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Case study

Physical, chemical, and geotechnical properties of coal fly ash: A global review

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A B S T R A C T

In 2015, fly ash utilization rates were 70% for China, 62% for India, and 50% for the US. This leaves substantial potential for increased utilization. This article summarizes available literature concerning physical and chemical and geotechnical properties of fly ash which affect its options for re-use. Fly ashes are broadly classified worldwide into two chemical types for their industrial applications, mostly in cement industries, namely class C and class F. Class C fly ash, with its higher levels of calcium oxide, generally has self-cementing properties. In terms of global fly ash composition, fly ash from India on average contains higher levels of silicon dioxide than that from the US and China. In terms of particle size, studies report that fly ash more often is poorly graded than well-graded; fly ash from India in particular tends to be poorly graded. Optimum moisture content (OMC) values for fly ashes vary from 11 to 53%, and maximum dry density values range from 1.01 to 1.78 g/cm^3. Country-specific trends in terms of fly ash OMC and maximum dry density values are not readily apparent. Fly ash tends to be non-plastic, meaning it will not swell if used as a foundation material for structures. Reported fly ash shrinkage limits range from 38 to 65. Permeability of pure fly ash generally varies from 10^{-4} to 10^{-7} cm/sec, and angle of friction varies from 25° to 40°.

1. Introduction

Coal is used as a major source of energy throughout the world. In 2015 coal supplied 29% of energy world-wide; despite increases in use of renewables, the share of coal is expected to still be 24% by 2035. Since global energy consumption is expected to increase by 30% by 2035, the actual amount of coal consumed per year will increase from 3840 million tons oil equivalent (mtoe) in 2015 to 4032 mtoe in 2035. In 2015, China was the world's largest coal consumer (50% of global demand, or 1920 mtoe), and is expected to remain so, accounting for 47% of global coal demand in 2035 (1876 mtoe). India's coal consumption is expected to more than double between 2015 and 2035 (from 407 to 833 mtoe) to feed its power sector, although the United States' demand will fall by half (from 396 mtoe in 2015 to 198 in 2035) [1]. Fig. 1 provides global coal fly

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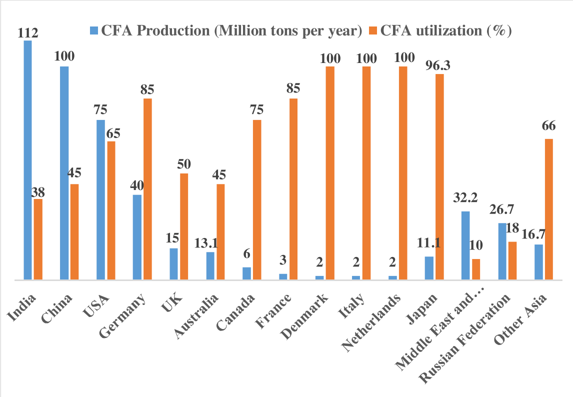

Fig. 1. Global Coal Fly Ash Production and Utilization [2].

ash production and utilization. Fly ash utilization is only 1/4th of the total production. The top producers, India and China have less than 50% utilization rate, while Denmark, Italy and Netherlands have 100% fly ash utilization rate.

Burning coal produces coal combustion residuals (CCR), or byproducts, which include fly ash, bottom ash, boiler slag, flue-gas desulfurization residues, and fluidized bed combustion ash. Over 70% of waste coal ash is categorized as fly ash (FA), fine particulates captured by particulate control equipment, ranging in size from 0.5 μm to 300 μm [3,4]. In 2015, fly ash utilization rates were 70% for China, 43% for India, and 53% for the US [4]. This leaves substantial potential for increased utilization. Re-use of fly ash can decrease disposal volumes and costs, as well as replace non-renewable or expensive resources.

There has been an increasing attempt for fly ash utilization in different sectors. Loya and Rawani [5] identified top areas for the quantity of fly ash utilization as 44.19% in cement and concrete sectors, 15.25% of ash in roads, embankments and ash dyke raising, followed by 12.49% in reclamation of low lying areas and land filling, 8.84% in mine filling, 7.61% in bricks, blocks and tiles, 2.47% in agriculture and 9.14% in others. The breakdown of modes of utilization for four countries is provided in Fig. 2 [4].

Fly ash is used as a supplementary cementitious material (SCM) to produce Portland cement concrete. Fly ash when used as SCM contributes to properties of hardened concrete through pozzolanic and/or hydraulic activity. Fly ash has been used in concrete ranging from 15 to 25% by mass and high dosage of 40–60% can be used in structural uses [6]. Incorporation of fly ash can strongly affect the properties of fresh concrete and durability of hardened concrete. The extent to which fly ash affects concrete properties is dependent on composition and proportion of other ingredients in the mixture, type and size of concrete, exposure conditions during and after placement, construction practices etc. Therefore, there is no single replacement level best suited for all applications.

Physical and chemical properties of fly ashes affect their options for re-use. Many potential re-use options for fly ash involve geotechnical applications, such as soil stabilization for roadways [7,8]; backfill for excavations, mine fill, trenches, and retaining walls [9]; landfill liners or covers [10–13] and as a geopolymer material [14–16]. To increase the re-use of fly ash, many separation techniques have been developed to segregate value-added components, such as magnetites, aluminosilicates, unburned carbon, and cenospheres. Cenospheres are one of the most valuable materials found in fly ash. Their properties, such as high compressive strength, light weight, low water absorption, chemical inertness, and good thermal resistance, make them suitable to a wide range of applications. Cenospheres can be used as mullite-coated diesel engine components, heat exchangers, and for aluminum reclamation; in the construction industry, cenospheres can be used as an additive to make lightweight cements, and can be incorporated with cement to create lightweight workable materials [17].

The goal of this article is to summarize available literature concerning physical/chemical and geotechnical properties of fly ash. The article will first review physical/chemical properties and then discuss the geotechnical properties of grain size distribution, moisture content/dry density relation, Atterberg limits, hydraulic conductivity, unconfined compressive strength, and angle of friction.

2. Physical and chemical properties of fly ash

2.1. Physical properties

Fly ash consists of fine, powdery particles predominantly spherical in shape, either solid or hollow, and mostly amorphous in nature. In general, the specific gravity of coal ashes lies around 2.0 but varies to a large extent, from 1.6-3.1. This variation is due to a combination of several factors such as particle shape, gradation, and chemical composition [18]. Based

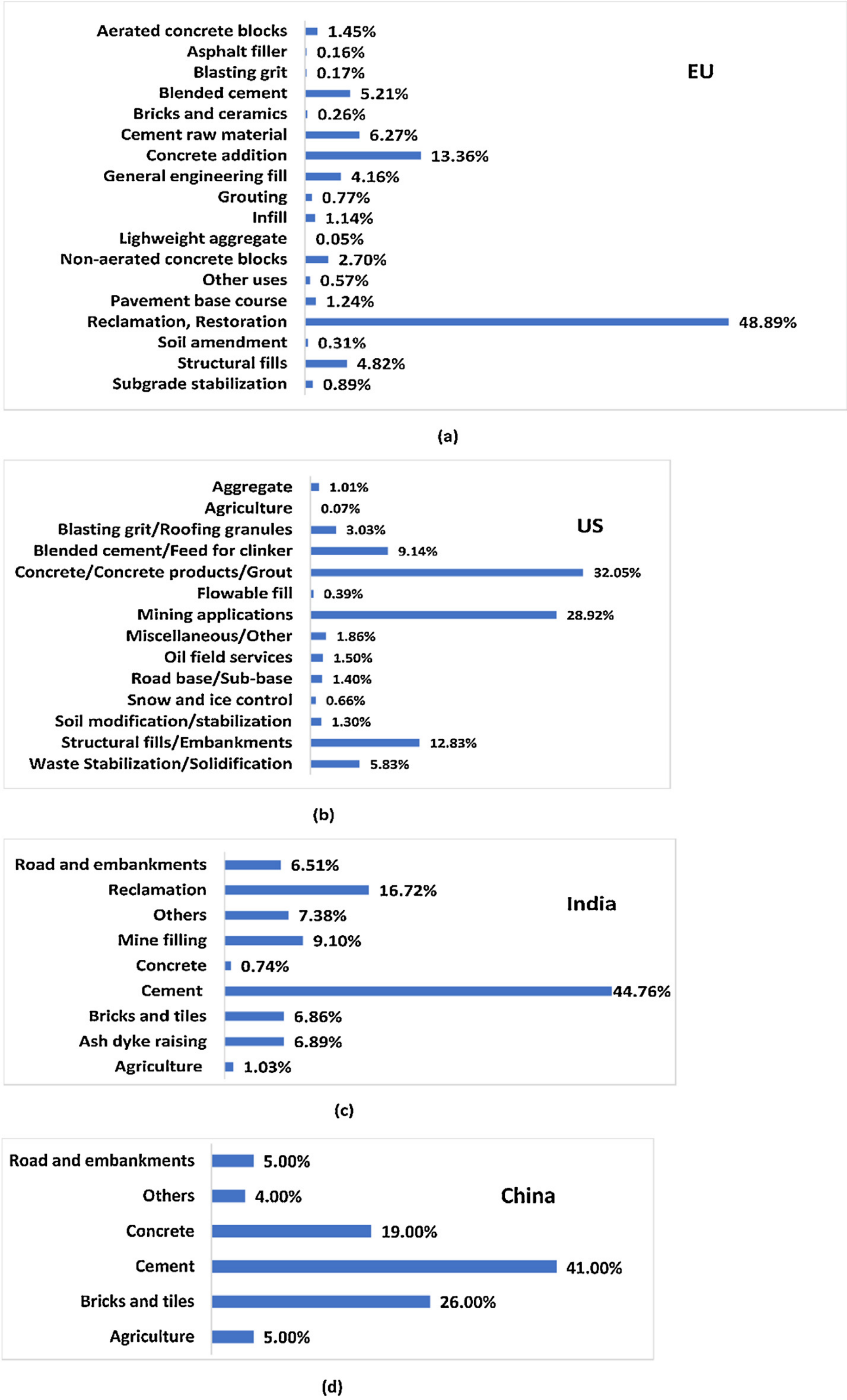

Fig. 2. Fly ash Utilization Modes for EU, US, India and China.

on the grain size distribution fly ashes can be classified as sandy silt to silty sand. Particularly, Indian coal ashes are predominantly of silt-size, with some clay-size fraction [19]. Fly ash has high specific surface area and low bulk density [20]. The amount of unburned carbon and iron impact the color of fly ash, which can vary from orange to deep red, brown, or white to yellow [21].

2.2. Major chemical components

Since 316 individual minerals and 188 mineral groups are recognized in fly ash, it is one of the most complex materials in terms of characteristics [22]. However, all fly ash includes substantial amounts of silicon dioxide (SiO_2) (both amorphous and crystalline), aluminum oxide (Al_2O_3) and calcium oxide (CaO), the main mineral compounds in coal-bearing rock strata. Depending on pH value and calcium/sulfur ratio, fly ashes are classified as acidic ash (pH 1.2 up to 7), mildly alkaline ash (pH 8–9), and strongly alkaline ash (pH 11–13) [23].

Fly ash can be classified according to the type of coal from which the ash was derived. There are basically four types/ranks of coal: anthracite, bituminous, sub-bituminous, and lignite. The principal components of bituminous coal fly ash are silica, alumina, iron oxide, and calcium, with varying amounts of carbon. Lignite and sub-bituminous coal fly ash is characterized by higher concentrations of calcium and magnesium oxide and reduced percentages of silica and iron oxide, as well as lower carbon content, compared with bituminous coal fly ash. Very little anthracite coal is burned in utility boilers, so there are only small amounts of anthracite coal fly ash [24]. The physical/chemical properties of fly ash depend not only on the type of coal used in a process but also on the techniques used to burn the coal. Specifically, properties of fly ash depend on: (i) boiler configuration, (ii) burning condition and temperature of the boiler, (iii) the particle size of the coal, and (iv) the gas cleaning equipment [25].

Fly ashes are broadly classified worldwide into two chemical types for their industrial applications, mostly in cement industries, namely Class C and Class F. According to the American Society for Testing Materials standard ASTM C618 [26], the ash containing more than 70% wt% $SiO_2+Al_2O_3+Fe_2O_3$ are defined as Class F, while those with a $SiO_2+Al_2O_3+Fe_2O_3$ content between 50 and 70 wt% are defined as Class C. Other chemical and physical requirements for class C and F in ASTM classification include contents of SO_3 ($\leq$ 5%), moisture ($\leq$ 3%), Na_2O ($\leq$ 1.5% optional), particle size ($\leq 34\% \pm 5\%$ on average value retained on 45 μm), loss on ignition (LOI) ($\leq$ 6% and up to 12% for class F based on performance). Fly ash classification systems for Canada, Russia, and the European Union differ from that of the US; there is currently no international classification system [22].

In addition to Class F and C fly ashes, the US ASTM C618 defines a third class of mineral admixture – Class N. Class N mineral admixtures are raw or natural pozzolans such as diatomaceous earths, opaline cherts and shales, volcanic ashes or pumicites, calcined or uncalcined, and various other materials that require calcination to induce pozzolanic or cementitious properties, such as some shales and clays.

According to ASTM, Class C fly ashes typically have calcium content (as CaO) higher than Class F fly ashes. Class C fly ash generally contains more than 15% CaO, and Class F fly ash normally contains less than 5% CaO [27]. In general, high-calcium Class C fly ash is produced from the burning of younger lignite or sub-bituminous coal, whereas the burning of harder, older

Table 1
Summary of worldwide coal fly ash chemical composition ranges.

Country	% Chemical composition											Ref.
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	SO_3	TiO_2	Na_2O	P_2O_5	MnO	LOI	
Australia	31.1-68.6	17-33	1-27.1	0.1-5.3	0.1-2.9	0-2	0-0.6	1.2-3.7	0-1.5	0-3.9	nd	na	[29] [34],
Bagladesh	55	24.7	7.7	6.2	1.1	0.7	1.1	na	na	0.9	0.1	na	[10]
Bulgaria	30.1-57.4	12.5-25.4	5.1-21.2	1.5-28.9	0.8-2.8	1.1-2.9	0.4-12.7	0.6-1	0.4-1.9	0.1-0.4	0-0.2	0.8-32.8	[1]
Canada	35.5-62.1	12.5-23.2	3-44.7	1.2-13.3	0.5-3.2	0.4-3.1	0.2-7.8	0.4-1	0.1-7.3	0.1-1.5	na	0.3-9.7	[20] [35],
China	35.6-57.2	18.8-55	2.3-19.3	1.1-7	0.8-0.9	0.7-4.8	1-2.9	0.2-0.7	0.6-1.3	1.1-1.5	nd	nd	[29]
Denmark	48-65	26-33	3.3-8.3	2.2-7.8	na	na	na	na	1.1-2.8	na	na	3.1-4.9	[36]
Europe	28.5-59.7	12.5-35.6	2.6-21.2	0.5-28.9	0.4-4	0.6-3.8	0.1-12.7	0.5-2.6	0.1-1.9	0.1-1.7	0-0.2	0.8-32.8	[29]
France	47-51	26-34	6.9-8.8	2.3-3.3	na	1.5-2.2	0.1-0.6	na	2.3-6.4	na	na	0.5-4.5	[36]
Germany	20-80	1-19	1-22	2-52	0-2	0.5-11	1-15	0.1-1	0-2	na	na	0-5	[33]
Greece	21-35	10-17.9	4.5-8.4	27.3-45	0.4-1	1.5-3.8	4-8.6	na	0.2-1	na	na	3-7	[33,1]
India	50.2-59.7	14-32.4	2.7-16.6	0.6-9	0.2-4.7	0.1-2.3	na	0.3-2.7	0.2-1.2	na	na	0.5-7.2	[19,29,37]
Israel	45.6-58.6	24.4-34.5	3-6.7	4.9-9.9	0.1	1.6-2.5	0.6-0.8	1.2-1.9	0-0.1	0.8-1.8	na	6	[13]
Italy	41.7-54	25.9-33.4	3-8.8	2-10	0-2.6	0-2.4	na	1-2.6	0-1	0-1.5	0-0.1	1.9-9	[1,38]
Japan	53.9-63	18.2-26.4	4.2-5.7	2-8.1	0.6-2.7	0.9-2.4	0.3-1.4	0.8-1.2	1.1-2.1	na	na	0.5-2.1	[23,24,39]
Korea	50-55.7	24.7-28.7	3.7-7.7	2.6-6.2	1.1	0.7-1.1	0.5-1.1	na	na	0.9	0.1	4.3-4.7	[10,11,12]
Mexico	59.6	22.8	5.6	3.1	1.3	0.9	0.4	0.9	0.5	0	na	na	[25]
Netherlands	45.1-59.7	24.8-28.9	3.3-9	0.5-6.8	0.6-2.9	0.6-3.7	0.2-1.3	0.9-1.8	0.1-1.2	0.1-1.5	0-0.1	2.7-8.1	[1,40]
Northern China	43.7	44	3.5	0.9	0.9	0.4	0.7	1.5	0.3	na	na	10	[41]
Poland	32.2-53.3	4-32.2	4.5-8.9	1.2-29.9	0.2-3.3	1.2-5.9	na	0.6-2.2	0.2-1.5	0.1-0.9	0-0.3	0.5-28	[42]
Russia	40.5-48.6	23.2-25.9	na	6.9-13.2	1.9-2.6	2.6-4	na	0.5-0.6	1.2-1.5	0.3-0.4	0.2-0.4	na	[32]
South Africa	46.3-67	21.3-27	2.4-4.7	6.4-9.8	0.5-1	1.9-2.7	na	1.2-1.6	0-1.3	0.3-0.9	0-0.5	na	[[25],26 [43],]
Spain	41.5-58.6	17.6-45.4	2.6-16.2	0.3-11.8	0.2-4	0.3-3.2	0.1-2.2	0.5-1.8	0-1.1	0.1-1.7	0-0.1	1.1-9.7	[1,3,4]
Spain	41.5-58.6	17.6-35.6	2.6-16	0.8-11.8	0.4-4	0.9-2.5	0.1-2.2	0.5-1.6	0.2-0.8	0.1-1.7	0-0.1	1.1-5.2	[40]
Turkey	37.9-57	20.5-24.3	4.1-10.6	0.2-27.9	0.4-3.5	1-3.2	0.6-4.8	0.6-1.5	0.1-0.6	0.2-0.3	0	0.4-2.7	[1,7,8,9]
United State	34.9-58.5	19.1-28.6	3.2-25.5	0.7-22.4	0.9-2.9	0.5-4.8	0.1-2.1	1-1.6	0.2-1.8	0.1-1.3	na	0.2-20.5	[28,29,30]
Minimum	20.0	1.0	1.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	
Maximum	80.0	55.0	44.7	52.0	4.7	11.0	15.0	3.7	7.3	3.9	0.5	32.8	

Note: nd = Not detected, na = Not available.

Table 2
Summary of worldwide coal fly ash grain size indices.

Location of fly ash origin		Fly ash class	Coefficient of uniformity	Coefficient of curvature	Quality of Grading†	Reference	Notes
Country	Plant, City or State						
India	Neyveli	C	3.16	1.04	Poor	[19]	Indian coal fly ashes consist predominantly of silt-size fraction with some clay-size fraction.
	Badarpur	F	5.5	2.47	Poor		
	Korba	F	6	1.14	Well		
	Ramagundam	F	1.59	1.09	Poor		
	Vijayawada	F	5.7	0.61	Poor		
	Dadri, New Delhi	F	5.65	0.9	Poor	[46]	According to Unified Soil Classification System, both Dadri and Rajghat fly ashes are ML-type soil, non-plastic silt.
	Rajghat, New Delhi	F	4.82	1.01	Poor		
	Orissa	F	4.02	0.94	Poor	[47]	Particle size analysis was conducted using a Malvern 3601 particle size analyzer with wet dispersion method in water.
	Orissa	F	3.96	0.93	Poor		
	Orissa	F	4	0.91	Poor		
	Captive Power Plant, Rourkela	F	5.88	1.55	Poor	[48]	86.6% fly ash passed 75 μm sieve.
	Kolaghat Thermal Power Station, West Bengal	F	5.44	3.12	Poor	[37]	N/A
	Gulbarga, Karnataka	F*	2.14	0.95	Poor	[13]	Fly ash particles are of silt size. GFA is finer than the other two. NFA and VFA possess almost similar gradation.
	Neyveli, Tamilnadu	F*	6.67	0.74	Poor		
	Vijayawada, AP	F*	3.67	0.76	Poor		
	Assam	F*	3.67	3.21	Poor	[49]	C_c and C_u values were determined according to Indian Standard Procedure.
	Orissa	F*	2.13	1.12	Poor	[50]	N/A
	Mouda (Tehsil), Nagpur (Dist.), Maharashtra		7	1.96	Well	[51]	Fly ash contained particles the size of silt (68 %), sand (17 %) and clay (5 %).
South Korea	Samchunpo	N/A	18.8	1.05	Well	[52]	N/A
	Dong-hae		6	0.91	Poor		
	Seocheon		12.5	1.2	Well		
	Tae-an		13.8	1.08	Well		
Thailand	Mae Moh power plant (Classified Fly Ash)	F	22	2.39	Well	[53]	31% of original fly ash (OFA, median size 19.1 μm) was retained on No. 325 sieve (45 μm). All classified fly ash (CFA, median size 6.4 μm) passed through No. 325 sieve.
	Mae Moh Power plant (Original Fly Ash)	F	50	1.68	Well		
	Mae Moh Power Plant	F*	16.67	0.67	Poor	[54]	Grain size distribution was obtained from laser particle size analysis.
Turkey	Soma Thermal Plant	C	11.2	1.03	Well	[10]	Particle size analyses were performed by sieving and hydrometer method (ASTM D 422, D 1140). Grain size distribution curve indicated predominantly silt-sized uniform material.
	Catalagzi, Zonguldak	F	2.14	0.95	Poor	[12]	70 wt% of fly ash consists of particles with dia 2-60 μm (silt size), 25 wt% with diameter 60-200 μm (fine sand size), and the rest medium sand size (200-600 μm).
United States	A. B. Brown Plant, Indiana, USA	F	36.5	2.98	Well	[55]	N/A
	Wabash River Plant, Indiana, USA	F	10.3	1.01	Well		
	Delaware	F	4	1.56	Poor	[56]	N/A
	Delaware	F	2.8	N/A	Poor		
	New Jersey	F	2.4	N/A	Poor		
	New Jersey	F	3	N/A	Poor		
	Pennsylvania	F	9	1.82	Well		
	Texas	F	28	26.42	Poor	[57]	N/A
	Alabama	F	30	18.15	Poor		
	San Juan Mine, New Mexico	F	7.5	1.8	Well	[58]	Fly ash was 85.4% finer than a #200 sieve (0.075 mm diameter)

† According to the classification for sand, N/A = Not available.
* Determined based on ASTM.

anthracite and bituminous coal typically produces Class F fly ash. Class F fly ash possesses pozzolanic properties, meaning it contains silica compounds which react with calcium hydroxide at room temperature to form compounds possessing cementitious properties. However, since CaO levels in Class F are low, addition of an activator (such as quicklime or hydrated lime mixed with water) is needed to form cement. On the other hand, Class C fly ash, with its higher levels of CaO, has self-cementing properties; in the presence of water, Class C fly ash hardens and gets stronger over time. Alkali and sulfate (SO_4) contents are generally higher in Class C fly ashes [28].

2.3. Carbon and metals

The loss of ignition (LOI) test is used to identify the portion of unburned carbon and metallic oxides in fly ash. The LOI content varies as operating conditions change. According to both ASTM C618 and EN 450-1, an increase in LOI reduces the quality of the fly ash due to higher carbon content, which limits its applicability in concrete due to significant air-entrainment, affecting the durability of concrete [29].

In terms of metals content, the US Environmental Protection Agency (EPA) issued a final ruling in 2014 that coal fly ash does not have to be classified as a hazardous waste. However, some metallic elements of fly ash, including mercury, cadmium, and arsenic, pose potential health concerns if they leach into the environment in high enough concentrations [30]. LEAF (Leaching Environmental Assessment Framework) Methods 1313 (leaching as a function of pH), 1314 (leaching as a function of solid/liquid ratio), and 1315 (leaching time) can be used to assess whether leaching of metals from a particular fly ash pose a concern [31]. In applications which rely on the cementitious properties of fly ash, leaching of metals is unlikely, since they are immobilized by the cement matrix.

2.4. Global variation in fly ash chemical composition

Table 1 summarizes coal fly ash chemical composition ranges worldwide. It appears that the SiO_2 content of India's fly ash (50–60%) is substantially higher than that of China and the US (36–38% up to 57–58%). Greece has the lowest range for SiO_2; the range listed in Table 1 for Greece is specifically for lignite coal, which has in general low SiO_2 content. The Al_2O_3 content range is comparatively wider for China than for other countries listed, while for the Netherlands, Greece, and South Africa, the range is the narrowest. Higher Al_2O_3 content tend to accelerate the setting of geopolymers, while addition of SiO_2 inhibits the setting. Nonetheless, high SiO_2 content tends to have low porosity, which enhances the strength of geopolymers [32]. High content of silica and alumina in fly ash potential uses for zeolite synthesis [33]. The range of CaO content extends above 15% for fly ash from the US, Germany, Poland, Greece, and Europe as a whole, indicating fly ash that would exhibit self-cementing properties. The range of LOI extends to around 30% for Europe in general and Poland in particular, indicating more unburned carbon, which can reduce the usability of the fly ash.

Table S-1 in supplemental information provides more detail about the particular studies from which the summary in Table 1 was derived.

3. Geotechnical properties of coal fly ash

3.1. Grain size distribution

Grain size distribution, or particle size distribution, is valuable in providing initial rough estimates of a material's engineering properties such as permeability, strength, and expansivity, as well as its applicability in cement industries and beyond [44,45]. Some commonly-used measures to describe the grain size distribution are the uniformity coefficient, C_u and coefficient of curvature or gradation, C_c, which are defined as follows:

$$C_u = D_{60}/D_{10}$$

$$C_c = (D_{30})^2/(D_{60} * D_{10})$$

Using data from a sieve analysis, the cumulative particle size distribution is plotted (cumulative percent finer by weight vs. particle size). Then D_{60}, D_{30}, and D_{10} are identified as the diameters with 60%, 30%, and 10% of the fly ash sample finer, or smaller, by weight. Generally, the greater the value of C_u, the more uniform the size distribution. However, a skip or gap distribution, with 2 or more uniformly graded fractions, can also show a high value of C_u. The C_c is used to overcome this problem. According to ASTM D-2487, gravel is classified as well-graded if $C_u \geq 4$ and $1 < C_c < 3$; sand is classified as well-graded (particle sizes are distributed over a wide range) if C_u is ≥ 6 and $1 \leq C_c \leq 3$. Otherwise, the soil is poorly graded (most of the particles are the same size).

Table 2 provides basic grain size indices for various coal fly ashes globally. Using the criteria for well-graded sand (C_u is ≥ 6 and $1 \leq C_c \leq 3$), 12 fly ashes from Table 2 can be considered well-graded; 25 are poorly graded. Only 2 of the fly ashes in Table 2 are Class C; one of these is classified as well-graded, and the other as poorly graded. However, since most fly ash is classified as silt rather than sand, using the grading criteria for sand may not be appropriate. Similar grading criteria is not available for silt.

3.2. Atterberg limits

The potential for volumetric change of soil or fly ash can be determined via Atterberg limits: the liquid limit (LL), the plastic limit (PL), and the difference between them (plasticity index, or PI). The most common Atterberg test for determining Liquid limit, Plastic Limit, and Plasticity Index of fly ash is ASTM D4318. Soils/fly ashes with a low PI (<10), exhibit a small change in volume when subjected to a change in moisture content; in other words, they have a low swelling potential [45]. Soils/fly ashes with a medium PI (10–20) have a moderate swelling potential. Soils/fly ashes with a high PI (>20) have a high swelling potential, and can thus cause damage to structures built on them.

Only 3 of the studies in Table 3 determined PI. One of these studies found PI values of 1 and 4, which means swelling potential is slight. Two additional studies reported the fly ash to be non-plastic (PI = 0), meaning there is no swelling potential. Three additional studies reported liquid limit, but not plastic limit.

When the water content of soil or fly ash is reduced gradually below the plastic limit, the sample will shrink, but the shrinkage become smaller and smaller. The water content at which additional water loss does not reduce the sample volume is called the shrinkage limit. The shrinkage limit is measured using ASTM Test Method D-427 for Shrinkage Factors of Soils. [45] Shrinkage limits reported in Table 3 for fly ash range from 38 to 65. By comparison, shrinkage limits for several clay minerals vary from 8.5 to 29 [44], a much lower range than that for fly ashes.

3.3. Optimum moisture Content/Maximum dry density

In the construction of highway embankments, earth dams, roadway subgrades, and many other structures, soil (or soil mixed with fly ash) is compacted to increase its strength and decrease its potential for settlement [45]. Compacting a

Table 3
Summary of worldwide coal fly ash Atterberg limits, optimum moisture content, and maximum dry density*.

Location of Fly Ash Origin		Class	LL (%)	SL (%)	PI (%)	OMC (%)	MDD (g/cm^3)	Reference
Country	Plant, City or State							
China	Jinling thermal power plant, Nanjing	F	–	–	No plasticity	N/A	2.1	[59]
Czech Republic	Melnik thermal power plant	N/A	N/A	N/A	N/A	22	1.252	[60]
India	Gulbarga	F	62	52		135	2.03-2.67	[13]**
	Neyveli	F	44	38		105		
	Vijayawada	F	49	42		88		
	Gulbarga	F	62	52		52.7	1.03	[61]+
	Neyveli	F	44	38		39.6	1.21	
	Vijayawada	F	49	42		42.4	1.01	
	Panipat	F	43	N/A	Non-Plastic	34	1.1	[62]
	Parichha	F	N/A		N/A	41	1.05	[44]
	Panki	F				30	1.28	
	Neyveli	C				19	1.58	
	RSP Rourkela, Odisha	C	51.5	41.5	Non-Plastic	40	1.16	[63]
Philippines	Manila Power Plant	Possibly C	66	65	N/A	N/A	N/A	[64]
Turkey	Catalagzi Power	F	N/A	N/A	N/A	18.5	1.31	[12]
United States	Red Hills Gen. Facility	Off spec				45.5	1.06	[65]
	Brown, IN	F				24.2	1.56	[55]
	Wabash, IN	F				19.6	1.45	
	Edgewater, OH	F				15	1.63	[66]
	New Jersey, NJSA	F				42	1.03	[56]
	New Jersey, NJFA	F				35	1.12	
	Delaware, DBA	F				28	1.07	
	Delaware, DFA	F				37	1.06	
	Delaware, DSA	F				34	1.07	
	Philadelphia, PA	F				26	1.33	
	Western Pennsylvania	F				24	1.35	
	Alabama	F	19.1		Non-plastic	13.3	1.68	[57]
	Texas	F	18.5		Non-plastic	10.9	1.78	
	Alabama	F	24.4		Non-plastic	11.3	1.34	
	Texas	C	24.2		4	10.8	1.64	
	Texas	C	23.4		1	13.2	1.58	
Minimum			18.5	38	N/A	10.8	1.01	
Maximum			66	65		52.7	1.78	

N/A Not available, * Limited information is available. **Optimum Moisture Content (OMC) values are on volumetric basis so numbers are high. They are excluded from maximum values. +This fly ash contained 0.5, 3.92, 0.86% for GFA, NFA, VFA respectively. LL = Liquid Limit, SL = Shrinkage Limit, PI = Plasticity Index.

granular material like soil or fly ash forces air out of its voids and thus increases its density. The maximum dry density (MDD) to which a granular material can be compacted, and the moisture content at which it occurs (optimum moisture content, or OMC), can be determined using ASTM Test Method D698-07: Standard Test Methods for Moisture-Density Relations of Soil and Soil-Aggregate Mixtures using 5.5# Rammer and 12" drop, also called the Proctor Density Test. The test determines the variation in soil (or fly ash) density as a function of moisture content.

Table 3 shows values of optimum moisture content/maximum dry density for fly ashes globally. According to Table 3, optimum moisture content values for fly ashes vary from 11 to 53%. Trends in OMC by fly ash country of origin are not readily apparent. Of the 4 fly ashes in Table 3 classified as C, the OMC ranges from 11% to 40%; the range for the Class F fly ashes is the same as the overall range (11 to 53%). By comparison, OMC values for bottom ash have been found to vary within a more limited range from 14 to 26% [44]. OMC values for sands, silts, and clays range from 6 to 10%, 11–15%, and 13–21%, respectively [45]. Hence, OMC values for fly ash span the ranges for silts, clays and above.

According to Table 3, maximum dry density values for fly ashes range from 1.01 to 1.78 g/cm^3. Trends in MDD by fly ash country of origin are not readily apparent. Of the 4 fly ashes in Table 3 classified as C, the MDD ranges from 1.16 to 1.64%; the range for the Class F fly ashes is the same as the overall range (1.01 to 1.78 g/cm^3). MDD values for bottom ash range from to 1.16 to 1.87 g/cm^3 [44]; these values are comparable to but slightly higher than those for fly ash. MDD values for silts and clays from 1.28 to 1.92 g/cm^3 [45]; these values are slightly higher than those for bottom ash. MDD values for sands range from to 1.68 to 2.08 g/cm^3 [45]; these values are considerably higher than those for fly ash.

If fly ash is mixed with soil, the value of MDD and OMC of all mixtures depends on the fraction of fly ash in the mixture, as well as the type of ash: fly ash, pond ash, or bottom ash. As fly ash content increases in soil-fly ash mixed samples, typically MDD decreases and OMC increases [67]. This is due to the typically lower density values for fly ash, and higher OMC values.

The value of maximum dry density and optimum moisture content differs depending on the particular power plant that is the source of the fly ash. The values can even vary for the same power plant over different time periods [44].

3.4. Permeability/hydraulic conductivity

Permeability/hydraulic conductivity denotes the ease with which water can flow through the interconnected voids in soil or concrete. Higher permeability values indicate reduction in durability of reinforced concrete structures. The particle size distribution, particle size, particle shape and texture, void ratio, mineralogical composition and degree of compaction are generally considered as the primary influencing factors [19,68]. When fly ash is re-used in concrete, the critical factors are permeability of concrete and the reactivity of the fly ash. Fly ash improves concrete durability by producing compact, denser and less permeable concrete. The permeability of the fly ash will affect the properties of the soil when used for soil stabilization. Hydraulic conductivity is measured using a constant-head test or falling-head test.

As shown in Table 4, the coefficient of permeability (k) of pure fly ash generally varies from 10^{-4} to 10^{-7} cm/sec. In Table 4, fly ashes from Canada, India, and the US generally span this range. For the particular application of landfill covers and liners, the permeability must be less than 10^{-5} and 10^{-7} cm/sec, respectively. Many fly ashes meet the requirement for a cover, but not liner. By comparison, hydraulic conductivities of sands, silty clays, and clays range from 10^{-3} to 1.0, 10^{-5} to 10^{-3}, and $<10^{-6}$, respectively [44]. Thus, the permeability of fly ash is comparable to that of silty clays and clays.

Joshi and Nagaraj [69] and Toth et al. [70] found the permeability of Canadian class C fly ash to be less than that of class F fly ash. Several studies have reported that the intergranular cementitious nature of class C fly ash due to high lime content results in lower permeability than class F fly ash. [69,71].

Table 4
Summary of worldwide coal fly ash hydraulic conductivity.

Location of Fly Ash Origin	Class	Range of Hydraulic conductivity (cm/sec)	Reference
Canada	F	10^{-4} to 10^{-7}	[72]
	N/A	4×10^{-4} to 6×10^{-6}	[69]
India	F	3.5×10^{-4} to 3.7×10^{-4}	[73]
	F	10^{-3} to 10^{-5}	[74]
	F	8×10^{-6} to 1.87×10^{-4}	[19]
	F	1.87×10^{-4} to 8×10^{-6}	[75]
	N/A	10^{-5} to 10^{-3}	[76]
	N/A	1.3×10^{-4} cm/sec	[77]
Japan	F	10^{-4} to 10^{-5}	[68]
Malaysia	F	4.87×10^{-7}	[78]
N/A	N/A	4.97×10^{-4} to 5.31×10^{-4}	[79]
United States	C	1.13×10^{-5}	[80]
	F	1.32×10^{-5}	[80]
	F	0.9×10^{-5}	[81]
	F	3×10^{-6} to 6×10^{-6}	[82]

N/A Not available.

Table 5
Summary of worldwide coal fly ash angle of internal friction*.

Location of Origin	Class	Angle of friction		Reference
		Range	Average	
Canada	F	28 to 37.5°	35°	[70]
India	F	30 to 43°	N/A	[19]
	F	24.84 to 27.34°	N/A	[48]
	F	29.91 to 36.93°	N/A	[83]
	F	30° - 40°	N/A	[74]
	N/A	30° - 40°	N/A	[76]
Malaysia	F	23° to 41°	NA	[78]
Turkey	F	NA	33°	[12]
United States	F	29° to 40°	34°	[71]

*Limited information is available.

3.5. Angle of internal friction Φ

The maximum shearing resistance developed by a material on the failure plane is called shear strength. Shear strength of fly ash is generally based on its angle of internal friction Φ or angle of shearing resistance, as it is a non-plastic material. Due to the potential applications of fly ash in highway embankments, roadway subgrades and as fill materials, the angle of friction is an important engineering property that is necessary for using fly ash in many geotechnical applications [19].

The friction angle Φ varies with the variety of fly ash. The value of Φ depends primarily on the angularity of fly ash particles: angularity provides higher resistance to particle rearrangement for sustained shearing [83]. According to Table 5, the angle of internal friction of fly ash generally varies from 25° to 40°. Trends by country of origin are not readily apparent. By comparison, the angle of friction of silts vary from 26-35°, and sands vary from 27-45° [44]. The friction angle increases marginally with aging of fly ash. Most of the literature addresses only drained cases; fly ash shows poor strength properties under saturated conditions. Bottom ash generally shows improved strength characteristics in comparison to fly ash [84].

The shear strength of Class F fly ash is mainly derived from internal friction (i.e. friction between the particles), whereas class C fly ashes gain a considerable amount of cohesive strength when exposed to moisture and allowed to cure [71,85,86].

4. Summary

Fly ashes are broadly classified worldwide into two chemical types for their industrial applications, mostly in cement industries, namely class C and class F. Class C fly ash, with its higher levels of calcium oxide, generally has self-cementing properties. In terms of global fly ash composition, fly ash from India on average contains higher levels of silicon dioxide than that from the US and China. In terms of particle size, studies report that fly ash more often is poorly graded than well-graded; fly ash from India in particular tends to be poorly graded. Optimum moisture content (OMC) values for fly ashes vary from 11 to 53%, and maximum dry density values range from 1.01 to 1.78 g/cm^3. Country-specific trends in terms of fly ash OMC and maximum dry density values are not readily apparent. Fly ash tends to be non-plastic, meaning it will not swell if used as a foundation material for structures. Reported fly ash shrinkage limits range from 38 to 65. Permeability of pure fly ash generally varies from 10^{-4} to 10^{-7} cm/s, and angle of friction varies from 25° to 40°.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cscm.2019.e00263.

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