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Literature-Derived Hydraulic Properties of Waste Materials for Use in Hydrologic Evaluation of Landfill Performance (HELP) Model

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Literature-Derived Hydraulic Properties of Waste Materials for Use in Hydrologic Evaluation of Landfill Performance (HELP) Model

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Disclaimer

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The Center for Environmental Solutions and Emergency Response (CESER) within the Office of Research and Development (ORD) conducts applied, stakeholder-driven research and provides responsive technical support to help solve the Nation's environmental challenges. The Center's research focuses on innovative approaches to address environmental challenges associated with the built environment. We develop technologies and decision-support tools to help safeguard public water systems and ground water, guide sustainable materials management, remediate sites from traditional contamination sources and emerging environmental stressors, and address potential threats from terrorism and natural disasters. CESER collaborates with both public and private sector partners to foster technologies that improve the effectiveness and reduce the cost of compliance, while anticipating emerging problems. We provide technical support to EPA regions and programs, states, tribal nations, and federal partners, and serve as the interagency liaison for EPA in homeland security research and technology. The Center is a leader in providing scientific solutions to protect human health and the environment.

This report presents a compilation of the published values of hydraulic properties of waste materials that are typically disposed of in landfills. The data presented in the report can be used to include new materials and to update the default values of the materials currently included in the Hydrologic Evaluation of Landfill Performance (HELP) model.

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1 Overview

The Hydrologic Evaluation of Landfill Performance (HELP) model uses waste-specific properties such as hydraulic conductivity, porosity, wilting point, and field capacity for modeling vertical percolation of leachate through the deposited waste and cover layers to estimate the leachate generation rate and the head on the liner. However, the model includes default values of hydraulic properties of only a limited number of waste materials. The objective of this study was to compile the published hydraulic properties of various waste materials that are typically disposed of in landfills but that were not included in the model and develop default values of hydraulic properties for these materials that can be used to update the HELP model. The published hydraulic properties data of the materials that are currently included in the HELP model were also compiled. These values can be used to update the current default values of the hydraulic properties of these materials. Table 1 lists the materials for which the hydraulic properties were compiled in this study.

Table 1. List of the Materials Reviewed in this Study

Waste Material	Description
Alum Sludge Lime Sludge Ferric Sludge	Sludge is typically produced in the form of lime, alum, or ferric sludge, depending on the treatment type and is a mixture of water and precipitated solids. Drinking water sludge is a byproduct of the water treatment processes used in water treatment plants. Coagulants are used in water treatment to facilitate flocculation to remove turbidity and pathogens and reduce hardness via precipitation softening. Through sedimentation and filtration, these residuals are removed in the form of sludge.
Domestic Wastewater Treatment Plant Sludge (Also referred to as Biosolids or Sewage Sludge)	Sludge refers to the solids-water mixture pumped from wastewater treatment lagoons having the characteristics of a liquid or slurry typically containing between 2% to 15% oven-dried solids (Arulrajah et al., 2011). Conventional secondary domestic wastewater treatment plants typically generate a primary sludge in the primary sedimentation stage of the treatment and secondary biological sludge in the final sedimentation after the biological process (Aziz et al., 2016).
Coal Bottom Ash	Coal combustion bottom ash is created from heavy ash particles that are formed in pulverized coal furnaces. Bottom ash is a coarse material with a grain size ranging from fine sand to fine gravel. Approximately 17.8 million tons of bottom ash were generated, and 7.5 million tons were beneficially used in the United States in 2010 (ACAA, 2011).
Coal Fly Ash	Coal combustion fly ash is light ash particles removed in exhaust gases during the combustion of coal for electricity production. Fly ash is a very fine material composed mostly of silica, ranging from silt to clay-sized particles. Fly ash could be in wet or dry form, dependent on the process used to collect and store the ash. Approximately 68 million tons of fly ash were produced in the United States in 2010 (ACAA, 2011).
FGD By-product	Flue gas desulfurization (FGD) byproduct is formed as a result of sulfur dioxide (SO_2) removal from the coal-fired boiler exhaust gas. Depending on the procedure used for SO_2 removal, FGD byproducts can be in the form of FGD gypsum, a wet sludge (wet scrubber byproduct), or a dry powdery material (dry scrubber byproduct). Dry FGD might also be referred to as lime spray dryer ash. Production rates for the varying types of FGD byproducts for 2011 were reported as 25 million tons as FGD gypsum, 11.1 million tons as FGD materials from wet scrubbers, 2.2 million tons as FGD material from dry scrubbers, and 143,000 tons of “other” FGD byproducts (ACAA, 2012).
Cement Kiln Dust	Cement kilns manufacture Portland cement by reacting calcium carbonate and silica-bearing materials. Cement kiln dust (CKD) is composed of the particles that are captured by air pollution control devices filtering the cement kiln exhaust gas. CKD is a fine-grained, highly alkaline, powdery substance. Approximately 15 million tons of CKD are generated annually in the United States.
Fine Copper Slag	Copper slag is produced during the recovery and processing of copper from natural ores.

Waste Material	Description
Foundry Sand	Foundry sands are a product of the metal casting process that takes place in metal foundries. New virgin sand is used to make casting molds for metals. The sand is reused within the casting process multiple times until the sand becomes unsuitable and is removed and replaced. Approximately 6 to 10 million tons of foundry sands are produced annually (US DOT, 2004).
MSW Combustion Bottom Ash	Municipal solid waste (MSW) bottom ash is composed of approximately 90% of the materials retained on the stoker or grate of a combustion facility and is representative of approximately 75% to 80% of the total combined ash byproduct. This grate material consists mainly of glass, ceramics, and ferrous and nonferrous metals and minerals. MSW bottom ash has a porous, grayish, silty-sand, and gravel-like appearance with small amounts of unburned organic materials and metals (US DOT, 2012).
MSW Combustion Fly Ash	Entrained particles in the flue gas that are removed by air pollution control devices from the combustion of municipal solid waste
MSW Compost	Composting transforms MSW into two components: organics with a size distribution of silty sand and residues (e.g., plastics, metal residues, large non-degradable)
MSW	MSW is generated from domestic, commercial, industrial, and institutional activities. Over 50% of MSW generated in the United States is disposed of in landfills. Due to the large particle size of this material stream, the values of hydraulic conductivity, porosity, and field capacity are all influenced by the scale of the measurement. The values measured in the field and laboratory are separately compiled and summarized.
Reclaimed Screened Material	Reclaimed screened material consists of soil along with fragments of rock, wood, drywall, and plastic. These materials are the leftover “fines” from the screening of the construction and demolition (C&D) debris stream at C&D processing facilities.
Dredging Sediment	Dredged sediments are generated from the removal of sediments accumulated at the bottom of waterways. The physical characteristics of dredged material can vary from fine clays to silts and coarse sand. The moisture content depends on the dredging process and the extent of dewatering before the offsite disposal of these sediments. Approximately 200 to 300 million yd^3 of material are dredged from harbors and waterways annually (US EPA, 2007).
Sugarcane Bagasse Ash	Sugarcane bagasse ash is a byproduct of the sugar and ethanol industry. Bagasse is commonly used as a fuel in cogeneration to produce steam and generate electricity and ash as a combustion byproduct. Each ton of burned bagasse could generate 25–40 kg of bagasse ash, which is generally used as a fertilizer or disposed of in landfills (Xu et al., 2018).
Shredded Tires	Used tires are shredded and typically used as fuel chips or in civil engineering applications. Processed tires are used in landfill applications as daily cover soil or a part of the leachate collection system (Cecich et al., 1995).
Tire Ash	Wood and tire ash is a byproduct of the cocombustion of vehicle scrap tires and waste wood (Tolaymat, 2003). It is estimated that there are more than 500 million tires stockpiled across the United States, and 270 million more are generated each year (Salgado et al., 2003). Approximately 57% of the scrap tires generated in 1999 in the United States were incinerated (Tolaymat, 2003).
Wood Ash	Wood ash is the byproduct of the combustion of wood or wood fiber. Wood ash composition can vary depending on the wood source (industrial, municipal) and the characteristics of the combustion system. Approximately 3 million tons of wood ash are generated in the United States annually (Risse, 2010).
Paper Mill Sludge	Paper mill sludge is the byproduct of the paper production process. Paper mill sludge consists of soft and fibrous soil-like materials with a high content of water (150-300%). Paper mill sludge is composed of fibrous organic material remaining from pulping, clay minerals (predominantly kaolinite), and other inert solids. Applications include agronomic amendments (e.g., admix to topsoil layers), lightweight backfill (after firing to harden the sludge), and hydraulic barrier layers in landfill final covers (Benson and Wang, 2000).

2 Approach

A comprehensive search of the scientific literature was conducted using both the Google Scholar and OneSearch search engines. Most of the identified values were obtained from the peer-reviewed scientific literature. Sources such as conference proceedings and official reports from various professional organizations were also reviewed to identify additional data. Search terms included numerous permutations of keywords such as geotechnical properties, porosity, wilting point, field capacity, hydraulic conductivity, permeability, and water retention curve along with each of the targeted waste materials (e.g., sewage sludge, lime sludge, FGD byproducts, coal fly ash, coal bottom ash, dredging sediment).

The HELP model uses the following parameters to calculate the unsaturated hydraulic conductivity of the soil and waste layers using the Brooks-Corey equation: saturated hydraulic conductivity/permeability (cm/s), porosity (m^3/m^3), field capacity (m^3/m^3), and volumetric wilting point (m^3/m^3) (Schroeder et al., 1994). The HELP model requires that the wilting point be greater than zero but less than the field capacity. The field capacity must be greater than the wilting point and less than the porosity, and the porosity must be greater than the field capacity but less than 1 (Schroeder et al., 1994). In summary, 0 <Wilting Point < Field Capacity < Porosity < 1.

The difference between field capacity and the wilting point represents the amount of water that the plant can takeup (Lopez and Barclay, 2017). Wilting point is the volumetric water content at a suction (capillary pressure) of 15 bars, or the lowest volumetric water content that can be achieved by plant transpiration (Schroeder et al., 1994), and field capacity is the volumetric water content at a suction (capillary pressure) of 0.33 bars. The laboratory measurement of these parameters generally involves placing a saturated soil or waste sample in a controlled vacuum apparatus and measuring the water content as higher rates of suction are applied (Breitmeyer and Benson, 2014).

The HELP model includes default values of various soil and waste materials currently included in the model. Based on a review of the HELP engineering document (Schroeder et al., 1994) and the relevant literature referenced in the HELP engineering document, measurements of field capacity, total porosity, and wilting point are scarcely available for the waste materials that are currently included in the HELP model. The field capacity and wilting points are properties relevant to irrigation needed to support plant growth. However, the waste materials that are the focus of this review are typically not used as soil amendments for plant growth. Applications such as the Portland Cement Concrete amendment are more pertinent beneficial uses of common waste materials such as ash and slags. The physical and geotechnical properties (e.g., density, particle size distribution, hydraulic conductivity) and chemical characterization (e.g., mineral content) are better indicators of their suitability for these applications (e.g., Portland Cement Concrete amendment) than wilting point and field capacity. For ash materials and fine copper slag, the HELP model default porosity values are not based on direct measurements but are calculated using a phase relationship at maximum dry density (Schroeder et al., 1994). Similarly, the HELP model default values of wilting point and field capacity for all the ash and slag wastes are not based on direct measurement of these properties but estimated based on the following equations published by Brakensiek et al. (1984) and literature-reported pore-size distribution:

$$\begin{aligned} \mathit{Field\ Capacity} \\ &= 0.1535 - (\,0.0018 \times \%\,\mathit{Sand}) + (0.0039 \times \%\,\mathit{Clay}) \\ &+ (0.1943 \times \mathit{Total\ Porosity}) \end{aligned}$$

$$Wilting\ Point = 0.0370 - (0.0004\ \times\ \%\,Sand) + (0.0044\ \times\ \%\,Clay) + (0.0482\ \times\ Total\ Porosity)$$

Using the U.S. Department of Agriculture (USDA) textural soil classification system, the HELP model defines sand as the fraction with particle size ranging from 0.05 mm to 2.0 mm and clay particles as the fraction with particle size less than 0.002 mm (Schroeder et al., 1994). The percent sand and clay fractions are estimated based on the particle size distribution (gradation) of the waste material developed using sieve analysis. Some studies provided gravimetric field capacity. The gravimetric values were multiplied with the reported density and divided by water density to calculate volumetric field capacity. Some studies reported the void ratio, which is the ratio of the volume of the voids in the material to the volume of the solids, instead of porosity. In these instances, the following equation was used for calculating porosity using the reported void ratio (Holtz et al., 2011):

$$Porosity = \frac{Void\ Ratio}{Void\ Ratio + 1}$$

3 Data Summary

The degree of the measurements reported varied among the data sources. Some sources reported a single value/measurement, some reported multiple individual measurements corresponding to the same/similar testing conditions (e.g., density), and some reported individual measurements corresponding to different testing conditions (e.g., confining pressure). The sole data point from the sources that reported a single data point was included in the database. The maximum and minimum values from the sources that reported the values corresponding to similar material and testing conditions were included in the database. All the reported individual data points from the sources that reported values corresponding to different materials and testing conditions were included in the database.

Published field capacity and wilting point data were not found for every waste type listed in Table 1. The reported field capacity and wilting point data were included in the database. Some sources provided only water retention plots but did not report a wilting point or field capacity value. The moisture content corresponding to the 0.33 bar and 15 bar capillary pressures were estimated from these plots and recorded, respectively, as the estimated field capacity and wilting point. Some sources reported just the particle size distribution. The available particle size distribution data were used to calculate the field capacity and wilting points using equations published by Brakensiek et al. (1984) (reproduced in Section 2). A field capacity and wilting point were calculated for each of the identified particle size distribution plots for each material. All the calculated values and the reported direct measurements were used to estimate the median field capacity and wilting point for each material. The field capacity, wilting point, water retention plots, and particle size distribution were scarcely reported when compared to the hydraulic conductivity data.

Figure 1 presents distributions (box-and-whisker plot) of the saturated hydraulic conductivity of identified values reported for various waste materials. All reported values were converted to consistent units (cm/s) for comparison and are shown on the logarithmic scale. The top, middle, and bottom of each box represent the 75th, 50th (i.e., the median), and 25th percentiles, respectively. The lines that extend upward and downward (whiskers) from the box represent the 90th and 10th percentiles, respectively. The values less than the 10th percentile or more than the 90th percentile are presented individually outside the whiskers. The reported hydraulic conductivities varied over multiple orders of magnitude. A distribution plot similar to Figure 1 is not presented for porosity, wilting point, or field capacity data due to the scarcity of the reported/estimated values.

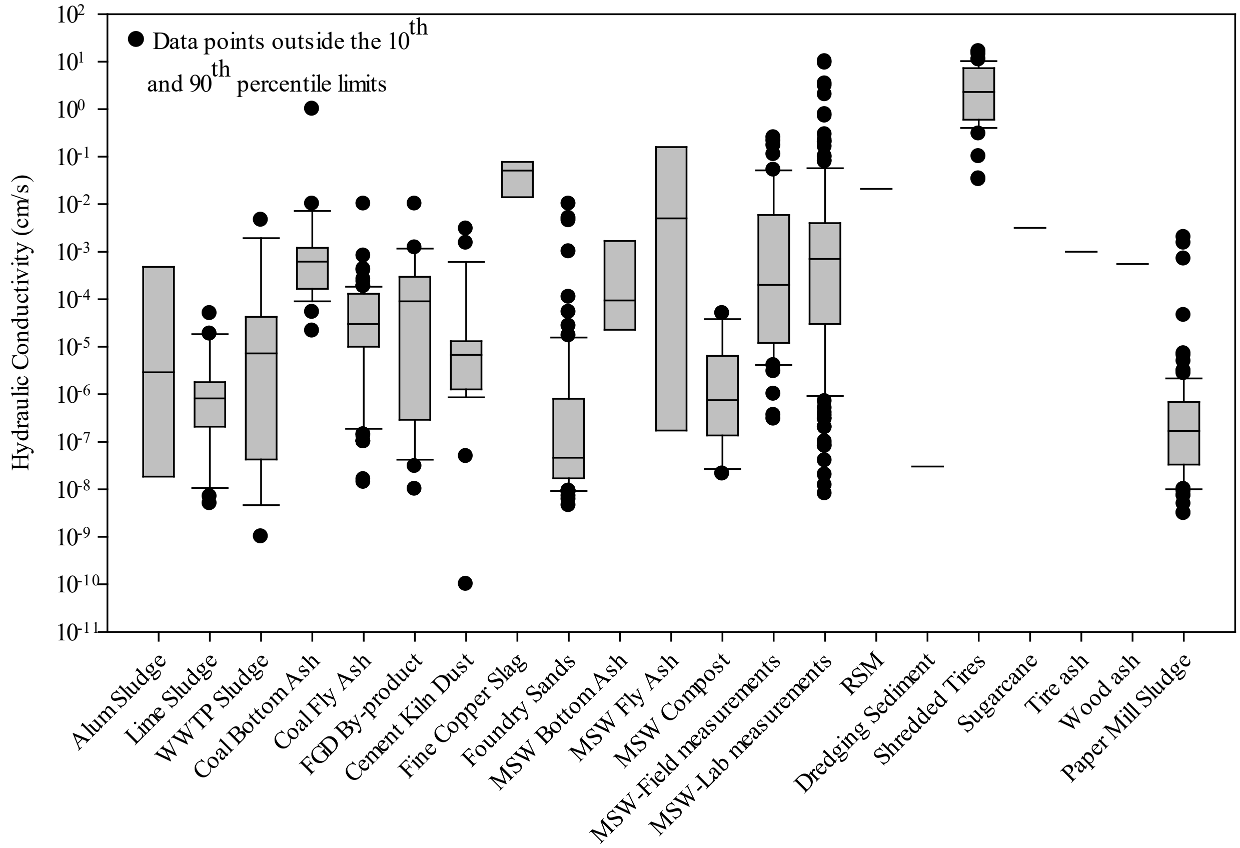

Figure 1. Distribution of published saturated hydraulic conductivity values.

Table 2 displays the summary of hydraulic properties compiled for different waste materials. The median, minimum, and maximum hydraulic conductivity/permeability are summarized from the data collected for each waste type. A median of all the compiled values for each of the hydraulic properties is proposed as the HELP model default value. Published properties for tire ash were not available. The tire ash properties included in Figure 1 and Table 2 correspond to ash from co-combustion of tires with wood debris reported by Tolaymat et al. (2003). The properties of tire combustion ash were not available in the literature. The hydraulic properties of a material are influenced by the material characteristics (e.g., particle size gradation), which are dependent on generation source and in-situ conditions (e.g., moisture content, degree of compactness, density). The pertinent waste material detail (e.g., source, generation details), testing conditions (e.g., density), and test methods, where available, corresponding to the reported hydraulic properties values, are provided in the companion database. The users should consider using site-specific measurements, if available, or measurements that are representative of material-specific site-specific conditions (e.g., density, overburden pressure) in lieu of the default values for the HELP model.

The current version of HELP model includes two categories of MSW (MSW with channeling and MSW-900 pcy). The density of MSW in modern MSW landfills has been reported to be more than 900 pounds per cubic yard (pcy). Two additional categories to reflect the range of density in the MSW landfill are proposed to be included: MSW (1300 pcy) and MSW (1700 pcy). The hydraulic conductivity, porosity, and field capacity of MSW have been reported to decline with an increase in overburden pressure and density (Townsend et al. 2015). The 10th, 25th, 50th, and 75th percentiles of the values reported for MSW based on laboratory and field-scale studies are proposed as the default values for MSW (1700 pcy), MSW (1300 pcy), MSW (900 pcy), and MSW with channeling, respectively. Since the 25th percentile of wilting point was found to be greater than the 25th percentile of the field capacity, 10th percentile of the wilting point was used as the wilting point for MSW (1300 pcy).

The scope of the study was limited to the waste materials listed in Table 1. Although the scope included a majority of the MSW and non-MSW waste streams currently disposed of in MSW landfills, it does not include all the waste streams that can be landfilled. The suite of waste streams that are disposed of in the landfills is driven by the nature of the products consumed, the industrial activities undertaken to manufacture these products, and their service life. All these driving factors are expected to evolve over time. Therefore, a routine evaluation of the streams of waste disposed of in landfills and the inclusion of these in the HELP model should be considered.

Table 2. Summary of Hydraulic Properties for the Waste Materials Evaluated

Material	Saturated Hydraulic Conductivity			Hydraulic Conductivity Data Points	Median Porosity (v/v)	Median Field Capacity (v/v)	Median Wilting Point (v/v)	Current HELP Model Values			
	Median (cm/s)	Minimum (cm/s)	Maximum (cm/s)					Hydraulic Conductivity (cm/s)	Porosity (v/v)	Field Capacity (v/v)	Wilting Point (v/v)
Alum Sludge	2.90E-06	1.85E-08	4.79E-04	3	0.8000	0.1847	0.0480	-	-	-	-
Lime Sludge	8.20E-07	5.00E-09	5.00E-05	20	-	-	-	-	-	-	-
Ferric Sludge	-	-	-	-	0.7564	-	-	-	-	-	-
Domestic WWTP Sludge	7.24E-06	1.00E-09	4.61E-03	16	0.7312	0.2044	0.0590	-	-	-	-
Coal Bottom Ash	6.18E-04	2.15E-05	1.00E+00	27	0.4997	0.1579	0.0440	4.10E-03	0.578	0.076	0.025
Coal Fly Ash	3.00E-05	1.40E-08	1.00E-02	97	0.4597	0.2188	0.0584	5.00E-05	0.541	0.187	0.047
FGD By-product	9.00E-05	1.00E-08	1.00E-02	21	0.8387	0.5550	0.2200	-	-	-	-
Cement Kiln Dust	6.75E-06	1.00E-10	3.00E-03	28	0.4835	0.2375	0.0759	-	-	-	-
Fine Copper Slag	5.10E-02	8.00E-03	8.00E-02	4	0.3001	0.0897	0.0279	4.10E-02	0.375	0.055	0.020
Foundry Sands	4.60E-08	4.50E-09	1.00E-02	81	0.4400	-	-	-	-	-	-
MSW Combustion Bottom Ash	9.43E-05	1.00E-06	2.50E-03	6	0.4500	0.3000	0.1500	-	-	-	-
MSW Combustion Fly Ash	5.00E-03	3.00E-08	1.59E-01	6	0.6000	0.1282	0.0379	1.00E-02	0.450	0.116	0.049
MSW Compost	7.50E-07	2.10E-08	5.00E-05	12	0.6845	0.2500	-	-	-	-	-
MSW with channeling	4.00E-03	8.00E-09	1.00E+01	217	0.6742	0.3500	0.2224	1.00E-03	0.168	0.073	0.019
MSW- 900 pcy	6.30E-04				0.5816	0.2000	0.1955	1.00E-03	0.671	0.292	0.077
MSW – 1300 pcy	3.00E-05				0.4623	0.1330	0.0720				
MSW – 1700 pcy	1.68E-06				0.3395	0.1236	0.0720				
Reclaimed Screened Material	2.10E-02	2.10E-02	2.10E-02	1	0.6500	-	-	-	-	-	-
Dredging Sediment	3.00E-08	-	-	1	0.7401	0.1981	0.0491	-	-	-	-
Shredded Tires	2.30	3.30E-02	16.3	57	0.4803	-	-	-	-	-	-
Sugarcane Bagasse Ash	3.15E-03	3.00E-04	6.00E-03	2	0.8389	0.3500	0.2400	-	-	-	-
Tire Ash	1.00E-03	-	-	1	-	-	-	-	-	-	-
Wood Ash	5.50E-04	1.00E-04	1.00E-03	2	0.6676	0.1557	0.0444	-	-	-	-
Paper Mill Sludge	1.70E-07	3.10E-09	2.00E-03	105	0.7301	0.1658	0.0434	-	-	-	-

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