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EXPERIMENTAL DETERMINATION OF THE SOLID PHASE DENSITY OF THERMAL POWER PLANT ASH

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Abstract. Recycling of ash and slag waste from thermal power plants is an important environmental and economic task. The widespread use of ash in construction is mainly hindered by the high content of unburned carbon. The fine granulometric composition of the ash makes most mechanical methods of recycling and flotation ineffective, and is the most effective, environmentally friendly, and cheapest method is hydraulic separation. It allows for the recovery of about 70% of construction raw materials, in which the carbon content is reduced to regulatory commercial values, from 20% in raw ash to 5–10%. A central element of hydraulic separation research is establishing the hydraulic characteristics of the fly ash, with a special focus on determining its actual density, considering that the ash includes more than 10 different mineral components that have also undergone high-temperature transformation. Theoretical determination of the solid phase density of a multi-component mixture does not yield a reliable result. This article examines methods for determining bulk, true, and actual density, experimental approaches to their measurement, and the impact of various factors on these parameters. Correct density determination underlies the calculation of hydraulic characteristics of ash suspensions, the speed of hydraulic flows, and the efficiency of extracting individual components by way of hydroclassification and hydroseparation. The purpose of the research is to refine the methodology and experimentally determine the density of the solid phase of fly ash in its natural state and ash classified by size -240+40 μm, -40+0 μm, using the sample of ash from Pridniprovska TPP. The results of this work are significant for engineering when creating new technologies, for hydraulic devices recycling ash aimed at minimizing environmental impact and optimizing the use of technogenic resources. It was found that the density of the solid phase of ash from the ash dump of Pridniprovska TPP varies from 1.783 g/cm³ to 2.3, averaging 2.0 g/cm³. Variations in density are related to the inhomogeneity of the chemical composition, the presence of closed cavities in the particles.

Keywords: fly ash, ash and slag waste.

1. Introduction

Recycling of technogenic deposits and stockpiles is a relevant task today both in our country and abroad. Such deposits include waste from thermal power plants (TPP), which are stored as ash and slag in wet conditions on large ash dump areas. In works [1–4], authors conduct a global review of the physical, chemical, and other properties of fly ash from various countries. It is noted that the properties of ash can vary not only depending on the rank of coal burned, the regime and type of boilers, but even from different annual periods of operation within the same TPP.

Abroad, TPP waste is almost entirely used in the construction industry: about 100% of annual output in Germany and Denmark, up to 80% in Portugal, Poland, and France. In Ukraine, such use is limited due to the high content of coal in the ash, typically around 20% and can reach up to 25%. To clean the silicate mass from coal impurities, flotation is most often used, but the cheapest and most economical method is gravitational enrichment or hydraulic separation of ash particles in rising streams. For analyzing hydraulic separation, it is necessary to know the characteristics of the ash suspension, among which the density of the solid phase of the ash suspension as a composite mixture of heterogeneous particles is the most important [5, 6].

In the research and calculations of ash recycling processes, whether by hydraulic or other methods, the density of the solid phase particles, ρ_t, is implicitly or explicitly included in the calculations. For multi-component finely dispersed media, such as fly ash, determining ρ_t is a challenging task due to certain difficulties.

2. The Research Object and the Problem Statement

It is known that the density of a finely dispersed multi-component mixture can be bulk, true, and apparent. The bulk density of dry ash strongly depends on its fluffiness, which, during measurements, requires vibrational compaction with specific parameters. True density is determined solely for single-component mixtures and suspensions as the density of the particle material, which is taken from reference books. For multi-component environments, such as fly ash, the apparent density of the solid phase should be considered, which is either calculated or more often measured experimentally.

Bulk density or bulk weight is usually used as a characteristic of dry building materials and mixtures, for example, the bulk density of building sand ranges from 1.4 g/cm³ to 1.7 g/cm³.

True density for monodisperse particles is determined from reference books, but for polydisperse mixtures, reference data is not always available, which poses a certain problem. The true density for a mixture of heterogeneous particles is sometimes determined as a weighted average of the densities of the constituent components.

$$\rho_t = \frac{\sum_{i=1}^{n}(\rho_i \cdot \gamma_i)}{\sum_{i=1}^{n}\gamma_i} \qquad (1)$$

where ρ_i , γ_i – represent the density and the output of the individual i-th component, respectively. The number of components i ranges from 1 to n.

In the ash from coal combustion, predominantly such rock types as aleurolite, argillite, sandstones, and to a lesser extent quartz and pyrite, along with unburned coal, are present. The content and combination of minerals vary within quite broad limits.

Spectrographic analysis of the ash from Pridniprovska TPP allowed for the determination of the output of components (oxides) and, afterwards, to calculate the density of the ash using formula (1), (Table 1).

Table 1 – Weighted Average Density of Solid Phase Particles of Fly Ash

Components	Output, %	Density of Component*, g/cm³	Part in Overall Density ρ_t, g/cm³
C	19.01	1.5	0.284
SiO_2	40.05	2.65	1.061
Al_2O_3	13.8	3.99	0.551
K_2O +Na_2O	10.27	2.32	0.238
Fe_2O_3	5.88	5.24	0.308
CaO	7.26	3.37	0.245
MgO	1.92	3.58	0.069
TiO_2	1.81	4.23	0.077
Total	100.0	-	**2.83**

* Density of oxides – from reference books, online resources.

The value obtained in Table 1 is too high. For instance, in work [7], the true density of individual ashes is indicated as 2.5–2.6 g/cm³, while the theoretical value obtained in Table 1 of 2.83 g/cm³ even exceeds the density of quartz at 2.65 g/cm³, which is not abundant in the ash. This suggests that theoretical and analytical methods for determining the density of the solid phase of a suspension of heterogeneous particles are unreliable.

The most common are experimental methods [8, 9]. Apparent density is a measure obtained using pycnometers or similar devices. They are based on determining the volume of gaps between particles relative to the total volume, known as porosity. Next, the true volume of the solid phase is determined, and then the weight of the sample is divided by this true volume.

In the stage of determining porosity, many theoretical models were developed. Mostly, they consider a densely packed layer of spherical particles with rhombohedral or cubic arrangement [10]. However, such models require experimental validation because natural particles have irregular shapes. Thus, for determining the density of the solid phase of a polydisperse multi-component mixture of fly ash, experimental methods are the most reliable.

Currently, the only recognized experimental method remains measuring the density of the solid phase of a composite suspension by filling the gaps between solid particles with gas or water while measuring the volume of the filler [8].

Purpose of the work is to refine the methodology and experimentally determine the density of the solid phase of fly ash in its natural state and ash classified for granular sizes +240-40 μm and -40+0 μm using the sample of ash from Pridniprovska TPP.

3. Methods

For experiments, a measuring tube with a volume of 50 ml, diameter of 20 mm, and height of 170 mm with a measurement accuracy of 0.5 ml and a scales with an accuracy of 0.01 g were used. The tube is sequentially filled with small portions, first of water (this is important), then dry ash with a measuring spoon by tilting the tube. After each filling, the tube is shaken, the suspension is stirred with a glass rod, and the tube is weighed along with the raw materials. This feature of the method ensures more complete wetting of the raw materials, considering the irregular geometric shape of the particles, especially the presence of open cavities which are difficult to fill with water. Thus, determining porosity becomes more accurate.

After each pouring or filling, the tube with the filler is weighed. This is important because it reduces the error which would occur if water and ash were weighed separately each time. A total of 6–10 fillings with water and ash are made until the tube is filled with suspension more than 2/3 of its height. This also reduces the measurement error which would occur with a small volume of suspension. The final filling is performed by washing the dry ash remained on the walls of the tube with water. This rinse is conveniently performed using a 5 ml syringe.

After all water pourings and dry ash fillings, we measure the total volume of the suspension in the tube V_{total}, which was about 45 ml. After this, the suspension is al-

lowed to settle for a while until sediment and a zone of clear water above the sediment are formed. We measure the volume of the sediment, $V_{sediment}$ and the volume of the water layer above the surface of the sediment $V^{liquid}_{above.sediment}$. We check the balance: $V_{total} = V_{sediment} + V^{liquid}_{above.sediment}$.

The calculation of the amount of added water and ash is performed after the last adding of either water or ash, based on the difference between the current and previous weight of the tube with the suspension. Next, we calculate the total weight of the water in the tube, P_{liquid} and the total weight of the added ash P_t, that is, the weight of the solid phase.

Based on the last measurement, we check the execution of the balance: $P_{total} - P_{tube} = P_{liquid} + P_t$. We consider that $P_{liquid} = \rho \cdot V_{liquid}$, ρ=1 g/cm^3 for water.

The volume of pores is the volume of liquid in the ash, determined as $V^{liquid}_{in.ash} = V_{liquid} - V^{liquid}_{above.sediment}$. The actual volume of the solid phase V without cavities is determined as $V_t = V_{sediment} - V^{liquid}_{in.ash}$. Knowing the weight of the ash mass P_t, the density of the solid phase equals $\rho_t = P_t / V_t$.

The algorithm for calculating the density of the solid phase of the suspension ρ_t based on the measurement results is as follows:

$$
\begin{aligned}
V_{total.} &= V_{sediment} + V^{liquid}_{above.sediment} \\
V_{sediment} &= \frac{P_t}{\rho_t} + V^{liquid}_{in.ash} \\
V^{liquid}_{in.ash} &= V_{liquid} - V^{liquid}_{above.sediment} \\
V_t &= V_{sediment} - V^{liquid}_{in.ash} \\
\rho_t &= \frac{P_t}{V_t} = \frac{P_t}{V_{sediment} - V^{liquid}_{in.ash}}
\end{aligned}
\qquad (2)
$$

where R_t – total weight of ash, $V_{total.}$ – measured volume of the entire ash sample with water, $V_{sediment}$ – volume of sediment, $V^{liquid}_{above.sediment}$ – volume of the water layer above the surface of the sediment.

The presented methodology and formulas (2) are suitable for determining the density of the solid phase not only of fly ash but also of any fine-dispersed multicomponent mixture.

4. Experimental Results

To determine the ρ_t of natural unclassified ash from the ash dump of Pridniprovska TPP, the above measurements and calculations were performed (Table 2).

Table 2 – Density of the Solid Phase of Unclassified Fly Ash

Added	Weight of Tube with Water and Sand, g г	Water R_{liquid}, g (cm³)	Ash R_t, g
Tare	40.21	0	0
Water	47.89	7.68	
Ash	50.36		2.47
Water	56.5	6.14	
Ash	57.8		1.3
Water	62.51	4.71	
Ash	66.3		3.79
Water	71.42	5.12	
Ash	73.8		2.38
Water	81.85	8.05	
Ash	83.76		1.91
Water	94.92	11.16	
Total		**42.86**	**11.85**
Volume, cm³			
Total		Above Ash	Sediment
49		38	11
Water Volume in Ash, cm³ 42.86-38=4.86		Solid Phase Volume, cm³ 11-4.86=6.14	Density, g/cm 11.85/6.14=**1.93**

Throughout the year, the density of the ash, ρt, was measured repeatedly. This allowed for the establishment of an average value, which was further used by the authors for calculations of hydraulic processes (Table 3).

Table 3 – Measurements of the Density of Ash from Pridniprovska TPP Throughout the Year

№	Ash Weight, R_t, g	Volume, cm³			Porosity $\varepsilon=V_{liquid}/V_{sed}$, unit	Density of Solid Phase $\rho_t = R_t / V_t$, g/cm³
		Sediment Volume, V_{sed}	Pore Volume, V_{liquid}	Solid Volume, V_t		
1	52.8	50	24	26	0.48	2.031
2	35.89	30	14.49	15.51	0.483	2.30
3	35.61	30	11.5	18.5	0.383	1.925
4	10.7	10	4	6	0.4	1.783
5	208.7	190	95	95	0.5	2.20
6	30.52	28.2	12.07	16.13	0.428	1.892
7	11.85	11	4.86	6.14	0.442	1.93
Average	55.15	49.89	23.70	26.18	0.45	2.01

As it is seen from Table 3, the density of the solid phase of ash varies from 1.783 g/cm³ to 2.3 g/cm³, with the average value being ρt = Pt /Vt = 55.15/26.18= 2.1 g/cm³. Of the seven values listed in the table, only two significantly exceed 2.0 g/cm³, therefore, the acceptable average should be recognized not as 2.1 g/cm³, but as 2.0 g/cm³.

Thus, for theoretical calculations and analytical computation, it is recommended to adopt the density of the solid phase of natural fly ash, $\rho t = 2.0$ g/cm³. In experimental studies, such as sedimentation rates, it is recommended to preliminarily determine the density of the solid phase of the sample under the study using the above methodology.

From Table 3, it is seen that the porosity ε of natural ash when it is fully moistened but not yet transformed into a suspension (lacking a water film on the surface), ranges from 0.383 units to 0.5 units, averaging 0.45 units. This is the lower limit of ε, above which the raw material begins to acquire the properties of a suspension, with maximum porosity aiming to reach 1 g/cm³ – the density of water. Based on average data from Table 3, the density of the dense moist mass, $\rho s = (55.15 + 23.7) / 49.89 = 1.58$ g/cm³, and the weight percentage of the solid phase $\theta = 100 \times 55.15 / (55.15 + 23.7) = 69.9\%$. At these indices, the raw material is not a suspension, only a moist mass.

Experimentally, it was established that for the hydraulic separation of natural fly ash, the porosity should be higher than 0.6–0.65, the density should be $\rho s < (1.3–1.35)$ g/cm³, and the weight percentage of the solid should be $\theta < (45–50)\%$. These ranges are associated with fluctuations in the density of the solid phase of the ash.

In the practice of recycling minerals, the density of the solid phase ρt is determined experimentally for the concentrate, intermediate product, and waste, and then with these values, the necessary calculations are performed, for example, the velocities of hydrodynamic flows, indicators of water-slurry schemes, etc. Considering this, it is appropriate to determine how ρt will change for classified ash.

Clumped ash from the ash dump was loosened [11] and the dried material was homogenized and sifted by the 40 μm class on a vibrational multifrequency screen developed by the IGTM of the NASU [12]. The classification products were averaged, and then the density of the solid phase of the oversize and undersize products was determined using the above methodology. Average results from 5 experiments are presented in Table 4.

Table 4 – Average Results of Measurements of the Solid Phase Density of Mechanical Vibration Classification Products of Ash for Classes plus 40 and minus 40 μm

Product	Density of the solid phase ρ_t, g/cm³		Content C, %
	Average	Range	
Unclassified Initial Ash	1.91	1.892–1.930	22
+40 μm, Oversize	1.75	1.639–1.852	16.6
-40 μm, Undersize	1.93	1.681–2.176	7.92

The reason for the fluctuations in the density of solid products is the variation in chemical composition. The coarser oversize product has density lower than the feed by 8.4% to 10%, possibly due to increased coal content. The finer undersize contains heavier particles, for which ρt is somewhat higher than in the feed, on average by 1%.

A slightly different situation is observed for the products of hydraulic separation, where the raw material is divided not so much by size as by material composition.

Tests for separating fine classes minus 56 μm were conducted by way of hydroseparation. The analysis of the hydroseparation products – the initial feed, sands, and slimes based on the average results of 5 experiments – is presented in Table 5.

Table 5 – Average Results of Measurements of the Solid Phase Density of Hydroseparation Products for Granularity Classes minus 56 μm of Fly Ash

Product	Density of Solid Phase ρ_t, g/cm³	Content C, %
Initial Ash	1.93	17.07
Sands	2.29	11.9
Slimes	1.89	21.7

From Table 5, it is evident that during hydroseparation, the sands retain the product denser than the slimes and the feed. The density of the solid sands is 18.6% to 20% higher, while the slimes are 2.3% less dense than the feed. This is likely due to a higher content of coal in the slimes, while the sands contain heavier mineral particles, including fused silicate growths. It should be noted that the density of products after hydroseparation or hydroclassification depends on the regime. The slower is the upward flow speed in the device, the finer are the slimes and the coarser are the sands, and the separation also occurs according to the density of the solid phase and chemical composition.

5. Conclusions

Typically, industrial recycling involves polymineral fine-dispersed raw materials in dry form or as an aqueous suspension. Such a suspension is unstructured and can be considered a Newtonian fluid. To describe the movement of particles of a certain size and density in multi-component suspensions, it is necessary to know the density of the solid phase particles of the composite suspension, ρt. Determining ρt by an experimental method based on filling the voids in the ash with water and determining its volume is recommended.

The measurement methodology is refined, and the calculation algorithm for , and the results of measuring the density of the solid phase of natural ash and its separation products on a vibratory screen and by hydroseparation are presented. The experimental measurement methodology ensures more thorough moistening of the raw materials and measurement of porosity, and consequently, the volume and density of the solid phase. It is suitable for determining ρt of any fine-dispersed multi-component mixture.

The new scientific results obtained include the following.

It is established that the density of the solid phase of fly ash from the ash dump of Pridniprovska TPP varies from 1.783 g/cm³ to 2.3 g/cm³, averaging 2.0 g/cm³. The fluctuation in density is related to the inhomogeneity of the chemical composition and the presence of enclosed voids in the particles. During mechanical and hydraulic classification, the separation of raw materials occurs not only by size and chemical composition but it also changes the density of the solid phase in the obtained products compared to the feed. For example, during vibratory screening by size -40 μm, the oversize product has an 8–10% lower density than the feed, while during hydrosepa-

ration of classes -56 μm, the sands have a 18–20% higher density than the feed. It is established that the volumetric fraction of voids, or porosity ε, of natural ash when it is fully moistened but not yet transformed into a suspension (lacking a water film above the surface), ranges from 0.383 units to 0.5 units, averaging 0.45 units. This is the lower limit, above which the raw material acquires the properties of a suspension (Newtonian fluid), with maximum ε aiming to reach 1 unit (density of water, g/cm³). Experimentally, it is further established that for the organization of hydraulic separation of particles of natural fly ash, the porosity should be higher than 0.6–0.65, with actual restrictions on the density of the ash suspension, ρs, and the weight percentage of the solid, θ, being: ρs <1.3–1.35 g/cm³ and θ < 45–50%.

The practical significance of the research results lies in the refinement of the ash density measurement methodologies, which are necessary for determining the parameters and efficiency of hydraulic ash recycling processes. The refined methodology allows more accurate measurement of porosity, volume, and density of the solid phase of ash, which is critically important for calculating the flow rate and sedimentation of specific particles in an ash suspension, which is the basis for selecting the regime and optimizing the hydraulic separation of materials. This enables to increase percentage of extraction of certain components from the ash, allows for obtaining purified products, and promotes more sustainable use of natural resources. The research results can be used to develop new and to improve existing technologies for ash recycling to reduce the content of coal and obtain quality building materials.

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ЕКСПЕРИМЕНТАЛЬНЕ ВИЗНАЧЕННЯ ЩІЛЬНОСТІ ТВЕРДОЇ ФАЗИ ЗОЛИ ВИНОСУ ТЕС

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Анотація. Переробка золошлакових відходів теплових електростанцій є важливою екологічною та економічною задачею. Широке використання золи в будівництві стримується в основному високим вмістом недопалу вуглецю. Тонкий гранулометричний склад золи робить малоефективним використання більшості механічних методів переробки і флотації, найбільш ефективним, екологічно чистим і дешевим являється гідравлічна сепарація. Вона дозволяє отримати близько 70% будівельної сировини в якій вміст вуглецю зменшений до нормативних товарних значень, з 20% у вихідній золі до 5–10%. Центральним елементом досліджень гідравлічної сепарації є встановлення гідравлічних характеристик золи виносу, з особливим акцентом на визначенні її фактичної щільності, враховуючи, що зола включає більше 10 різних мінеральних компонентів які до того ж пройшли високотемпературне перетворення. Теоретичне визначення щільності твердої фази полікомпонентної суміши не дає достовірного результату. В статті розглядаються методи визначення насипної, істинної, фактичної щільності, експериментальні підходи до їх вимірювання, та вплив різних факторів на ці параметри. Правильне визначення щільності лежить в основі розрахунку гідравлічних характеристик суспензій золи виносу, швидкості гідравлічних потоків, ефективності вилучення окремих компонентів при гідрокласифікації і гідросепарації. Метою дослідження є удосконалення методики і експериментальне визначення щільності твердої фази золи виносу в природному стані і золи класифікованої по крупності -240+40 мк, -40+0 мк на прикладі золи Придніпровської ТЕС. Результати цієї роботи мають важливе значення для конструкторських при створенні нових технологій для гідравлічних апаратів переробки золи, спрямованих на мінімізацію екологічного впливу і оптимізацію використання техногенних ресурсів. Встановлено, що щільність твердої фази золи виносу із золосховища Придніпровської ТЕС змінюється від 1,783 до 2,3, в середньому становить 2,0 г/см. Коливання щільності пов'язане з нерівномірністю хімічного складу, присутністю замкнених порожнин в частинках.

Ключові слова: зола виносу, золошлакові відходи.