The Usage of Coal Combustion (fly) Ash as Mitigation Method to Control Soil Erosion and Water Pollution: A state knowledge review

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Abstract. In the last few decades, the utilization of coal to generate electricity was rapidly increasing. Consequently, the production of coal combustion ash (CCA) as a by-product of coal utilization as primary energy sources was increased. The physical and geochemical characteristics of CCA were site-specific which determined by both inherent coal - source quality and combustion condition. This paper provides a state of knowledge review on the effects of CCA application as mitigation to control soil erosion and acid mine drainage (AMD) thus treating water pollution especially in coal mine and near future research needs.

1. Introduction
In the last few years there were massive shift of energy sources for electricity power plants from fuel of oil into coal. This shift has resulted in the rose of coal combustion ash (CCA) as the by-product of combustion processes afterwards. Indonesia is one of the largest coal exporters in the world, and the amount of coal production and the export has grown at an annual average rate of more than 10% since 2000 [1]. The increase in domestic demand for coal with economic growth has promoted the energy policy such as the conversion to coal-fired power generation and the construction of new coal-fired plant in Indonesia.

The fact that coal-mining industries keep increasing, also caused by the RIKEN (Rencana Induk Konservasi Energi Nasional) policy which attempts to generalize coal as Indonesia’s primary energy resources by 2020. This change created the problem of the disposal of a large amount of coal ash. Although (CCA) disposed of to landfill as industrial waste, the efficient use of them is required due to landfill shortage. In Indonesia, 80% of coal ash has ever been reutilized as cement raw materials; however, alternative proposal for effective use of them is needed in consideration of the increase in the amount of coal ash in the future, such as for controlling soil erosion and treating AMD Acid Mine Drainage) thus handling water pollution in post mining areas.

This paper provides a state of knowledge review on the effects of CCA application to control soil erosion and water pollution in Indonesia as a basis to propose near future research needs.

2. Data and Method
This research is based on the literature studies of CCA (Coal Combustion Ash) researches of recent publication done in Indonesia and abroad.
3. Result and Discussion

3.1. CCA (Coal Combustion Ash)
CCA is a solid waste produced from burning coal at a power plant. According to the U.S. CCA were mostly classified into two, bottom and fly ash. The Environmental Protection Agency (EPA) considered CCA is classified as "non-hazardous" waste.

![Image of Fly Ash Powder](image)

**Figure 1.** Fly Ash Powder [3]

Even though it is non-hazardous, if the CCA is buried in a large enough amount, it will need management so as not to cause environmental problems, such as air pollution, or water, and the degradation of ecosystem quality.

Class F: Produced from combustion of bituminous or anthracite coal, which has pozzolanic properties, where to obtain cementing properties it must be added with lime or cement. Class F fly ash is low in lime content (CaO <10%).

Class C: Produced from burning sub-bituminous or lignite coal besides having pozzolanic properties it as well has self-cementing properties (to increase strength and harden when reacting with water) which appear without the addition of lime. Usually contains lime (CaO)> 20%.

3.2. Acid Mine Drainage (AMD)
AMD; liquid/solution with low pH and substantial metal solubility as a result of a reaction between sulfide minerals that are exposed due to excavation, oxygen and water. Acid Mine Drainage (AMD) is considered as one of the most notable environmental issues in most surface mines. Escalation of mining industries especially coal mines in Indonesia recently require a more serious attention in solving AMD issues. sf pyrite, sulphuric acid and other (Potential Acid Forming) PAF materials.
3.3. CCA Physical Properties

3.3.1. Particle size distribution

Dwiki et al., 2017 conducted research on particle size dispersion of CCA, using two methods, for the particle size above 0.075 mm using sieve analysis and particle size below 0.075 mm using hydrometer analysis. The result can be seen in Figure 1. Fly ash is the finer particle size of CCA, resulted from coal combustion product that are driven out of the boiler with the flue gases, while bottom ash falls to the bottom of the boiler as residue. The difference in size is the reason why such segregation happens.

![Figure 2. AMD from PT. Singlurus Pratama, Samboja, Kutai Kartanegara](image)

![Figure 3. Particle size distribution of flyash and bottomash [2]](image)

3.3.2. Specific Gravity

Specific gravity of the samples was measured by using pycnometer based on the ASTM D85414. The physical and chemical characteristics of the coal ash samples were listed in Table 1. Specific gravity of each type of the coal ash showed similar values: those of FA1, BA1, and FA2 were 2.10, 1.96, and 2.07 (g/cm^3), respectively. Since fly ash’s specific gravity, typically, between 2.1 and 3.1(g/cm), they are typical fly ash samples.
Table 1. The substantial and chemical characteristics of the coal ash samples [1].

| Samples | FA1  | BA1  | FA2  |
|---------|------|------|------|
| Physical properties |      |      |      |
| Specific gravity (g/cm³) | 2.10 | 1.96 | 2.07 |
| Chemical composition (mass%) |      |      |      |
| SiO₂ | 30.93 | 44.56 | 67.39 |
| Al₂O₃ | 13.30 | 16.48 | 18.70 |
| FeO | 3.93 | 7.60 | 4.36 |
| MgO | 2.24 | 2.73 | 1.80 |
| CaO | 1.82 | 2.34 | 2.87 |
| Na₂O | 0.16 | 0.46 | 0.67 |
| K₂O | 1.54 | 1.69 | 1.23 |
| SO₂ | 1.21 | 7.22 | 0.22 |
| H₂O | 41.02 | 22.32 | 1.97 |

3.3.3. Capability of Reducing Soil Loss

Based on [1], the risk of soil erosion was significantly reduced by applying coal ash to topsoil. The application of the coal ash which consisted of more than 90% of clay and silt to topsoil promoted soil erosion. Meanwhile, soil erosion was prevented by mixing the coal ash which consisted of more than 85% of sand at the mixing ratio of over 30% (see Figure 2), this is align with Hjulström curve (Figure 3). However, the mixing ratio of coal ash to topsoil has to be decided in consideration of the effects of soil composition on plant growth as well as that on soil erosion.

Figure 4: Soil loss of the simulated top soil mixed with the coal ash at the mixing ratio of 0%, 30%, 60%, and 100% [1].

Figure 5. Hjulström curve
3.3.4 Increase Cohesion($c'$) and Angle of Repose($\phi'$)

The investigation began with the sample gathering, drying, sieving, and then cement mixing with the percentage of 2%, 4% and 6% each to the dry weight. Mixture’s physical and mechanical characteristics (Direct Shear Test) then conducted.

Results showed that the addition of lime and coal combustion ash could improve the physical and mechanical characteristics of soil which were to decrease soil plasticity and increase the angle of repose along with its cohesion value. The experiment were done to both pure soil and the mixture that refers to the Annual Book of ASTM Standards. Before tested, overall sample were dried under sunlight. Direct shear test showed the cohesion ($c'$) value of pure soil without treatment time which was ($c'$) 0, 1087 kg/cm$^2$, while the angle of repose value ($\phi'$) 7, 3675. The maximum increase of angle of repose value occurred in the addition of 6% cement and 6% fly ash which was 38,1744 to the pure soil without treatment time. Another observation was done by investigating subgrade soil stabilizing behavior using 2% lime + 4% coal combustion ash and 1% lime + 3% coal combustion ash with repeated (cyclic) loading.

![Figure 6. The relation of angle of repose value without treatment time and the addition of cement and fly ash.](image)

![Figure 7. (A) Saturation Process [3] (B) Cyclic Loading Experiment [3](image)

The conducted experiment showed that:

- Mixture of 2% lime + 4% coal combustion ash adds to the increase of cohesion.
- Given that the pure soil cohesion ($c'$) equals to 10.5 kPa, while
- For 1% lime + 3% coal combustion ash ($c'$) equals to 25 kPa dan
- For 2% lime + 4% coal combustion ash ($c'$) equals to 45.8 kPa
- The result occurred is consistent as Clough (1981), which stated that the additives increased effective cohesion of soil. (Wardani, S.P.R. 2008)$^{23}$
- Given the soil’s angle of repose ($\phi'$) = 37.48°
- For 1% cement + 3% fly ash ($\phi'$) = 39.5°
- For 2% cement + 4% fly ash ($\phi'$) = 36.8°
This result showed that by adding 2% lime + 4% coal combustion ash, the angle of repose outcome was lower than pure soil (Parent soil) and lower than the addition of 1% lime + 3% coal combustion ash. (Wardani, S.P.R. 2008)

The extended observation proved that the effect of additive addition to cohesion and angle of repose depended on the range of stress that was given on fitting process which showed a linear relation of \( q = \frac{\sigma_a - \sigma_r}{f} \) and \( p = \frac{\sigma_a + 2.\sigma_r}{3} \) = Mean stress.

3.3.5 Reduce Soil Permeability

Specific gravity measurement by using pycnometer, X-Ray Fluorescent (XRF), X-Ray Diffraction (XRD), scanning electron microscope (SEM), and water retention test were performed. The grain size analysis, the standard test for the Atterberg limits, and the Falling head permeability test were performed with the samples in order to understand the effects of the application of coal ash on chemical and physical properties of soils [1].

**SEM Observation** The surface condition of FA1, BA, and FA2 was observed by using KEYENCE VE-9800. The AuPd coating was conducted prior to making SEM observations on the surface of the samples with the MSP-1S Magnetron Sputter. The specimens were vacuum-dried using a beam at 20 kV, followed by the beginning of SEM observation.

![SEM images of CCA](image)

**Figure 8.** SEM images of CCA [1]

There were no voids which can retain water among the spherical particles in FA2, resulting in low water retention capacity in spite of a high content of silt. Thereby, microstructure of coal ash has to be taken into account in order to evaluate water retention capacity since high water retention capacity is obtained in the coal ash with microporous structures despite a low content of fine fractions. Figure 7 shows the permeability of the samples and the Atterberg limits of soils. Soil composition affects permeability and the Atterberg limits of soils [7].

![Permeability of simulated topsoil mixed with coal ash](image)

**Figure 9.** Permeability of the simulated topsoil mixed with the coal ash at the mixing ratio of 0%, 30%, 60%, and 100% [1].
Results showed microporous structures in FA1 affected water retention capacity, leading to prevention of soil erosion. The coal ash of FA1 with the structures showed high water retention in spite of low content of clay, and For the purpose of prevention of soil erosion by mixing coal ash in topsoil in postmine land, microporous structures in coal ash and soil composition which affect permeability and water retention capacity are useful to select coal ash and to decide the mixing ratio [1].

3.4. CCA Chemical Properties
3.4.1. Chemical Composition

Bulk chemical analysis was measured by using the XRF (X-ray Fluorescence) technique for total 7 samples of fly ash and bottom ash. The result of XRF measurement is provided in Table 2.

| Sample | Source            |
|--------|-------------------|
| FA Al  | South Kalimantan  |
| FA ADR | East Kalimantan   |
| FA KYU | Fukuoka           |
| FA KPC | East Kalimantan   |
| FA ICA | West Kalimantan   |
| BA ICA | West Kalimantan   |
| BA BA  | South Sumatera    |
| BA BA  | South Sumatera    |

All of samples are mainly composed by SiO2, indicates that most of unburned material from coal is the silicate minerals. Moreover, samples of FA ADR, FA KYU, FA BA and FA AI were high in the CaO concentration, suggest its higher capacity in producing alkalinity. All of samples are classified into class F, ASTM C-618 classification.

| Sample | SiO2 (%) | TiO2 (%) | Al2O3 (%) | Fe2O3 (%) | MnO (%) | MgO (%) | CaO (%) | Na2O (%) | K2O (%) | P2O5 (%) | Loss on Ignition (%) | Total (%) |
|--------|----------|----------|-----------|-----------|---------|---------|---------|----------|---------|----------|---------------------|----------|
| FA ADR | 36.2     | 1.1      | 20.4      | 21.8      | 0.4     | 4.9     | 10.7    | 0.8      | 0.8     | 9.1      | 1.4                 | 98.1     |
| FA KPC | 33.1     | 0.8      | 14.1      | 5.8       | 0.1     | 1.4     | 1.3     | 0.2      | 0.1     | 9.8      | 99.2                |          |
| FA ICA | 50.6     | 1.2      | 29.3      | 10.9      | 0.1     | 1.9     | 1.9     | 0.6      | 2.0     | 9.1      | 5.3                 | 97.9     |
| BA ICA | 53.5     | 0.5      | 15.6      | 5.3       | 0.0     | 1.1     | 1.4     | 0.5      | 1.0     | 9.1      | 0.2                 | 99.7     |
| FA KYU | 67.4     | 1.1      | 18.7      | 4.2       | 0.0     | 1.1     | 2.8     | 0.7      | 1.2     | 9.1      | 2.0                 | 99.5     |
| FA BA  | 46.5     | 0.9      | 21.1      | 5.5       | 0.1     | 2.8     | 3.0     | 0.9      | 0.8     | 9.2      | 16.5                | 98.0     |
| BA BA  | 64.8     | 0.7      | 18.2      | 3.9       | 0.0     | 2.1     | 1.7     | 0.8      | 0.8     | 9.1      | 2.5                 | 99.9     |
| FA Al  | 42.1     | 0.6      | 9.9       | 25.0      | 0.4     | 7.7     | 11.3    | 0.5      | 0.5     | 9.0      | 0.2                 | 98.6     |
3.4.2 pH Stabilizer
Tested by Column Leach Test that was conducted in ten cycles. Those aforementioned columns then later were flushed in which will be resulted in accumulation of leachates. These leachates would be collected as samples which later be evaluated. Column test scenarios could be seen in Figure 5. The pH, EC (electrical conductivity) and ORP (Oxidation Reduction Potential) were gauged based on the help of TOA-DK pH meter and to be exact the HM-21P series, HORIBA EC meter type B-173 and CUSTOM ORP meter type ORP5041. (Ginting et. al 2017).

The results of the measurements were the CCA column pH has the highest point with trend that tended to be downward which indicated in decrement of dissolution rate as well as the alkaline elements availability within the column. Another observation was done by creating synthetic mine waters (SAMD) to be reacted with CCA leachate. The SAMD composition that had to be prepared for the titration experiments were Al = 12.7 mmol/l, Fe3+ = 7.3 mmol/l, Fe 2+ = 3.6 mmol/l, Ca2+ = 5.2 mmol/l and SO42- = 40.8 mmol/l. The SAMD was prepared with distilled water in fresh condition which was flushed by Nitrogen gas. The reagents Al 2 (SO 4 ) 3, CaSO4 and FeSO were dissolved in about 750 ml of distilled water that was put inside volumetric flasks. (Petrik et. al 2003)
3.4.3 Role to Speed Up Liming

A few experiments were conducted to investigate treatment of AMD with different materials; lime, limestone and fly ash. These experiments were conducted to investigate the relativity of ash as a liming agent (the mass that is required to neutralize an AMD volume) effectiveness and to monitor the changes of EC. These liming agents were lime, limestone and Arnot FA. In each experiment, a fixed amount of AMD (e.g. 100 ml) was stirred continuously with an overhead stirrer and then a mass of solid reagent was later added.
Figure 14. EC and pH curves for experiments in which different AMD sources (set volume) were co-disposed with fly ash. Petrik et. al (2003)\(^8\)

Results stated that the given ratios in the figure above refer to the AMD are solid ratios. The stand-out difference as the result of each solution’s EC is attributable to different AMDs’ start. In most cases =, the EC always remains somehow constant.

Figure 15. It showed data for experiments of AMD neutralization using CCA, lime or limestone. Petrik et. al (2003)\(^9\)

Result are all of these experiments proved that fly ash is a more suitable liming agent for AMD treatment. In some cases, fly ash will produce a lower liquid EC compared to lime or limestone which was found for the neutralization. All usage of solid reagents resulted in a small decrease of EC in time. Rapid pH adjustment occurred in all of the experiments with the first 15 to 20 minutes of each experiment showing the most noticeable pH change. The Arnot FA is greater than those of lime to cause neutralization.

3.4.4 Role of Fly-ash to Minimize Metal Ion Discharge

Tested by Column Leach Test that was conducted in ten cycles. Those aforementioned columns then later were flushed in which will be resulted in accumulation of leachates. These leachates would be collected as samples which later be evaluated. The content of metal was calculated using ICP-MS Agilent 7500 series. To simulate the co-placement system scenario, the six columns with multi-layer of
materials were then set-up, also with an addition of 3 other columns (PM, NM, CCA/FA) as the monitoring agents [10].

It is discovered that iron dissolution of CCA Column tended to precipitate as the iron dissolution in the NAF column. Most of those dissolved irons inside the PAF and multi-layer material column was estimated to remain stable as Fe$^{2+}$, even though the trend was shifting to precipitate because of the increment of pH value.

![Figure 16. Column Test Scenarios and Result for Major Metal Content in Leachate [8]](image)

![Figure 17. Column Test Scenarios and Result for Trace Metal Content in Leachate [8][1]](image)

Each metal ion and trace metal ion showed different behaviour under each column condition. It also showed that proportional ratio between PAF, NAF, CCA should be achieved in order to minimalize the leaching of certain ions in this case scenario B1 & C1 is the most likely to performed well.

4. Conclusion
CCA with a proper composition and utilization can be a one-stop solution for a lot of ongoing and post coal mining issues. It has proven to thrive as a good mitigation reference for slope failure and water pollution, utilize as the mixture of backfilling and top soil in several coal mines. This finding need should be follow up by intensive dissemination through various media not only to corporate but also government (research and education, and training agencies). Further researches are needed to analyze geohazard mitigation using CCA in areas having high vulnerability to erosion and landslides (morpho erosion). Aspects to be considered related to the use of fly ash are such as site drainage, slope stability, erosion analysis, soil bearing capacity, climate condition, and lithological analysis.
Further researches regarding methods on finding a proper combination model of combustion and coal–source quality to produce the most suitable CCA while maintaining the best energy outcome are recommended.

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References

[1] Matsumoto S, Ogata S, Shimada H, Sasaoka T, Kusuma G J and Gautama R S 2016 Application of Coal Ash to Postmine Land for Prevention of Soil Erosion in Coal Mine in Indonesia: Utilization of Fly Ash and Bottom Ash Adv. Mater. Sci. Eng. 2016 3–7
[2] Dwiki S, Shimada H, Sasaoka T, Hamanaka A, Sayoga R, Gautama and Kusuma J G 2017 Classification of Fly Ash based on Physical and Chemical Characterization for The Usage of Acid Mine Drainage Prevention 33–35
[3] Wardani S P R 2008 Pemanfaatan Limbah Batubara (Fly Ash) untuk Stabilisasi Tanah maupun Keperluan Teknik Sipil Lainnya dalam Mengurangi Pencemaran Lingkungan Pidato Pengukuhan Guru Besar 1–71
[4] ASTM 1557 2000 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)) Annu. B. Stand. 4
[5] ASTM 2015 Standard Test Method for Particle Size of Soaps and Other Detergents 1 Annu. B. ASTM Stand. 89 2–3
[6] Shen L, Farid H and Mcpeek M A 2008 [ No Title ] Evolution pp 1–14
[7] Igwe C A and Ejiofor N 2005 Structural stability of exposed gully wall in Central Eastern Nigeria as affected by soil properties Int. Agrophysics 19 215–22
[8] Kusuma G, Shimada H, Sasaoka T, Matsui K, Nugraha C, S. Gautama R and Sulistianto B 2012 An Evaluation on the Physical and Chemical Composition of Coal Combustion Ash and Its Co-Placement with Coal-Mine Waste Rock J. Environ. Prot. (Irvine,. Calif). 03 589–96
[9] Petrik L F, White R a, Link M J, Somerset V S, Burgers C L and Fey M V 2003 Utilization of South African fly ash to treat acid coal mine drainage, and production of high quality zeolites from the residual solids 2003 Int. Fly Ash Symp. 2 6–8
[10] Sobek A, Schuller W, Freeman J and Smith R 1978 Field and Laboratory Methods Applicable to Overburden and Minesoil (Washington, D.C.)