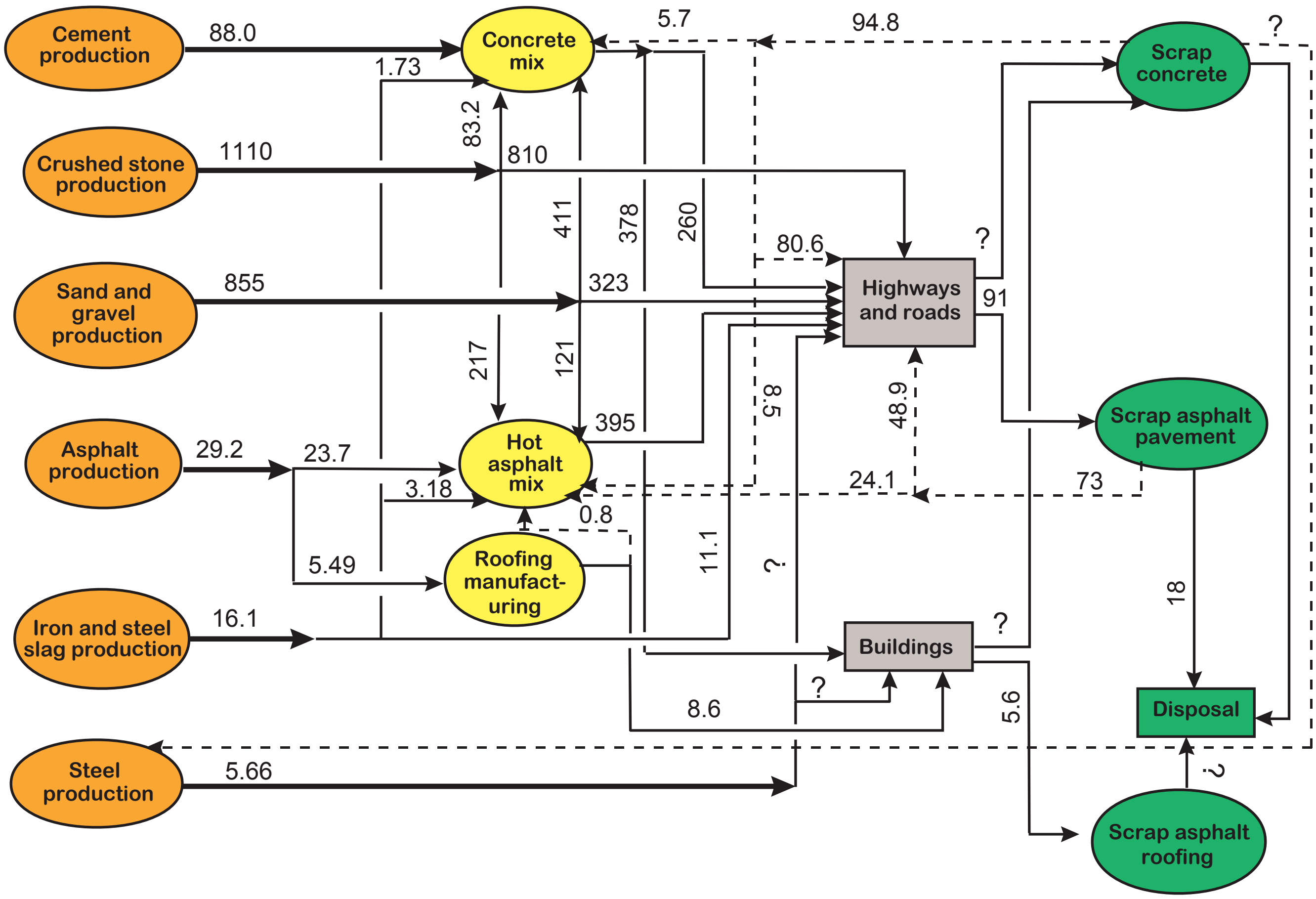

Figure 6. Flow of construction materials (construction aggregates vs. crushed concrete), 1996. Flows in million metric tons.

AVAILABILITY AND TRANSPORTATION COST FACTORS IN USE AS ROAD BASE

Eighty-five percent of concrete recyclers have the ability to go to the job site in order to crush concrete (Deal, 1997, p. 10). Only 24 percent are actually going to the job site to crush concrete, but the ability to locate a yard near a job site can also be a consideration in the costs of recycling, because transportation cost is a major competitive factor among sources of aggregate. Portability of the crushing operation can provide the cost advantage to crushed cement concrete over other aggregate sources at a particular job site. This is especially true for road base, because the material can be crushed on site or nearby and set in place. Crushed cement concrete for use in bituminous and cement concretes, however, may require transportation from the site of demolition to a crushing operation, then to a mixing plant, and finally back to a construction site. The advantage in transportation costs for road base materials can be viewed as an advantage in availability as well as an advantage in transportation cost. It is as if the mine site were located on the construction site.

Cement concrete pavements in highways, roads, parking lots, airport runways, and sidewalks contain less steel than the concrete demolished from buildings. Steel is generally not placed in pavement layers, because it can cause cracking during freeze-thaw cycles. This also increases the recyclability of the crushed cement concrete from pavements, because it is easier to produce a product without the complication of having to remove and recycle or dispose of the steel byproduct of the crushing operation.

EFFECTS OF PHYSICAL PROPERTIES OF CRUSHED CEMENT CONCRETE ON ITS USE

The difference in physical properties between natural aggregates and crushed cement concrete is strongly influenced by the inclusion of the cement paste surrounding the aggregate in crushed cement concrete. (This fact was noted by Stephen W. Forster of the Federal Highway Administration (FHWA) on October 5, 1997, in a talk given at a Construction Materials Recycling Seminar in Minneapolis, Minn.) Physical properties of this paste are markedly different from the properties of natural aggregates. The specific gravity of crushed cement concrete is commonly lower than that of the natural aggregate used to make the concrete, and the absorption of water is always higher. The cement paste component of crushed cement concrete produces more fines than when stone is crushed. These fines have an absorption as much as eight times greater than fines produced by crushing stone. As a result, the use of crushed cement concrete in hot asphalt mix requires the use of more asphalt binder than does the use of crushed stone, which then increases the cost of bituminous concrete because asphalt is the most expensive component of bituminous concrete pavement.

If crushed cement concrete is being used for aggregate in cement concrete mix, specific gravity, absorption, fineness, and angularity are all important physical properties. Crushed cement concrete's absorption, when substituted in cement concrete, requires that more water be used in the cement mixing ratio than when natural aggregate is used. Furthermore, the irregular surface of crushed cement concrete has more nooks and crannies than does natural aggregate, and this causes more cement to be used to fill these small holes (Wilson, 1993, p. 4). Cement is the most expensive component of cement concrete, so this adds to the cost of using crushed cement concrete. The angularity of crushed cement concrete, especially in the fine sizes, affects concrete finishability and workability. Experience indicates that up to 75 percent natural aggregate fines may be necessary to obtain a workable cement concrete mix that is capable of being finished. (This fact was noted by Stephen W. Forster of the Federal Highway Administration (FHWA) on October 5, 1997, in a talk given at a Construction Materials Recycling Seminar in Minneapolis, Minn.) This is a problem with the use of crushed stone sand also, and it is resolved by the use of natural sand (McCarl, 1983, p. 72). The availability and transportation costs of natural sand may affect the amount of crushed cement concrete used in a cement mix.

For the category "road base and others," crushed cement concrete must have the appropriate physical properties that permit servicing that particular end use. For both road base and fill material, fines may be a problem where drainability is required. Washing the crushed cement concrete to remove fines may be required, but this adds to the cost of using crushed cement concrete. Dissolution of the crushed cement concrete can occur over time in a fill or road base application, so the soundness of the concrete may be an important factor for these end uses. Soundness is a test that measures the aggregate's general resistance to environmental exposure, including heating and cooling, wetting and drying, and freezing and thawing. If dissolution occurs, a possible consequence is an elevation of ground-water pH by the leaching of calcium hydroxide from the cement paste. If this ground water contacts air, calcium carbonate will precipitate out of the solution, possibly clogging drainage systems. Contact between vegetation and the high-pH ground water may cause vegetation damage (Snyder, 1995, p. 3). Dense road bases will be less susceptible to leaching, and, in fact, may even become more tightly cemented together by the chemical activity occurring when water passes through the material. (This fact was noted by Stephen W. Forster of the Federal Highway Administration (FHWA) on October 5, 1997, in a talk given at a Construction Materials Recycling Seminar in Minneapolis, Minn.) Whether the use is for road base or fill, crushed cement concrete must be able to support the load applied to it over time, so the ability to retain compressive strength, as measured by soundness, is a property that must be considered.

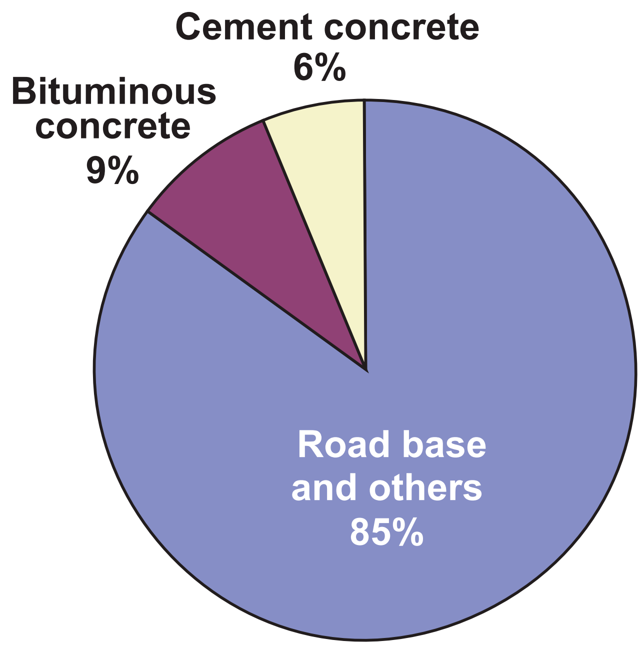

Figure 7. End uses of crushed cement concrete (combining several categories).

For other uses in the "road base and others" category (riprap or jetty stone or any use in which weathering may have an effect on the useful life of the product), soundness may be an important consideration. Aesthetic properties are a consideration for use as landscaping rock. There have been attempts to paint crushed cement concrete to increase its aesthetic appeal. This extra treatment adds to the cost of using crushed cement concrete.

In summary, crushed cement concrete must first meet the physical specifications required by the end use and then be competitively priced in order to substitute for construction aggregates from natural sources. It is able to meet these specifications for all three categories of end uses, "road base and others," "bituminous concrete," and "cement concrete." For use as road base, transportation cost is an important factor in the preference exhibited in the material flow of crushed cement concrete to this end use. The higher costs of using crushed cement concrete in bituminous concrete or cement concrete are due to its increased absorption, requiring more

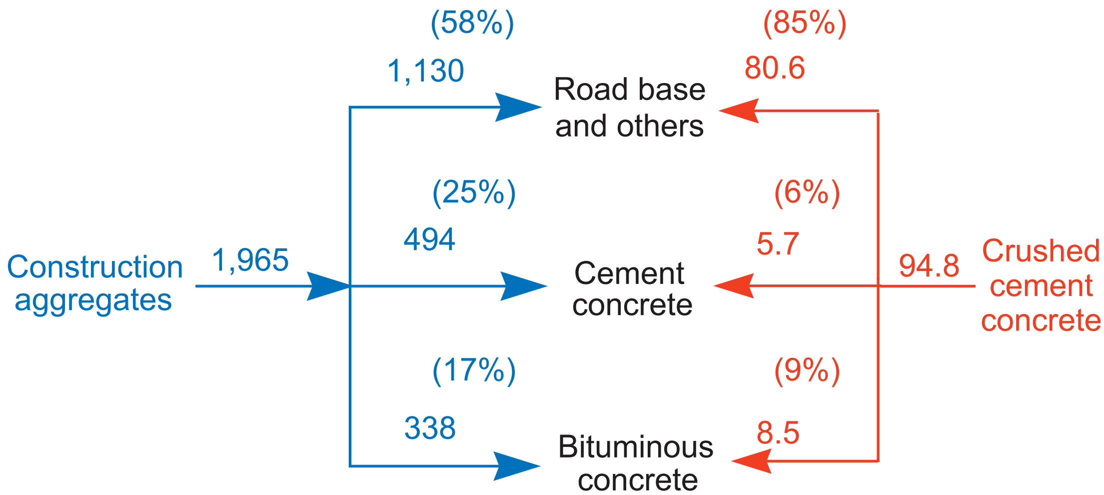

Figure 8. Flow into end uses (construction aggregates vs. crushed cement concrete). Flows in million metric tons.

asphalt or cement—a clear example of a materials flow being changed by a substitution process. Note that for these two end uses the materials flow is changed in the quantity, not the type of materials required. However, because construction aggregate is a mix of coarse and fine aggregates, the use of crushed cement concrete may also change the mix requirements of the aggregate, depending on the end use. If crushed cement concrete is used for cement concrete, the natural sand component of the mix may need to be increased, to give finishability and workability to the cement mix.

OTHER APPLICATIONS FOR THE MATERIALS FLOW DIAGRAM

The generic materials flow diagram, figure 4, is a first step in tracking a material through its lifecycle from resource production through manufacturing processes, consumption, and disposal or recycling. Laying out this flow clarifies the processes affecting a material's flow. These processes can then be studied in greater detail so that estimation can be made of the material losses occurring in each process. The same knowledge can be obtained from a materials flow diagram designed to study a material substitution, such as figure 6. Moreover, figure 6 establishes a quantitative relationship between flows for several materials which can be tracked over time to measure changes in the substitution process. But, as figure 6 also demonstrates, one needs more than a simple comparison of the substitution of crushed cement concrete for construction aggregates to understand the flow of construction aggregates. Construction aggregates are recycled from waste bituminous pavements, asphalt roofing materials, and iron and steel slag. All these forms of recycling help meet demand for construction aggregates. By presenting the known data in an organized manner as in figure 6, a greater understanding of the processes involved in several materials' lifecycles is achieved because both the flow direction and quantity of material flow are illustrated.

Another example of an increased understanding of the flow of materials in the construction industry is given by examining the preferential flows of sand and gravel to "cement mix" and of crushed stone to "hot asphalt mix." Figure 9 is an excerpt of the materials flow diagram, figure 6.

Figure 9 shows that sand and gravel flow preferentially to cement mix and crushed stone flows preferentially to hot asphalt mix. The reason for the preferential flows is the different shapes of the two materials. Construction aggregates are a mixture of fine and coarse aggregates and the mixture may vary depending on the product for which the aggregate is to be used. Larger sizes of coarse aggregate are used for more massive structures. In areas where natural sand is scarce, stone may be crushed to produce a stone sand used for the fine portion of the aggregate mix. A mixture of crushed stone and sand and gravel may be used to give the aggregate mix the properties necessary for a particular product. Sand and gravel mix has sphericity in both the coarse and fine aggregate components and crushed stone has a sharp angular shape. The sphericity of fine aggregate in sand and gravel provides cement mix the ability to flow into forms, workability, and to be finished with a smooth surface, finishability. The coarse aggregate, gravel, in a sand and gravel mix does not provide resistance to creep in bituminous concrete pavement because the round edges of the gravel slide past one another with less resistance than the sharp angular faces of crushed stone. Thus crushed stone flows preferentially to hot asphalt mix. Furthermore, the fine aggregate portion of crushed stone, crushed stone sand, does not give the workability and finishability provided by the fine aggregate component of sand and gravel. Thus a mix of materials may be used to give the properties required for the product. This is another example of the usefulness of the materials flow diagram. Analyzing all materials used to make the products “highways and roads” and “buildings” highlights differences between material flows.

The crushed cement concrete flows illustrated in figure 8 also show this preference in flow. Crushed cement concrete has a shape closer to crushed stone than does sand and gravel mix. It flows preferentially to “bituminous concrete” in comparison to flow towards “cement concrete.” Crushed cement concrete is more angular than sand and gravel and thus can provide resistance to creep in asphalt pavement made with bituminous concrete.

TRACKING WASTE AND DISSIPATIVE LOSSES

The tracking of the material flows in figure 6 is the first step in measuring the waste and dissipative losses involved in the use of these construction materials to build our Nation’s highways, roads, and buildings. However, there are important data gaps in figure 6, indicated by question marks, which need to be filled before an estimate of waste and dissipative losses can be done. The amount of concrete demolished annually is the most obvious missing data on the figure. Franklin Associates, under contract with the Environmental Protection Agency, published a report in the Summer of 1998 which estimated the amount of materials produced from building demolition in the United States in 1996 at 123 million t (Beachey, 1998, p. 1-1). However, the amount of concrete in this is unknown; some more information is necessary to estimate the amount of concrete from demolition. There are plans to follow this report with another on the materials released from the demolition of our Nation’s infrastructure. These estimates combined with a measure of the recycling rate will give a more complete picture of the waste and dissipative losses incurred in the use of the two construction materials, construction aggregates and crushed cement concrete. For the other materials in figure 6, the tracking of the flows is necessary in order to measure the waste and dissipative losses involved in producing, using, and discarding or recycling each material, because it is necessary to know the amount of flow passing through each process oval in order to quantify the possible waste created for disposal or material dissipated into the environment. The value of figure 6 is that it quantifies amounts of material passing through these process ovals, so that once estimates of process losses are made, based on an understanding of the process, an estimate of total loss can be calculated because the amount of material flowing through a process is known.

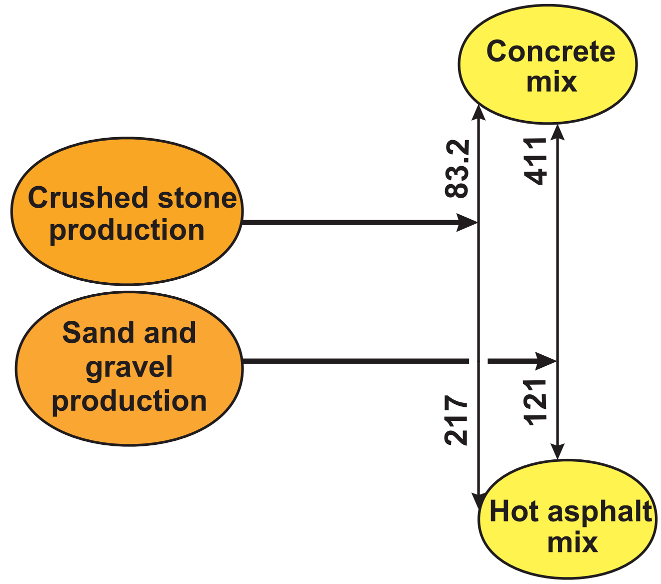

Figure 9. Flow of natural aggregates, 1996. Flows in million metric tons.

A STATIC REPRESENTATION OF A DYNAMIC PROCESS

Figure 6 is a static representation for the year 1996 of the flow of materials through their lifecycles. In order to use this information more accurately in predicting the future for the substitution process, a dynamic model would have to be developed. Looking at the changing quantitative relationships between materials in the past would be a first step at developing this model. Figure 1 is a historical look at the use of natural aggregates in the United States since 1900. The rapid rise in consumption of natural aggregates from 1945 to 1965 may indicate a future rapid rise in availability of demolished concrete. To predict the timing of this release of crushed cement concrete requires an estimate of lifetimes of construction products. Studying the consumption patterns in the past may lead to an understanding of those factors which will affect the lifetimes of construction products. These factors could be included in a dynamic model, so that estimates of future substitution rates could be made based on a projection of these factors into the future. For example, the ratio between building construction and road and highway construction may have an effect on the time of residence for concrete in a structure. Knowing the factors which influence the ratio in the past may allow more accurate predictions of concrete available to be crushed in the future. With so many variables to consider, the problem of predicting quickly becomes complicated, making a dynamic model necessary. Factors expected to influence the substitution process could be evaluated by performing several runs on the model analyzing the sensitivity of the model to the factors.

Even this simple static model contains many different data sources and assumptions, and the author realizes that it is only a first step in analyzing the material flows in figure 6. If another source of information is perceived as more accurate than that used by the author, a contact will be greatly appreciated at the email address:

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CONCLUSIONS AND IMPLICATIONS FOR THE FUTURE

This report demonstrates that a materials flow analysis examining a material substitution can lead to a greater understanding of the flow of several materials through their lifetimes. The materials flow diagram, figure 6, provides an understanding of both the direction of materials' flows and the quantity of these flows. This information can be used to provide an overview of the use of these materials in the construction industry, or a section of the diagram can be isolated and investigated for the relationships between just a few material flows. An example of an overview is the comparison made in studying the substitution of crushed cement concrete for construction aggregates. This was the original goal of this report, and it led to designing the materials flow diagram, figure 6, with specified constraints on the data included. Once the diagram was produced, however, more relationships among materials' flows became evident. An example of this is the preferential flows of sand and gravel and crushed stone illustrated in figure 9, an isolated portion of the total flow diagram. The overview of flow relationships provided by figure 6 can lead to new questions concerning the use of materials in the construction industry. For example: How much substitution will occur in the future? The large difference between concrete put in place in 1996 and concrete recycled indicates that a future supply of material is potentially available; will it meet the specifications for the end uses? The preferential flows illustrated in figure 9 take on greater importance when they can be compared through time; will sand and gravel continue to decline in use compared to crushed stone? The relationships between material use and substitution in 1996 provide insights into demand for natural materials and waste reduction in the future; should this pattern of materials flows shown in figure 6 be tracked over time?

Finally, other advantages to organizing the data into a flow diagram are that material balances can be used to calculate unknown flows, and data gaps are revealed. In this report crushed stone flows were calculated by material balance, and the important data gaps concerning materials flowing from demolition of highways, roads, and buildings were noted.

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APPENDIX OF SUPPLEMENTAL INFORMATION

Why use 1996 in the title of figure 6?

The year 1996 in the title of the chart indicates that the data in the chart are a static representation of the flow amounts as reported in the year 1996. This is true for most of the data in the chart. Specifically, the data from the Minerals Yearbook 1996 (MYB1996) are used because 1996 is the most accurate year currently reported. Other data in the chart are reported as an annual amount or are outdated by several years. This inconsistency between data sets is reconciled by one of two ways. Outdated data are estimated by using the latest reported year as the value of the flow in 1996 or by using a data series to calculate an estimate. If an annual estimated rate is all that is available, then the annual rate is assumed to apply in 1996 also. Improvements to these flow amounts in 1996 may be possible, and the possible improvements for each data source are discussed in the section of this report that deals with the particular data source.

The data in figure 6 of the main report are given superscripts in the following version of figure 6, figure 10. The superscripts identify a data source listed in the table that follows. Details concerning a particular number in figure 10 may be found by reading the text that follows the table.

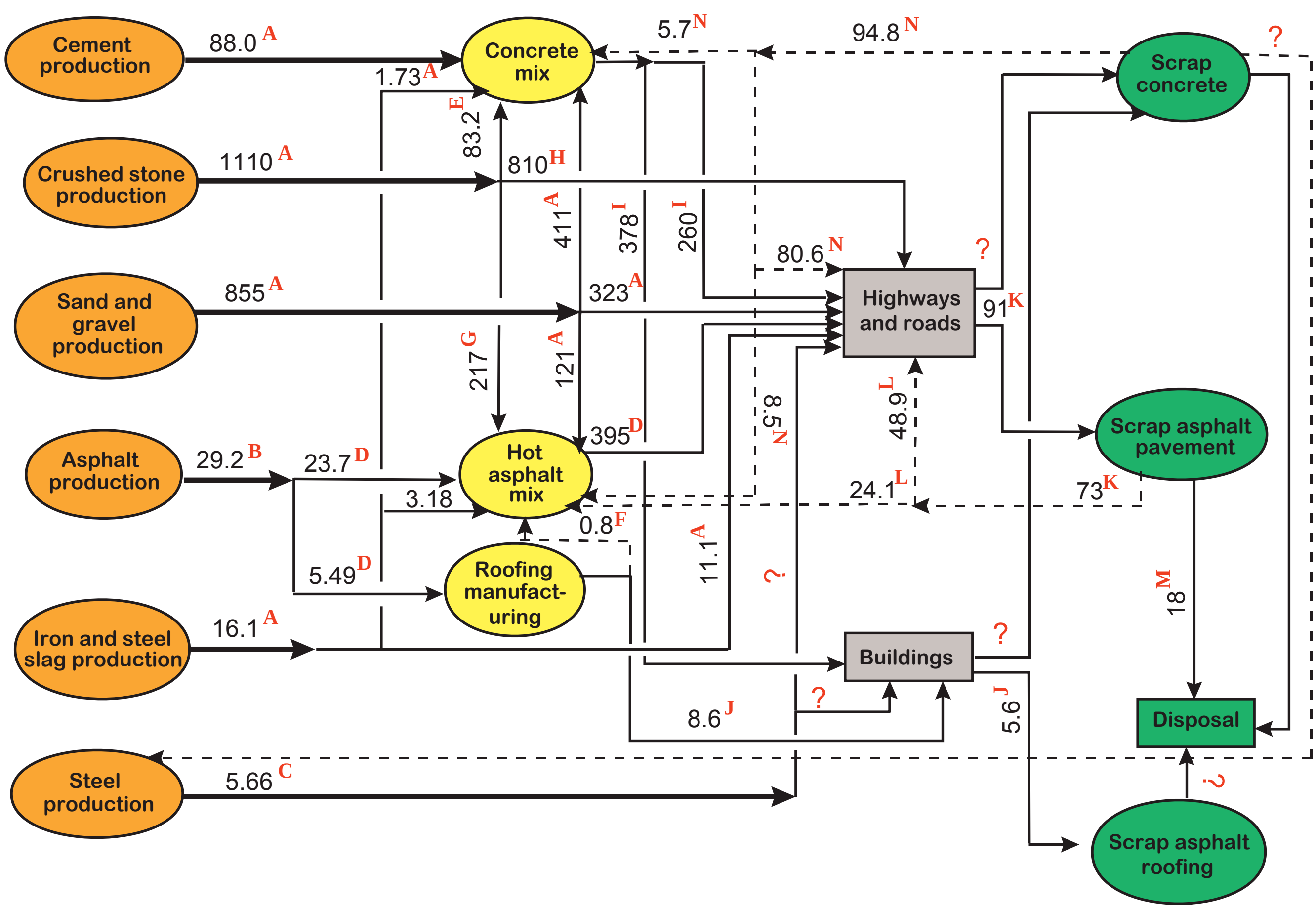

Figure 10. Flow of construction materials (construction aggregates vs. crushed concrete), 1996 (annotated). Flows in million metric tons.

The following table lists the superscript letters and the data source used for the superscripted flow amounts.

Table 1:

LETTER	DATA SOURCE
A	USGS, Minerals Yearbook 1996
B	Annual Energy Review 1996
C	American Iron and Steel Institute phone call March 10, 1998
D	National Asphalt Pavement Association FAX of data table and a calculation
E	CALCULATION by author
F	Recycling and Use of Waste Materials and By-Products in Highway Construction
G	CALCULATION by author
H	CALCULATION by author
I	Portland Cement Association and a calculation by author
J	USDOT, A Study of the Use of Recycled Paving Material
K	USDOT, A Study of the Use of Recycled Paving Material
L	USDOT, Pavement Recycling Executive Summary and Report March 1996
M	USDOT, A Study of the Use of Recycled Paving Material and a calculation
N	C&D Debris Recycling Sep/Oct 97
?	Unknown Flows

Letter A:

Cement

Cement Production = 88.0 million t. This is a direct report of the Minerals Yearbook 1996 (MYB1996) amount (90.4 million t) minus a 2.7 percent deduction for nonconstruction uses (oil wells, mining and miscellaneous). The 2.7 percent deduction is a 6 year average for nonconstruction uses from the Portland Cement Association (1990–1995). 90.4–0.027*90.4 = 88.0 million t.

Crushed Stone

Crushed Stone Production = 1,110 million t. This is a result of multiplying the total apparent consumption of crushed stone by the percentage used in construction for the year 1996 in the MYB1996. Calculation: 1,330*0.832 =1,110. These construction categories comprise 83.2 percent of crushed stone consumption. Not included are crushed stone for metal flux, and limestone for cement, water treatment, whiting, glass manufacture, chemical uses, and others.

Not included on the diagram are 2.45 million t of crushed stone flowing to roofing manufacture as roofing granules from table 13 of MYB1996. At first, this use was included but the diagram became too cluttered to include a small amount of material that does not play a part in any of the material balance equations. The same mention of use by weight for roofing granules in the commodities sand and gravel and iron and steel slag will be made, and in a like manner they will not be included on the diagram.

Sand and Gravel

Sand and Gravel Production = 855 million t. This is a calculated report of apparent consumption of sand and gravel (construction) from the MYB1996 for the four categories mentioned below:

1. Sand and gravel flowing to concrete = 914*.45 = 411 million t.
2. Sand and gravel flowing to road base and coverings = 914*.234 = 214 million t.
3. Sand and gravel flowing to hot asphalt mix = 914*.132 = 121 million t.
4. Sand and gravel flowing to construction fill = 914* .119 = 109 million t.

Note that in figure 6 (the materials flow diagram) road base and coverings are combined into one flow with construction fill as "road base and others," as discussed previously.

All these flows are an application of respective percentages in the MYB1996 applied to the apparent consumption figure for sand and gravel for the year 1996, 914 million t. This is 93.5 percent of construction sand and gravel. Not included are sand and gravel for plaster and gunite sands, and snow and ice control.

From table 6 of MYB 1996, 0.515 million t of sand and gravel flowed to roofing granules.

Iron and Steel Slag

These values are from the MYB96 chapter on Iron and Steel Slag. Iron and Steel Slag = 16.1 million t from the following categories:

1. Iron and steel slag flowing to asphaltic concrete = 3.18 million t
2. Iron and steel slag flowing to cement concrete= 1.73 million t
3. Iron and steel slag flowing to road base, construction fill, and railroad ballast = 11.1 million t
4. Iron and steel slag flowing to roofing granules = 0.059 million t

These uses comprise 85 percent of total iron and steel slag consumption. Not included are uses for pozzalanic cement, sewage treatment, and soil conditioning, among others.

Roofing granules from iron and steel slag amounted to 0.059 million t in 1996, from table 4 of MYB1996 in the iron and steel slag commodity chapter.

Letter B:

Asphalt production is a quote of 1996 asphalt production from table 1.16, Fossil Fuel Consumption for Nonfuel Uses 1980–1996 in the Annual Energy Review 1997(AER). It is necessary to convert the barrels of reported asphalt produced in 1996 (177 million barrels) to metric tons for this flow chart. A conversion factor of 6.06 barrels/t (metric ton) was used. This conversion factor is available in the International Energy Annual 1996 appendix.

177 million barrels/ 6.06 barrels/t = 29.2 million t.

Letter C:

This is the amount of steel reinforcing bars consumed in 1996. It is calculated as consumption = production + imports – exports. All values are reported by the American Iron and Steel Institute (AISI) in its annual statistical book, which contains 10 years of data. This estimate of steel in concrete does not account for wire mesh, so it is an underestimate. (Wire mesh production is not recorded by AISI.)

Letter D:

The National Asphalt Pavement Association (NAPA) produced a table of “estimated liquid asphalt cement sales for paving” for the years 1970-1990. Unfortunately the asphalt data are outdated because NAPA no longer purchases the regional data from the Asphalt Institute to produce national consumption figures. The Asphalt Institute still does produce the regional data for marketing purposes (available for $1,000 for each year). Using the 20 years of data available, however, a percentage of total asphalt production that is used for paving can be estimated. This percentage can then be applied to the total asphalt production available in the Annual Energy Review to estimate the amounts of asphalt flowing to pavement and to roofing.

Comparing data from 1980 to 1990 gives 18.8 percent of asphalt production flowing to roofing and the rest to pavement. Applying this average to the total asphalt production for 1996 gives 5.49 million t flowing to roofing and 23.7 million t flowing to pavement. Assuming a by-weight ratio of 6 percent asphalt in asphalt pavement gives 395 million t of asphalt pavement for 1996.

Letter E:

This flow is done by calculation using a typical cement concrete mix ratio from Van Vlack (1987, p. 581). The ratio by weight is 3.1 gravel: 2.6 sand: 1 cement: 0.55 water. Applying this ratio:

88.0/1 = (411 + 1.73 + 5.7+ x)/5.7 x = amount of crushed stone

x = 83.2 million t of crushed stone flowing into concrete. This is an underestimate if you compare to table 13 of MYB1996, but it does not affect any of the assertions made in the discussions of the relative flow directions and amounts because it is the same order of magnitude.

Letter F:

This is a reported value, 0.8 million t, of annual recycled roofing manufacturing waste reported in “A Study of the Use of Recycled Paving Material,” A report to Congress June 1993 (p. 20), a U.S. Department of Transportation Publication.

Letter G:

This estimate is calculated by subtracting the sum of the inflows into the hot asphalt mix box from the total outflow. The remaining amount is estimated to be the crushed stone that is used in hot asphalt mix:

395 million t hot asphalt mix – 121 million t sand and gravel – 23.7 million t asphalt – 0.800 million t roofing material manufacturing waste – 24.1 million t recycled asphalt pavement – 8.5million t crushed cement concrete = 217 million t crushed stone used to manufacture hot asphalt mix in 1996.

Letter H:

This value is calculated by subtracting the known flows of crushed stone from the total flow of crushed stone to construction, 1,110 million t:

1,110 – 83 – 217 = 810 million t flowing into road base and other end uses.

Letter I:

These two flows are estimated using data from the May 1996 edition of “The Monitor,” a Portland Cement Association (PCA) publication. The PCA has data available on consumption patterns of cement since the late 1970’s.

Lumping the 17 categories of data for 1996 into two categories (highways and roads, and buildings) gives a good estimate of the amount of cement flowing to each of the two categories. Using a by-weight ratio of a typical concrete mix (Van Vlack, 1987), these cement flows can be turned into concrete flows.

Cement flowed in 1996 in the following manner: 59.3 percent to buildings and 40.7 percent to highways. A typical mix ratio by-weight is 3.1 gravel: 2.6 sand: 1 cement: 0.55 water. Combining this information with total cement consumption, 88 million t allows the calculation of the total weight of concrete manufactured in 1996:

88.0/1=x/6.25 x=550 Therefore 550+88= 638 million t of concrete was consumed in 1996 for these two categories ("buildings", and "highways and roads"). The water is assumed to be all hydrated in this concentration, an assumption that leads to an overestimate because a slight excess of water is used in order to assure the stoichiometric amount needed for the hydration reaction.

Thus 378 million t flowed to buildings and 260 million t flowed to highways.

Letter J:

From "A Study of the Use of Recycled Paving Materials," page 20: "Approximately 8.6 million t of roofing shingles are manufactured each year. Approximately 65 percent of these shingles are used for reroofing, producing 5.6 million t of old waste shingles."

Letter K:

This flow amount is a reporting of an annual amount of recycled asphalt pavement, 73 million t, and waste asphalt pavement from "A Study of the Use of Recycled Paving Material," A report to Congress June 1993, table 4, page 15.

Ciesielski and Collins also had an estimate (1994) converted to metric tons:

50 million short tons * .9072 t/short ton = 45.4 million t.

Letter L:

This value is obtained by applying the percentage of milled asphalt that goes to hot mix asphalt reported in Pavement Recycling Executive Summary and Report, U.S. Department of Transportation, Federal Highway Administration, March 1996, page 13. Sixty-seven percent goes to other uses than hot mix asphalt and 33 percent flows to hot mix asphalt.

Letter M:

From table 4 of "A Study of the Use of Recycled Paving Material," A report to Congress June 1993, 91 million t of asphalt pavement are reclaimed and 73 million t are recycled. This indicates that 91–73= 18 million t are disposed.

Letter N:

This flow amount is a result of a Spring 1998 phone survey done by the Portland Cement Association for Bill Turley of C&D Debris Recycling. The average amount of crushed cement concrete recycled was 104,507 tons according to the survey. Combining this with Bill Turley's estimate of 1,000 recyclers gives an estimate of 104,507,000 tons (94.8 million t) of crushed cement concrete recycled in the United States for the year 1997. A larger average amount of crushed cement concrete recycled per company was reported in a previous survey from a smaller sample. This previous survey is discussed following.

The estimate of percentage flows to end uses comes from a previous survey done by Vanderbilt University and C&D Debris Recycling. The results of the survey of crushed cement concrete producers are published in the September/October 1997 issue. A personal communication with Tara Deal, the author, was used to make the following calculations of total crushed cement concrete:

Average quantity recycled per year per company = 170,000 tons

Number of companies actually recycling concrete = 48

calculation:

48 * 170,000=8.16 million tons

8.16 * 0.9072=7.14 million t

A previous estimate (Collins and Ciesielski, 1994, p. 19) was 2.72 million t in 1994.

The question mark (?):

The unknown flows are indicated by a question mark. These flows are not reported because the author is unaware of any data that exist. There are six of these unknown flows on the diagram: three associated with the use of steel in concrete, two associated with the cement concrete made available by the demolition of "buildings" and "highways and roads," and one flow associated with the disposal of scrap asphalt roofing.

The three flows associated with the use of steel in concrete can be broken into two flows that go into structures for reinforcement of concrete and one flow of steel released by the crushing of cement concrete. The two flows into "buildings" and "highways and roads" may be estimated once a use factor for reinforcing bar is established (remember the total steel flow is only for reinforcing bar as discussed under the letter C on page 14). The C & D Debris Recycling Survey (Deal, 1997, p. 11) reported that 86 percent of recyclers were able to sell the rebar recovered. So the amount of steel recovered from demolition could also be estimated, once the annual amount of concrete demolished and recovered is estimated.

The value of concrete demolished annually is being estimated by studies performed for the EPA by Franklin Associates. These two flows from "buildings" and "highways and roads" will help to fill in all the remaining question marks except for the asphalt shingles recycled from reroofing and building demolition.

The roofing shingle waste released from reroofing and building demolition is contaminated with nails, which complicates the recycling process. The waste contains approximately 20 percent asphalt binder as well as aggregates, so it is a valuable material for recycling as an additive to hot mix asphalt. At least 11 States are allowing inclusion of old asphalt shingles in hot asphalt mix at up to 5 percent by weight content (California Integrated Waste Management Board, 1997). As this process becomes more accepted, the recycling rate should increase.