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Key Papers & Abstracts



Assessment of Geotechnical Properties of Cemented Coal Fly Ash Backfill

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***Abstract* —**

*The use of coal mining wastes (e.g., fly ash) in the construction materials are poor to effectively manage such high amounts of existing and ever-increasing wastes. Hence, there is an urgent need to search for alternate techniques or ways to reuse/recycle and hence lessen the surface discharged amounts of coal wastes. In this study, cemented coal fly ash backfill (CCB) was utilized as a ground support element in a Turkish lignite coal mine. To reduce the cement-related costs, CCB samples were prepared by using a fly ash content of 75%, 77.5%, and 80% as a function of curing time (2, 7, 28, and 90 days). The fresh (e.g., slump and setting time) and hardened (e.g., compressive strength and mercury porosity) geotechnical properties of CCB samples were investigated in the laboratory. Results illustrate that, at a constant slump value (20 cm), the backfill containing a fly ash content of 75%, 77.5%, and 80% provided a water/cement (**w/c**) ratio of 0.99, 1.08, 1.19. The **w/c** ratio of CCB increases from 0.99 to 1.19 due to the decreased cement amount (25% to 20%) which led to the strength reduction of backfill formulated with high amounts of fly ash. Finally, understanding the geotechnical properties of CCB mix still remains critical for the ultimate design of an effective and efficient CCB material for underground mines.*

Keywords—*cemented coal fly ash backfill; setting times; slump; water/cement ratio; compressive strength; porosity*

I. INTRODUCTION

Coal resources are one of the largest main energy sources to generate electricity worldwide [1, 2]. The huge amounts of coal are produced every year by using both underground and opencast mining techniques to meet the needs of the industry [3]. Indeed, the most of the coals produced are mined out by underground mining methods, which cause a large volume of underground opening or voids [4]. Mining-induced voids can trigger ground stability problems which can cause destructive effects on the environment. Besides, they can build an unsafe work environment for miners [5]. It is a well-known fact that coal is burned to generate electricity in thermal power plants after being extracted from underground or opencast mining [6]. After the burning process, some unwanted ashes like fly ash and bottom ash occur inevitably [7]. However, excessive quantities of these wastes are too much for the municipal and local authorities since they have an undesirable impact on the environment [8]. Fly ash particles vary from 0.5 μm to 200 μm and constitutes a large part of these problematic wastes [9]. With the introduction of advanced technologies to the industry, these wastes can be ably utilized in different sectors (e.g., construction and building materials and agriculture) as raw material. This mainly prevents the use of a new resource from nature and helps to protect the environment [10, 11]. But, fly ashes are often stacked near coal mines due to the costs of shipping long spaces and the inconvenience of its pozzolanic properties [12]. Stacking these ashes can cause environmental disadvantages because of their sulfide mineral contents [13]. It is apparent that innovative techniques and approaches are needed to effectively dispose of these wastes [14]. Recently, fly ash has been filled into underground voids as backfill material (i.e., cemented coal fly ash backfill, CCB) to



overcome these problems [15]. This technique has recently been used in underground mines to ensure adequate ground stability and easy disposal of waste [3, 16].

Basically, CCB is an engineered mixture of coal fly ash, Portland or other blended cement, and mixing water (Fig. 1). The backfill mixture is prepared in the surface fill plant and sent to underground cavities via pipes [17]. Some chemical additives such as plasticizer and accelerator are also used in the mixtures for ensuring proper workability, shorter setting time, and target compressive strengths [13, 18-20]. CCBs are mostly designed to have a certain mechanical strength value so that they can prevent subsidence and collapse events that might take place in underground mining sites [21, 22]. These strength values vary openly based on coal production speed and the geometry of underground voids [23]. The quality of filling is meaningfully influenced by its physical, chemical, thermal, hydraulic and mechanical mechanisms [3, 24-27]. Examining these mechanisms that occur in CCB is crucial to evaluate the backfill performance and thus design a durable, profitable, and environmentally friendly backfill mass [28]. Some scholars have examined experimentally the influence of internal parameters (e.g., cement, coal fly ash and water) on backfill strength as a function of curing time [29-31].

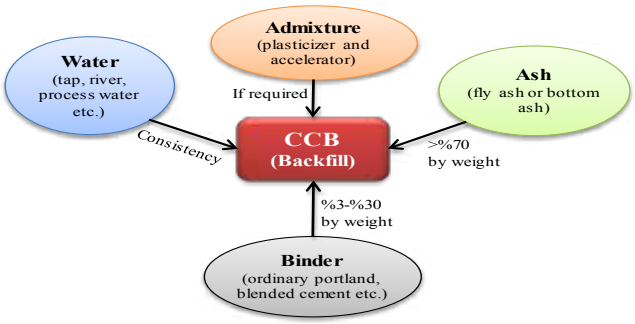


Fig. 1. Schematic of cemented coal fly ash backfill components.

Although CCB is mainly accepted as a kind of cemented backfills such as cemented paste fill, rock fill, and hydraulic fill, it fairly differs from others in terms of the application form, material content, and desired properties [3, 14, 22]. In this study, the geotechnical properties of CCB technique are assessed in detail and its application is tried to depict as a case study. In addition, the effect of the use of different ratios of coal fly ash used as waste material in CCB on the backfill properties was investigated in the laboratory. To investigate the effect of different fly ash content on properties of CCB, several laboratory testing such as slump consistency, uniaxial compressive strength, and Vicat tests were carried out. Also, the pore structure of CCB was assessed by using the mercury intrusive porosimetry (MIP) measurements.

II. UNDERGROUND COAL MINING: A CASE STUDY (CAYIRHAN, TURKEY)

In the Cayirhan basin, there are nearly 350 million tons of coal. Park Teknik AS extracts coal from underground and surface lignite coal mines, washes them and performs other enrichment operations [23]. Coal seams are separated by thin layers of interburden and positioned in two strata [24, 25].

While the thickness of the interburden between the two coal strata in the field's west is 1.2-1.8 m, the thickness of the interburden in the field's eastern part varies between 0.5-1 m. Therefore, while two coal strata in the west of the field are planned to be excavated separately, the east of the field is planned to be excavated with a single pass, and all machinery and equipment in the basin have been selected accordingly [3, 12, 15]. The coal production in the Cayirhan underground coal mine is carried out by a fully mechanized in the form of a longwall with a caving system (Fig. 2). Since the backfill is a part of the mining system, it is also possible to describe the system exactly as a fully mechanized longwall method with delayed backfill. In this coal mining system, to minimize the need for gate roadway, to ensure better use of reserves, and to reduce the risk of spontaneous combustion of coal, the lower gate roads of the panels in each field were planned as the upper gate road for the next panel. The backfill process applied on the main gate of these panels helps to be used in the next panel by supporting the existing support system in the gate roads [3, 28].

The backfill process in the Cayirhan coal mine is mainly implemented in three stages. In the first stage, coal fly ash and cement, which are the basic fill materials, are dry mixed in predetermined proportions in the surface filling plant [3, 9]. In the second stage, materials are transferred in dry form to the underground fill station with the help of compressed air and pipelines. In the last stage, mixing water is added to the dry mixture (fly

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ash plus cement) until it provides enough consistency for transport, then all the backfill materials are filled into mined-out openings or voids through pipes [17]. In underground fully mechanized coal mining, the backfill is required to reach early strength since the production process is very fast when compared to the conventional coal mining methods. Nonetheless, experience in the Cayirhan coal mine indicates that the 2-day strength value is generally important in this type of coal mining method due to the formation of newly mined-out openings after 2-day coal production. The expected and desired strengths for 2 days after the backfill is placed into opening should be greater than 5 MPa to ensure underground stability [18, 19].

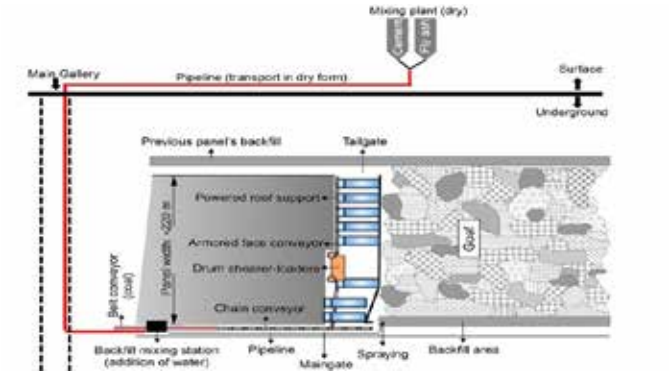


Fig. 2. A typical view of the backfill process implemented in the Cayirhan coal mine.

III. MATERIAL

In this study, cement (CEM I 42.5R), coal fly ash, and water were used for the preparation of CCB mixtures.

A. Fly ash and cement

The fly ash obtained from Cayirhan thermal power plant was used as a waste material. In the Cayirhan coal region, 5 million tons of the coal is produced annually by the fully mechanized underground technique and fed to the thermal power plant. The burning of the coal in the Cayirhan thermal power plant produces fly ash waste of approximately 750 thousand tons annually [12, 17]. The majority of the waste is sent to the cement factory to be used in cement production and the remaining part of it is sent to the backfill plant to use as backfill material in the underground [14, 15]. In this study, Portland cement (CEM I 42.5R) was utilized as the leading binding agent. The particle size distribution (PSD) analyses of Portland cement and coal fly ash products were carried out by using the Malvern Mastersizer device. The obtained PSD graphs are presented in Fig. 3. The grains of different sizes should be homogeneously distributed in the backfill sample. Furthermore, the aggregate content of less than 20 μm in the backfill materials should be greater than 15% to satisfy the material properties within the pipelines [26]. Fig. 3 illustrate that, the rate of coal fly ash below 20 μm is 35%. This means that coal fly ash keeps adequate water to form a unique fill mixture. It is also seen from Fig. 3 that coal fly ash is coarser than cement and ranged from 1 μm to 1000 μm.

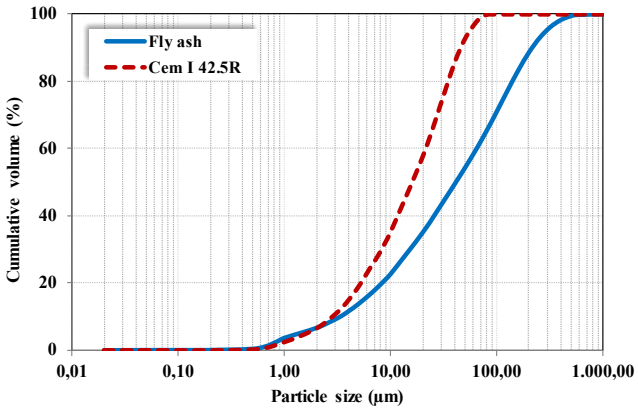


Fig. 3. The PSD curves of Portland cement and coal fly ash products.

Some physical properties of Portland cement and coal fly ash are listed in Table I. Coal fly ash was found to have an average particle size of 41 μm. In addition, the coefficient of uniformity (Cu) and curvature (Cc) of fly ash was calculated as 19.1 and 1.2, respectively. Note that coal fly ashes have an average particle size (D_{50}, the grain size corresponding to the 50% passing size from PSD curve) of 40 μm while its clay-size (< 2 μm) content is 7 wt.%. From the performed other physical test results, one can say that specific gravity (Gs) and specific surface area (Ss) values of coal fly ash and Portland cement products were found to be 2.15 and 0.78 m^2/g, and 3.10 and 4.7 m^2/g, respectively.

Table I. Physical Properties Of Coal Fly Ash And Cement.

Parameter	C_C	C_U	G_s (-)	P_{20} (%)	S_s (m^2/g)
Fly ash class F	1.18	19.14	2.15	35.09	0.784
CEM I 42.5R	1.15	7.62	3.1	63.39	4.692

The chemical compositions of coal fly ash and Portland cement are listed in Table II. It is important

to highlight that fly ashes are divided into two different classes according to ASTM C618 standards [27]. This classification is based on the sum of oxide composition (i.e., S+A+F: SiO_2, Al_2O_3, and Fe_2O_3) in the structure of coal fly ash. If the S+A+F value of coal fly ash is greater than 70%, it is called 'class F' ash. If the composition is only 50% or more, then it is classified as 'class C' ash [28]. Considering the chemistry of Cayirhan fly ash, the material used in the study was determined as 'class F' ash according to the relevant ASTM standard.

Table II. Chemical Properties of Fly Ash And Cement.

Oxide compound	Fly ash Class F	CEM I 42.5R
SiO_2	50.38	19.61
Al_2O_3	14.06	4.86
Fe_2O_3	9.90	3.10
CaO	13.25	61.35
MgO	1.20	2.92
SO_3	3.16	3.03
K_2O	1.97	0.65
Na_2O	3.18	0.38
LOI	0.86	4.21

B. Mixing water

The mixing water added to the backfill is one of the most key ingredients which can greatly affect the mechanical and rheological properties of CCB samples. In this study, tap water was used as mixing water to homogeneously blend the coal fly ash and Portland cement.

C. Preparation of CCB samples

A mortar mixer having a capacity of 20 liters was used in the preparation of CCB samples. The mortar mixer with 1.5 HP motor power has 3 different rotation speeds (84/145/352 rpm). Backfill materials were first pre-mixed in the mixing bucket with the help of an iron rod and then placed in the machine. The coal fly ash, Portland cement and mixing water were thoroughly homogenized in the mixer for 6 minutes and then removed to be placed in the cubic molds. In this study, a constant slump value was chosen as 20 cm, which enables delivering the prepared filling mixture to underground voids. The details of CCB's mix design was listed in Table III. The CCB mixtures formed after the mixing process were placed into cubic molds (5×5×5 cm). The cubic molds filled were then stored in a chamber at 90% relative humidity and 22 °C ± 1 to simulate underground curing conditions in the studied coal mine. The backfill samples were removed from molds after 1 day and then kept in the relevant conditions for curing times of 2, 7, 28 and 90 days.

Table III. Composition Of The Designed Backfill Mixtures.

Designation	Cement rate, %	Fly ash rate, %	Water/cement ratio	Slump value
OPC20%-CFA80%	20	80	1.19	20
OPC22.5%-CFA77.5%	22.5	77.5	1.08	20
OPC25-CFA75	25	75	0.99	20

IV. METHODS

A. Slump consistency tests

Slump consistency is one of the experiments performed to find the consistency and fluidity of cementitious mixtures [29]. Slump test (Fig. 4a) was carried out by using a cone having height 30 cm, based on ASTM C143 standard [30], which determine the consistency of backfilling. The fresh fill mixture is filled into cylinder mold in three layers of equal thickness. The thickness of each layer in compressed state is approximately 1/3 of the mold height. During the filling, each layer was compacted by rod with 16 mm at least 25 times. Then the mold was taken by holding the hand grips and pulling it vertically upwards in 2-4 seconds. The distance between the upper surface of the mold and the top surface of the deposited material was measured as the slump value. The amount of water was adjusted so that the slump consistency value of all the backfill samples was 20 cm.

B. Setting time tests

The initial and final setting time of backfill samples was carried out using the automatic Vicat instrument according to ASTM C191 standard [31]. This method provides a means of defining compliance with a specification limit for Vicat time of setting (Fig. 4b). Two methods are given; Method A is the reference way using the manually operated standard Vicat device while Method B allows the use of an automatic Vicat device. In this study, Method A was followed.

Setting times were measured by inserting the vicat needle into the backfill placed in Vicat chamber at 10 min intervals. In the fresh mixture filled into 40 mm long Vicat chamber, the initial setting time was figured by this needle remaining 4 mm (±1) above, and the final setting time was calculated by entering up to 0.5 mm.

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C. Mechanical strength tests

The backfill samples prepared after the blending process were kept in the curing room for the specified times. At the end of these curing times (i.e., 2, 7, 28 and 90 days), uniaxial compressive strength test was performed on backfill samples. After the rectification of backfill cubic faces (i.e., end sides were corrected by a cutter), the length and weight of CCB samples were recorded and then were placed between the two plates of a mechanical press for compression testing. In this study, a computer-controlled testing machine with a 300 N loading capacity and displacement speed of 2.400 N/s was used for strength testing (Fig. 4c). Three samples were tested from each backfill mix for the strength values in each curing time and the average strength value was calculated.

D. Pore structure measurements

Porosity is a key parameter to realize the microstructure of cemented backfill and greatly influences the permeability, strength, and density. In this study, the incremental and cumulative pore size distribution analysis of CCB is done by using the mercury intrusion porosimetry (MIP) tes (Fig. 4d). The Micromeritics Auto Pore III 9420 MIP device was used for measuring the pore structure of backfilling. This device allows operator to measure a pore diameter range from 360 to 0.003 μm after applying a pressure of up to 414 MPa. For the MIP tests, small pieces were taken from the 90-day-old samples. After UCS tests, small cubic-shaped pieces were taken representatively and immersed in ethanol prior to the drying to stop hydration. The small samples were placed in the oven set at 50°C and kept for 4 days.



Fig. 4. Typical view of the CCB process in the underground fully mechanized coal mine

V. RESULTS AND DISCUSSION

A. Effect of fly ash content on w/c ratio of CCB

Fig. 5 indicates the effect of fly ash content in the backfill mix on its *w/c* ratio. One can observe from Fig. 5 that the *w/c* ratio decreases as fly ash content in the mixture decreases, which means cement content increases. It is known that the increase in the water-to-cement ratio in the backfill mixtures causes a decrease in the corresponding strength gain.

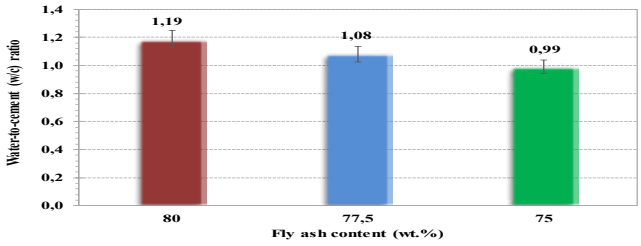


Fig. 5. Effect of fly ash content on the w/c ratio

CCB having a lower *w/c* ratio generates lower porosity as less water penetrates into pores. Thus, more porosity causes a decrease in the backfill strength. In fact, it is environmentally beneficial to deposit more waste material (e.g., fly ash) into underground voids as backfilling. However, the recipe of the backfill should be prepared in an optimum way for proper consistency and strength acquisition, which govern the fill's transfer and stability, respectively.

B. Effect of fly ash content on setting time of CCB

In underground coal mining, the setting times of backfill are key factors in determining mining cycle which affects the production speed and hence the mine's life. Fig. 6 shows the effect of the quantity of fly ash content on the setting times of CCB samples. One can comment that, as expected, the setting times increase with an increase in the amount of fly ash added in CCB samples. The prolongation of setting times can be explained in the two ways; i) lower cement content, ii) increasing *w/c* ratio. Since fly ash has lower pozzolanic properties compared to the cement, the increase in its amount prolongs the setting time. It is also known that lower hydration temperatures and hydration reaction rates of coal fly ash than Portland cement caused the setting times of cementitious mixtures to be added longer [32, 33].

The CaO content of fly ash has a great influence on the setting time of the matrix. Generally, the CaO content of fly ash class F is lower than that of fly ash class C [34, 35]. So, the setting times of the pastes formulated with fly ash class F are prolonged compared to sample with fly ash class C and without fly ash. Since the fly ash used is class F, the prolongation of setting times is seriously affected.

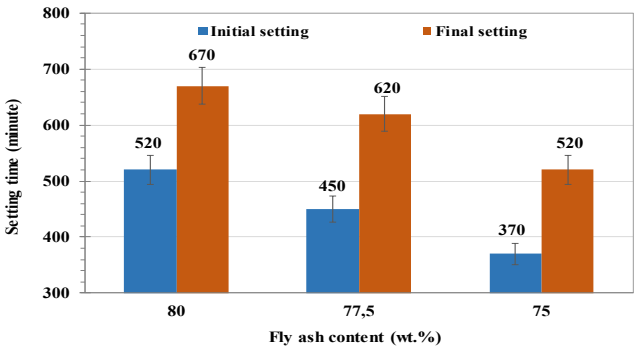


Fig. 6. Effect of fly ash content on setting time (initial and final) of CCB.

Among the materials used in CCB samples, the cement constitutes a large part of the cost of backfilling and hence the mining economy is negatively affected [36]. Increased use of waste material in the backfill improves the economy of backfill. Thus, more sustainable, and economical mining is provided. However, use of more wastes (e.g., fly ash) means low cement content, which also enables low strength and prolonged setting times in the backfill. Low strength backfills offer unsafe working environments in underground coal mining, which is an adverse situation for underground miners. A longer setting time period caused by relatively low cement content provokes longer mining cycles, which enables economic losses of mining. Consequently, the ratio of waste material and binder should be designed optimally to provide the desired setting time and mechanical strength values in the backfill mixtures.

C. Effect of fly ash content on strength properties of CCB

Fig. 7 shows the influence of fly ash content on uniaxial compressive strength of CCB samples for curing times of 2, 7, 28 and 90 days. It can be concluded from Fig. 7 that there is a decrease in the mechanical strength development of all CCB samples with the amount of fly ash decreasing over all curing time. The strength values of samples with the lowest amount of fly ash (75%) were found to be higher than others at all cure ages. In other words, the high amount of cement caused the strength value to increase. The main reason for this is the volume reduction in hydration products due to the increasing amount of coal fly ash over time. This reduction in hydration products minimized volumetrically the filling of pores in cement-fly ash matrix [37-39].

Table IV lists the strength gain of all CCB samples. The strength of the backfill mixtures having 75% fly ash at 2-day curing time was the highest (7.65 MPa). In the same way, the highest strengths for the backfill sample formulated with 75% fly ash content for a given curing time of 7, 28, and 90 were 14.4, 38.27, and 58.92 MPa, respectively. The strength values in Table IV also indicate that, when the amount of fly ash in the backfill decreases from 25% to 20% during the short-term curing time (2-7 days), the strength decreases by about 25%. Similarly, in the long-term curing time (28-90 days), there was a 24% reduction in the strength gaining.

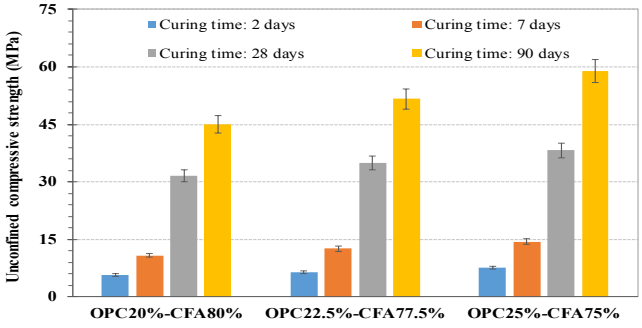


Fig. 7. Effect of fly ash content on compressive strength gain of CCB.

The C_3S and C_2S components of the cement are effective in the development of short- and long-term strengths [40]. These components contribute to strength development as the amount of the cement increases. Coal fly ash is fairly less pozzolanic than the cement. So, the increase in the amount of fly ash caused a drop in the short- and long-term strength values. It is also known that as the *w/c* ratio increases or the corresponding cement content in the mix drops, the strength gaining of backfill decreases. From the data listed in Table III, one can see that the *w/c* ratio of the CCB increases from 0.99 to 1.19 due to the decreased cement amount (25% to 20%). This led to the strength reduction of backfill samples formulated with high amounts of fly ash.

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Table IV. Unconfined Compressive Strength Of Backfill Samples.

Name	Compressive strength (MPa)			
	2 days	7 days	28 days	90 days
OPC20%-CFA80%	5.74	10.85	31.55	44.99
OPC22.5%-CFA77.5%	6.51	12.54	34.88	51.64
OPC25%-CFA75%	7.65	14.42	38.27	58.92

D. Effect of fly ash content on porosity of CCB

The porous structure of cementitious materials has a key role in the mechanical properties of hardened cement paste [41, 42]. Fig. 8 shows the results of the MIP total porosity applied on 90-day cured CCB samples. One can observe that the total porosity of CCB samples was significantly affected by the change of fly ash amount. Besides, the lowest amount of porosity was measured as 28.4% in the sample with lower fly ash content. The porosity values of the backfill samples containing a fly ash content of 77.5% and 80% are measured to be 44.76% and 45.86%, respectively.

The experimental results also showed that decreasing the amount of cement in these types of backfill or using more waste material increases the porosity of backfill. In fact, it can be stated that the most important issue affecting the MIP total porosity here is the increase in the *w/c* ratio mainly due to the decrease in the quantity of the cement added in the backfill mixture. The porosity values increased further in the samples with a higher *w/c* ratio.

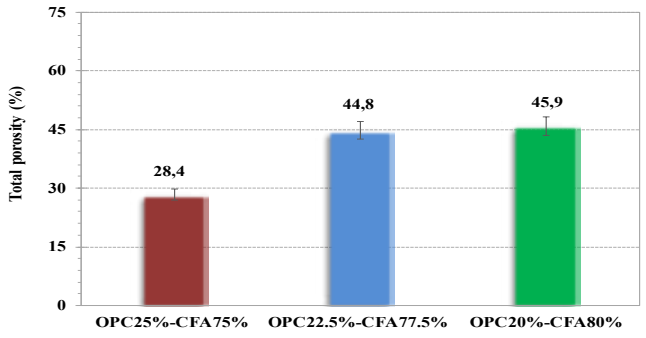


Fig. 8. Effect of fly ash content on compressive strength gain of CCB.

This type of pores (also known as capillary) that ensue in concrete and cementitious materials, usually occur after the full hydration of the cement. These pores are usually filled by water, but they are also filled by the air and shrinkage in the concrete. If the *w/c* ratio in the backfill mix increases, the evaporation of water occurs easier, and the amount and size of pores increase. In addition, due to the further fly ash usage instead of the cement, there was a drop in hydration products. Hence, higher porosities were found in the sample with lower cement content due to fewer hydration products that allow the complete filling of pores in the matrix.

E. Effect of fly ash content on pore structure of CCB

The pore structure is a key microstructural property of a cementitious material since it greatly influences the physical and mechanical properties and governs the stability of CCB. The distribution of numerous pores in solid wastes seriously affects the behavior of a porous material [43]. The tailings particle size and packing affect pore size distribution (PSD), which is closely related to the permeability and pore water pressure within backfill samples [44]. Some pore structure factors such as total porosity, macro-pores, meso-pores, PSD, threshold diameter, and critical pore diameter strictly affect the structural integrity (i.e., the connectivity between pores) of backfilling. Among the many methods reported in the literature to portray the pore structure, mercury intrusion porosimetry (MIP) is one of the most commonly employed since it provides good repeatability and covers almost the whole range of pore sizes to be analyzed in the hydrated material [45-47].

The experimental results are affected not only by the pore structure of CCB samples, but also by the experimental parameters, such as pre-treatment technique, sample size, pressure build-up rate, pore structure alteration, surface tension of mercury and contact angle [48]. The influence of microstructural changes on the pore structure parameters of backfilling using the MIP technique have been investigated by researchers [49, 50]. Fig. 9 demonstrations the variation in cumulative and incremental PSD curves of 90-day cured CCB samples with a fly ash content of 80wt.%, 77,5wt.%, and 75wt.%. From these MIP results, one can conclude that the pore structure of backfilling is affected by both the *w/c* ratio and cement content. The results indicated that as *w/c* ratio decreases, the total porosity is reduced (from 45.9% to 28.4%), primarily because of the reduction in the number of larger-sized pores. Indeed, these pores are filled by hydrate precipitates in originally water-filled spaces. The increased cement content (from 20% to 25%) also contributes to cut the porosity by increasing pore fineness.

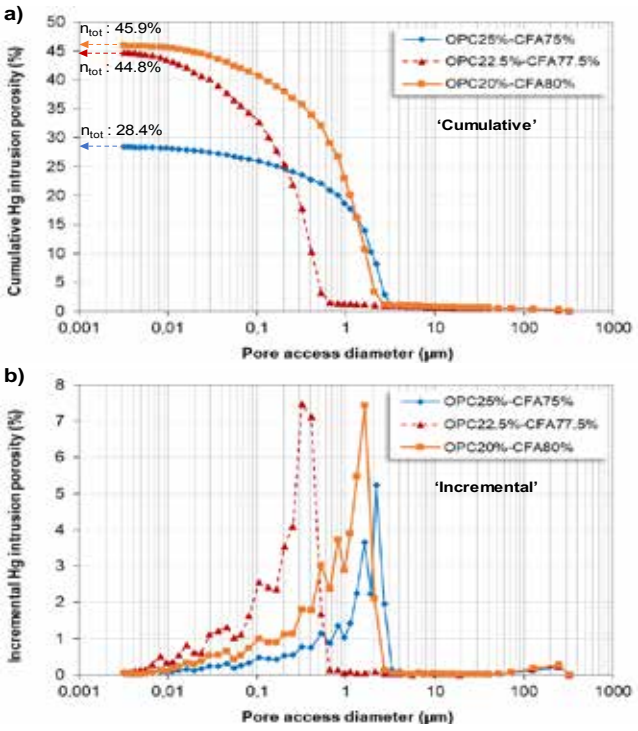


Fig. 9. Effect of fly ash content on pore size distribution of CCB samples: a) cumulative and b) incremental curves.

One can state that, in the PSD curves, total porosity n_{tot} corresponds to the last recorded point (the highest intrusion pressure and the smallest equivalent pore throat size). As cement content increases, pore throat openings become finer due to the cementation effect by cement hydration products. The cumulative PSD curves shift toward smaller average pore diameters with increasing cement proportion. This shift is evident for the backfill samples with a cement content of 25%. This backfill consistently shows lower total porosity and hence higher bulk density than others. This is because of the *w/c* ratio of coal backfilling which decreases with the consumption of excess water through cement hydration mechanism. A reduction in the *w/c* ratio for filling samples is accompanied by a slight decline in total porosity [51, 52]. A drop in pore size distribution observed in the backfills with high cement amount as the pores in CCB are filled by hydrates and/or precipitates (i.e., C-S-H gel, gypsum).

VI. CONCLUSIONS

In this study, the influence of fly ash on the geotechnical characteristics (e.g., slump, setting time, strength, porosity, and pore structure) of different CCB samples were assessed. Several experiments were done to study fresh and hardened properties of the backfill containing fly ash, cement and mix water. According to the results obtained from these tests, the following conclusions can be made below:

- The *w/c* ratio reduces as fly ash content in the mixture drops, which means cement content increases. The rise in the *w/c* ratio in the backfill causes a decrease in the corresponding strength gain.
- Setting times increase with an increase in the amount of fly ash added to CCB samples. The prolongation of setting times is entirely as a result of lower cement and increasing *w/c* ratio.
- The highest strengths for CCB formulated with 75% fly ash content for a given curing age of 7, 28, and 90 were 14.4, 38.3, and 58.93 MPa, respectively.
- Higher porosities were found in the CCB with lower cement content due to fewer hydration products that allow the complete filling of pores in the matrix

As a result, this work offers coal mining operators with an effective technique to evaluate the development of CCB samples as a function of fly ash content and curing time. It also provides an efficient design the fill reticulation system and operating conditions for coal mines.

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