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Full Length Research Paper

The engineering characteristics of fly-ash and bottom-ash soil mixtures

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The purpose of this study was to provide basic information on a method for the utilization of fly-ash and bottom-ash soil mixtures, including the physical and mechanical properties of the mixed soil, such as the unconfined compression test, the tensile strength test, and the freezing-thawing resistance in relation to the volume and curing time of the fly-ash and bottom-ash soil mixtures. Specimens with four different cement contents (4, 6, 8 and 10% of the total weight) and three different sizes (φ50 × 100 mm, φ100 × 200 mm and φ150 × 300 mm) were prepared to examine the characteristics related to specimen size and features, including the compression strength, microscopic structure, the freezing-thawing resistance and degree of wet-dry resistance. The results show that the larger-sized specimens and those with greater cement content had higher compressive strength, freezing-thawing resistance, and wet-dry resistance. Moreover, the reactive products for each specimen size were examined by microscopic structural analyses, such as SEM and EDS analyses, and it was observed that typical needle-structured ettringite was generated due to the blending of the cement.

Key words: Fly ash, bottom ash, soil mixtures, freezing and thawing, wet-dry.

INTRODUCTION

In accordance with the increasing power demand caused by the drastic industrial development in recent times, the use of coal in thermoelectric power plants has rapidly increased. In Korea, only 64% of the 8.35 million tons of coal ashes produced annually are recycled; the rest are buried. Most of the recycled by-product is fly ash, and there remains a small portion of bottom ash (Kuk et al., 2009; Shin et al., 2009).

The reclamation of industrial wastes is directly connected to environmental impacts and results in promoting the eco-plans related to national environmental preservation. While the utilization of energy resources is increasing with the acceleration of industrialization, the task of securing the repository of industrial wastes has come to the fore, and there is an urgent need to seek solutions to this problem (Metha, 1984).

As the research related to the development and use of eco-friendly materials has increased in response to the current needs, studies on mixed soils, that is, blended with various admixtures to improve soil properties, have progressed in great degree. Although there have been numerous studies and patents on attempts to utilize bottom ash as a substitute aggregate, to date, it has not been widely used due to financial issues related to efficiency and shipping expense (DiGioia et al., 1986; Thorne and Watt, 1965).

To overcome these problems, we manufactured planting revetment blocks after mixing soil materials, cement and water with fly ash and bottom ash on-site as a method to improve the value of fly ash and bottom ash and to further research on improving the recyclability of these ashes.

We present an analysis of micro-structural and engineering properties of the fly- and bottom-ash soil mixtures to provide basic data for the utilization of fly- and bottom-ash soil mixtures as eco-friendly aggregate substitutes.

MATERIAS AND METHODS

When burning coal, the majority of minerals contained in the coal

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Table 1. Physical properties of normal Portland cement.

Specific gravity	Setting time (h-min)		Compressive strength (MPa)		
	Initial	Final	3days	7days	28days
3.15	5-7	7-20	19.4	21.6	32.3

Table 2. Chemical compositions of normal Portland cement (Unit: %)

SiO_2	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Fe_2O_3
21.09	4.84	63.85	3.32	3.09	1.13	0.29	2.39

are converted to oxides; whatever remains behind is called coal ash, and, because this coal ash differs considerably in its properties depending on the coal-manufacturing process and the processing methods after discharge, it is very difficult to accurately specify the engineering properties of coal ash. However, one of the significant properties of coal ash is the self-stiffening property caused by the pozzolan reaction. The self-hardening property of the coal ash gradually manifests over time, and factors such as the specific surface area, compactness and coal-burning conditions have been reported as greatly influential on the self-hardening properties of coal ash.

According to the soil-classification system, fly ash belongs to class ML, whereas bottom ash is classified as SW, SP or SP-SM. Moreover, these coal ashes are all non-plastic, with a low density of approximately 2.3. Coal ash is composed mainly of silica (SiO_2: 43 to 65%), alumina (Al_2O_3: 16 to 26%) and ferric oxide (Fe_2O_3: 4 to 12%), with smaller amounts CaO, MgO, SO_3 and Na_2O. The chemical components do not exist as pure compounds but instead form complex compounds, chiefly the crystalline minerals quartz (SiO_2), mullite ($3Al_2O_3{\cdot}SiO_2$) and magnetite (Fe_2O_4).

The present experiment used the fly and bottom ashes from the coal ash produced by the combustion of coals at the Young-Heung Thermal Power Plant in Korea. A grading machine was used to sort the material excavated during bed excavation at the new construction site near the Kangwon National University; the sandy soil was separated into size fractions of 20 to 40, 10 to 20, 4.76 to 10 and 4.76 mm. Domestic Portland cement was used for the cement.

Tables 1 and 2 display the physical and chemical properties of the used cement and Figure 1 displays the grain-size distribution of the used composite sample to control the reduction grading with the fixed amount substitution method.

Mix design and production

Mixture

The mix design determines the amount of cement, water and aggregate to meet the final design strength as measured in the laboratory by compaction and durability tests. Moreover, it is important to deduce the optimal mixture by confirmation with a trial mix. Generally, accurate standards for mix designs with fly- and bottom-ash soil mixtures are not found in the literature; generally, they are classified with the soil-mechanics methods using the compaction test and the concrete-mix design method.

Following the soil-mechanics method, we mixed fly ash, bottom ash and soil (including aggregate) in the ratios of 1:4:5 and added cement at 4, 6, 8 and 10% of the total weight and then analyzed the resulting compressive strength, micro-structure, freezing-thawing as well as wetting-drying properties.

Compaction testing

In Korea, accurate standards for the compaction method for fly- and bottom-ash soil mixtures are not available, and, therefore, we selected the existing compaction methods used in soil mechanics. The compaction test was performed by controlling the compaction numbers for the compaction energy, fixed according to the compaction method (φ50 × 100mm), of the tamping bar. The A (φ100×200 mm) and E (φ150 ×300 mm) compaction method restrict the maximum permissible grain-size to 37.5 mm.

Production of test-piece specimens

To analyze the unconfined compression strength and tensile strength of fly- and bottom-ash soil mixtures according to the amount of cement and age, based on the optimal moisture content and the maximum dry unit weight calculated from the compaction test, a three-phase relationship was used to calculate the optimal amounts, and the resulting mixture was then tested to reveal an equal amount of compaction energy.

Automatic compactors were used to compact the samples 140 times at each level, divided into seven levels in the case of E compaction in the φ150 × 300 mm, φ100 × 200 mm and φ50 × 100 mm molds; for the A compaction and the compaction by the tamping bar, compaction was divided into five levels, and the samples were compacted 25 times at each level. To investigation the unconfined compressive strength of test-piece specimens according to curing time, each group of specimens with different volumes of cement was cured for 3, 7 and 28 days. Figure 2(a) is a photograph of the automatic compactor used for producing the test-piece specimens and Figure 2(b) shows the test-piece specimens cured.

MATERIALS AND METHODS

Unconfined compression test

The compressive strength test was performed on the basis of the KS F 2405 method, which tests the compressive strength of concrete, by sustaining the load at a rate of 1 mm/min with a universal testing machine from the Instrong Company.

Tensile strength test

In accordance with the KS F 2423 method (tensile strength test of

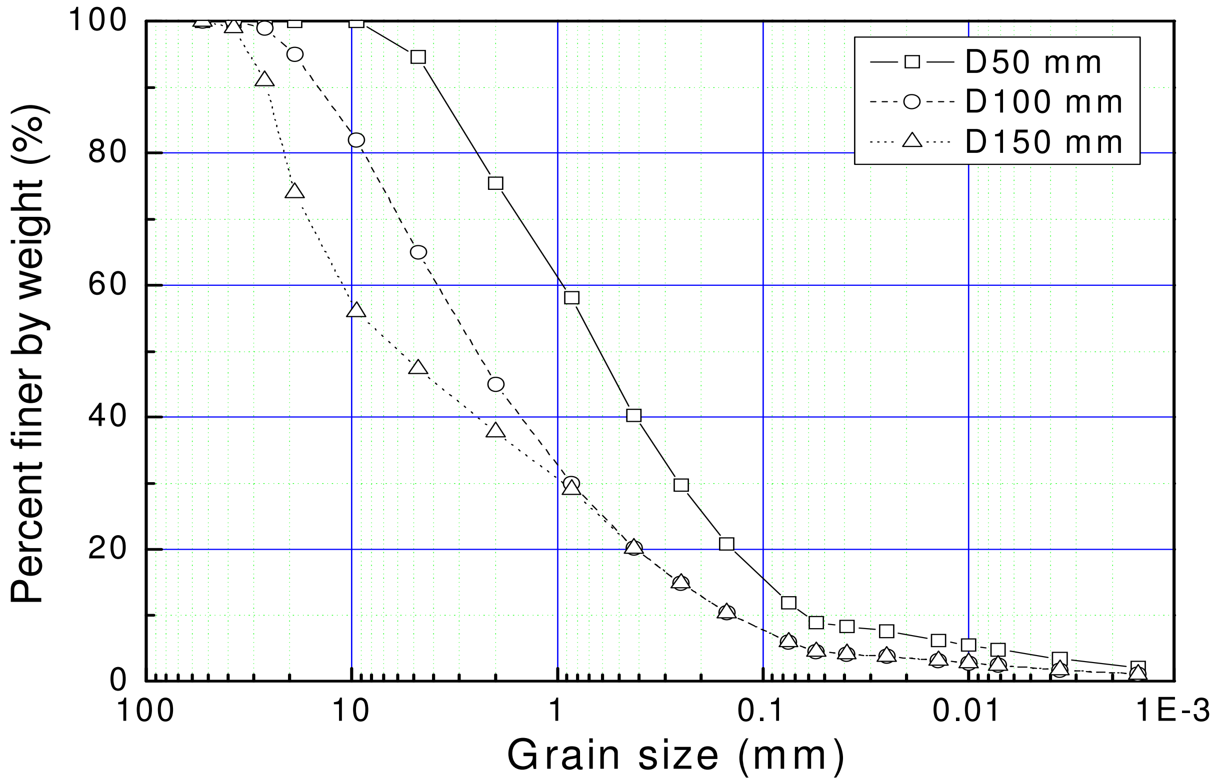
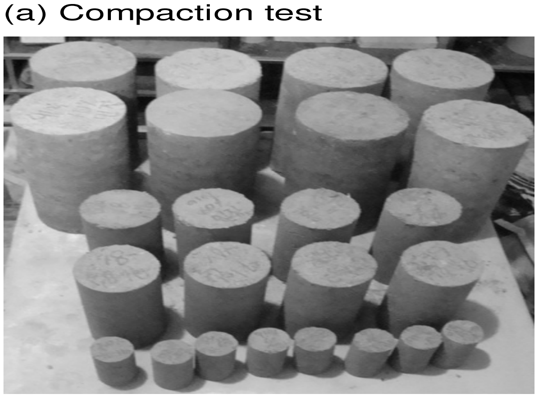


Figure 1. Grain size distribution curve.

(a) Compaction test



(b) Curing view

Figure 2. The test-piece specimens produced.

concrete), the Tensile strength Test used the Instron universal tester for the test-piece specimens on the third, seventh and 28th days to apply load at the speed of 1 mm/min.

SEM and EDS

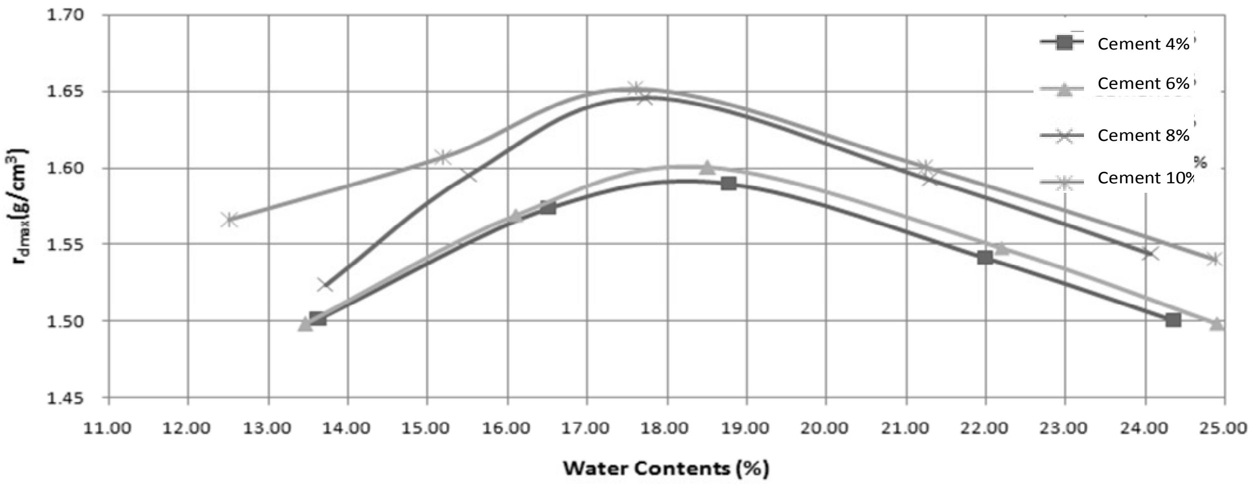
To analyze the hydration properties of fly- and bottom-ash soil mixtures, the samples were collected from test sample specimens on the seventh and 28th days and examined by scanning electronic microscopy (SEM) at 10kx to compare the form and dispersion of hydration products on the surfaces of the samples. To confirm the constituents of the main products, energy dispersive spectroscopy (EDS) was used to determine the elemental composition.

XRD

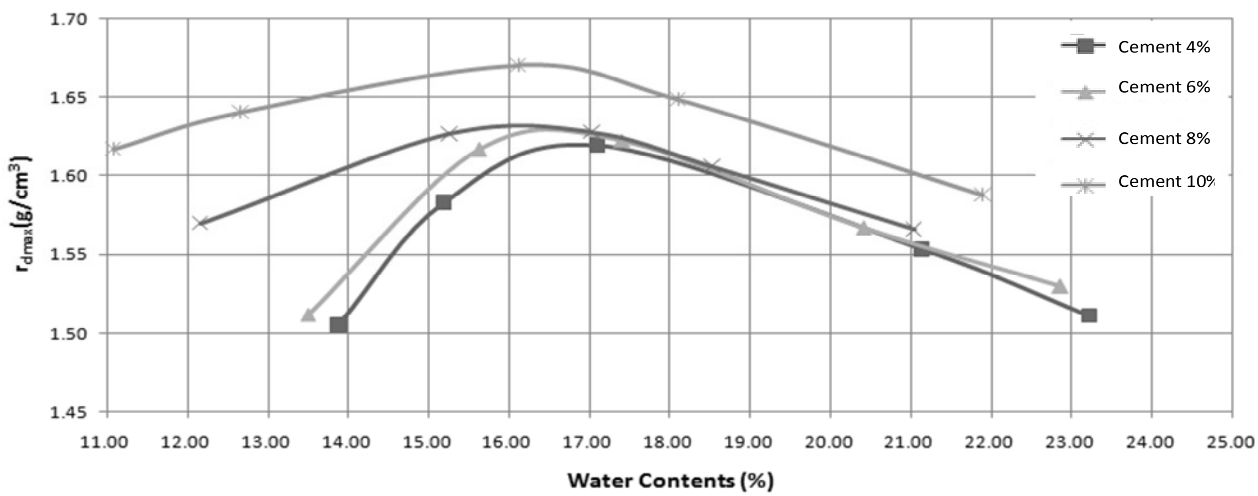
To analyze the hydration properties of the cement materials in the fly- and bottom-ash soil mixtures, portions of 7- and 28-day-old specimens were collected for X-ray diffraction analysis using Cu K-α radiation at 36kV and 20 mA at the rate of 5,000 deg/min in the range of 5 to 80°.

Leaching test

After preparing specimen solutions following Chapter 2, Article 5, of the Korean Ministry of the Environment Standard Method for Examination of Wastes, the instrumental analysis was executed using inductively coupled plasma (ICP) spectroscopy according to Chapter 3, Article 3.



(a) A method



(b) Modified E method

Figure 3. The results of A and modified E compaction tests.

Freezing and thawing test

The freezing and thawing test was executed in accordance with the KS F 2332 (Testing methods for freezing and thawing of compacted soil-cement mixtures) and the loss rate calculated according to the following formula:

Loss rate of soil and cement (%) = (A/B) × 100 (1)

Where, A= is the difference in the final and initial dry masses, and B= is the initial dry mass.

Wetting and drying test

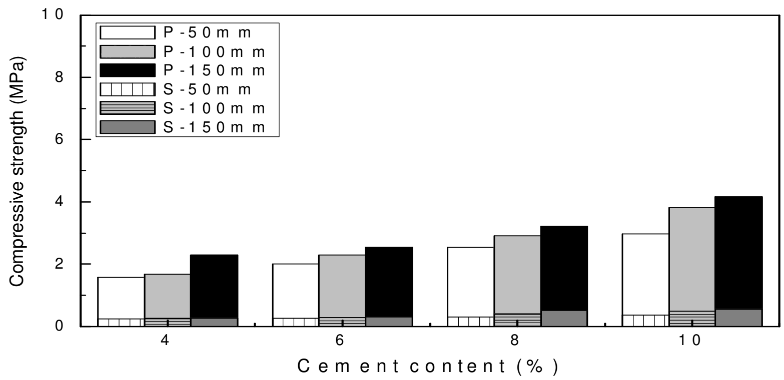
The wetting and drying test was performed according to the KS F 2330 (Testing methods for wetting and drying of compacted soil-cement mixtures) and the loss rate was calculated by the same method as in the freezing and thawing test.

RESULTS AND DISCUSSION

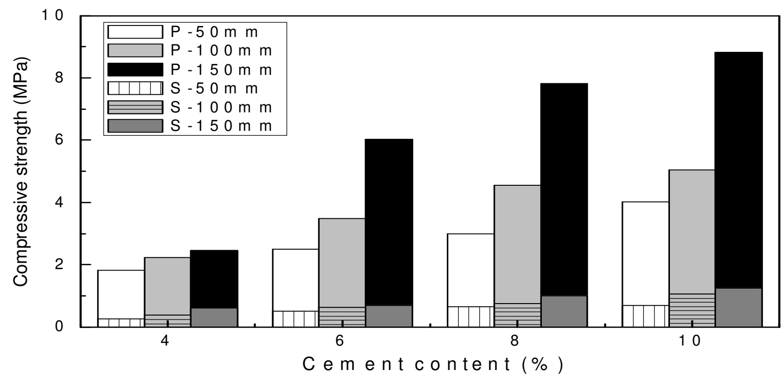
Compaction test

To determine the maximum dry unit weight and the optimum moisture content by measuring the compaction properties of fly- and bottom-ash soil mixtures depending on their cement contents, mixtures with 4, 6, 8 and 10% cement were prepared for the A compaction and revised E compaction test.

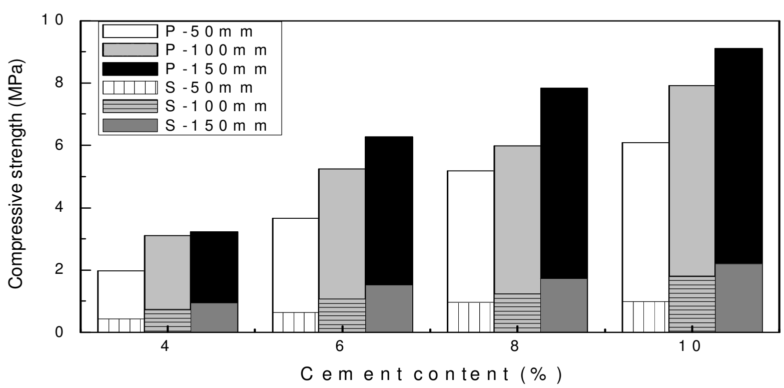
Figure 3 displays the results of the A and revised E compaction tests; here, the optimum moisture contents in the A and E tests were 17.5 to 18.2% and 16 to 16.5%,



(a) Curing age (3 days)



(b) Curing age (7 days)



(c) Curing age (28 days)

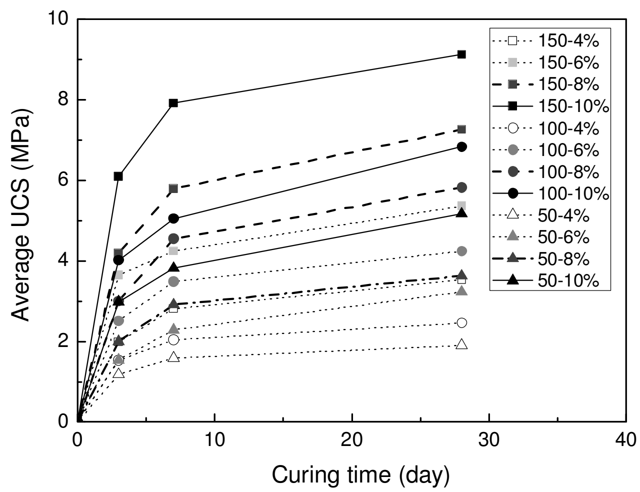
Figure 4. The results of the UCS and tensile strength tests of soil mixtures according to the cement contents and aging times.

respectively, and the maximum dry density were 1.59 to 1.65 g/cm^3 and 1.62 to 1.67 g/cm^3.

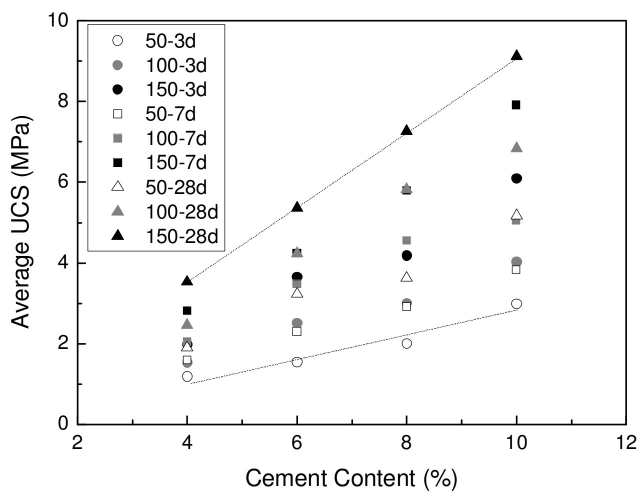
Considering that typical CSG materials have optimum moisture contents of approximately 5-8.7% and a maximum dry density of 2.15 to 2.2 g/cm^3, the fly- and bottom-ash soil mixtures produced here had approximately twice this moisture content but were approximately 0.75 lower in maximum dry density than typical CSG.

Unconfined compression strength and tensile strength test

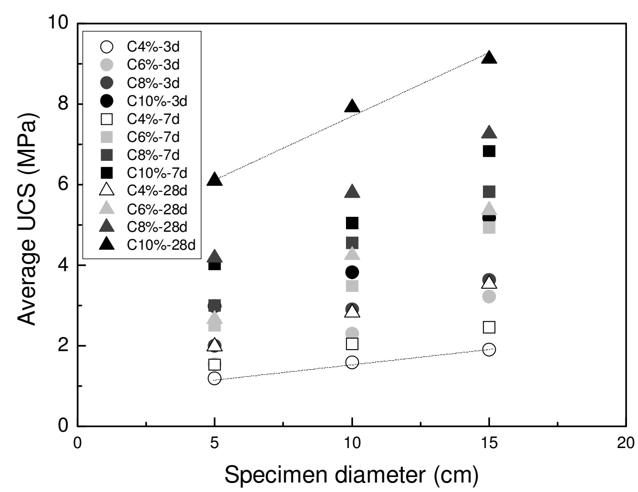
Although the cement content has a great influence on the final strength, it is important to formulate the optimum mix proportions according to the cement content by considering design strength and economic feasibility. Figure 4 shows the results of the unconfined compression strength and tensile strength tests of fly-



(a) Specimen diameter vs. average UCS



(b) Cement content vs. average UCS



(c) Curing time vs. average UCS

Figure 5. The relationship of the UCS and specimen diameter, cement content and curing time.

and bottom-ash soil mixtures according to the cement contents and aging times. The differences between tensile strengths and unconfined compression strengths were a minimum of 6 times to a maximum of 9.5 times on the third day, 4-8.5 times on the seventh day and 3.5 to 6 times on the 28th day; the differences between the two strengths thus decreased with a longer curing period.

Figure 5(a) shows the relationship of the unconfined compression strength and the maximum specimen diameters; it appeared to increase as the size of the specimen was increased, with a corresponding increase in strength. There is little published data on the relationships between strength and specimen size or grain-size; however, Varadarajan et al. (2003) stated that the strength was reduced as the particle size was increased in materials that were more easily crushed, whereas in materials with low fragmentation, there appeared to be an increase in strength with an increase in particle size.

Figure 5(b) displays the relationship of the unconfined compression strengths of fly- and bottom-ash soil mixtures with cement content. The unconfined compression strength increased with cement content in a linear behavior, and the slope of the line increased with the specimen size on, indicating the close relation of cement content and strength.

Figure 5(c) displays the relationship of compressive strength and curing period; here, it can be seen that most of the strength was developed during three to seven days, but the rate increase slowed thereafter. The strength on day 7 was 80 to 95% of the strength on day 28, and the rate of strength increase was greater in the larger specimens.

SEM and EDS

Figure 6 shows the micro-structures of the fly- and bottom-ash soil mixtures revealed by SEM at 10kx for each of the cement contents at day seven. In Figure 6, the hydration products found were formed by hydration of the mixed cement in the fly- and bottom-ash soil mixtures. Moreover, it was found that the formation of hydration products differed, example, the formation of ettringite differed according to the cement content, and the mullite was present in 8 and 10% cement formulations. Normal concrete has a high cement content, facilitating the formation of hydration products, whereas the fly- and bottom-ash soil mixtures had relatively small cement contents and, therefore, smaller amounts of hydration products were formed. According to degree of cement hydration, it filled in the gaps of these mixtures and bridged the gabs to different degrees.

Examination of the micro-structures confirmed that the hydration products were also dispersed according to the cement content; this factor can also explain the partial contribution of the hydration products to the strength properties.

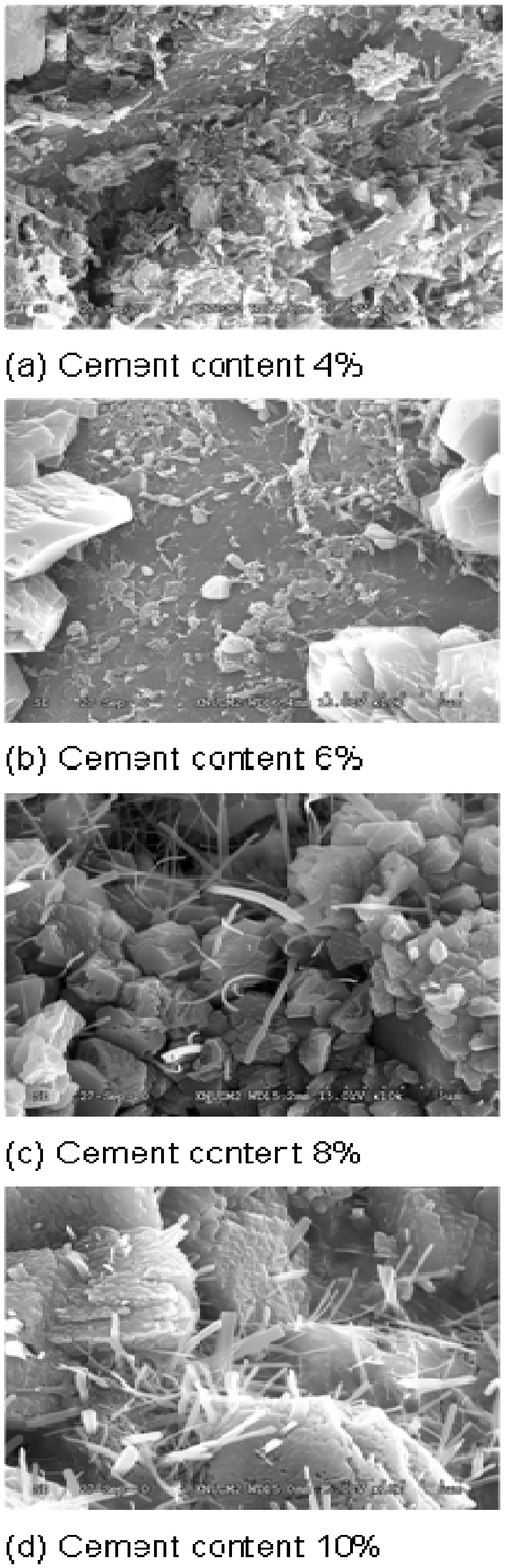


Figure 6. The micro-structures of the fly- and bottom-ash soil mixtures revealed by SEM at 10,000X for each of the cement contents at day seven.

Figure 7 shows the results of the EDS analysis according of the specimens cured for 28 days. With the exclusion of O and C, the Si and Al contents dominated in the case of the 4% cement formulation, and Mg, K, Ti and S components were additionally detected in the 10% formulation. Coal-ash components were likely source of the Ti and Fe detected and, unlike the other hydration products, S was detected, which was likely involved in the formation of ettringite.

XRD

To determine the mineral state and chemical components of the fly- and bottom-ash soil mixtures, specimens cured for 7 and 28 days were ground to a powder form for analysis.

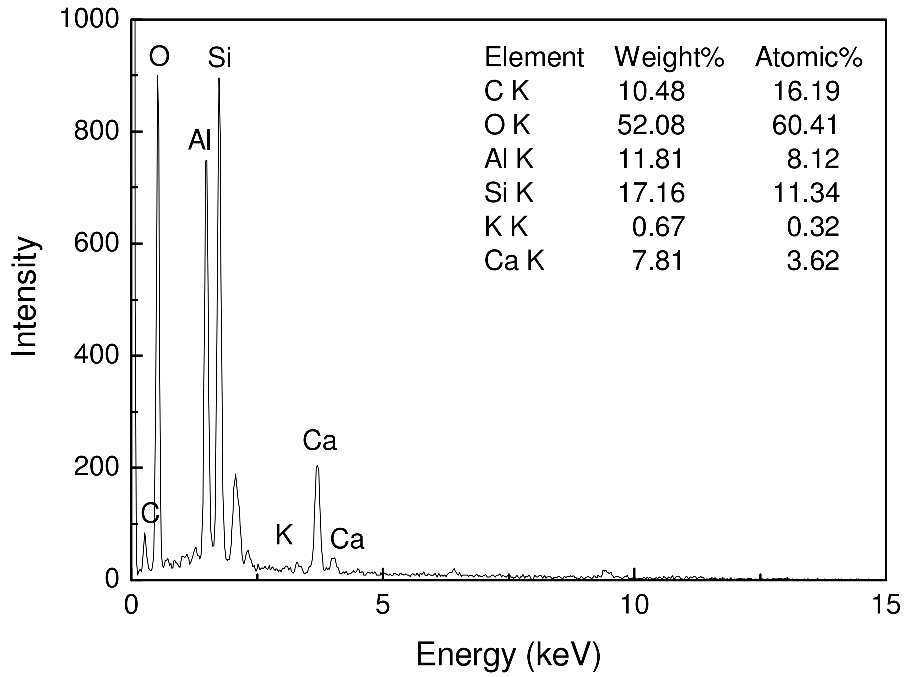
Figure 8 shows the results of the XRD analysis, revealing the variation in hydration products, depending on the curing time. Quartz and mullite, the main crystal minerals found in coal ash, dominated, as revealed by the peaks near $2\theta=25°$. On Day 7, the peak value of quartz was dominant, whereas the peak value of mullite was dominant on Day 28. This implies that the SiO_2 component was dominant on Day 7, whereas $3Al_2O_3 \cdot SiO_2$ was the main component on Day 28. Moreover, the covellite that appeared in the 10% mixture was composed of a CaS component, partially related to the fact that S appeared in the EDS result.

Leaching testing

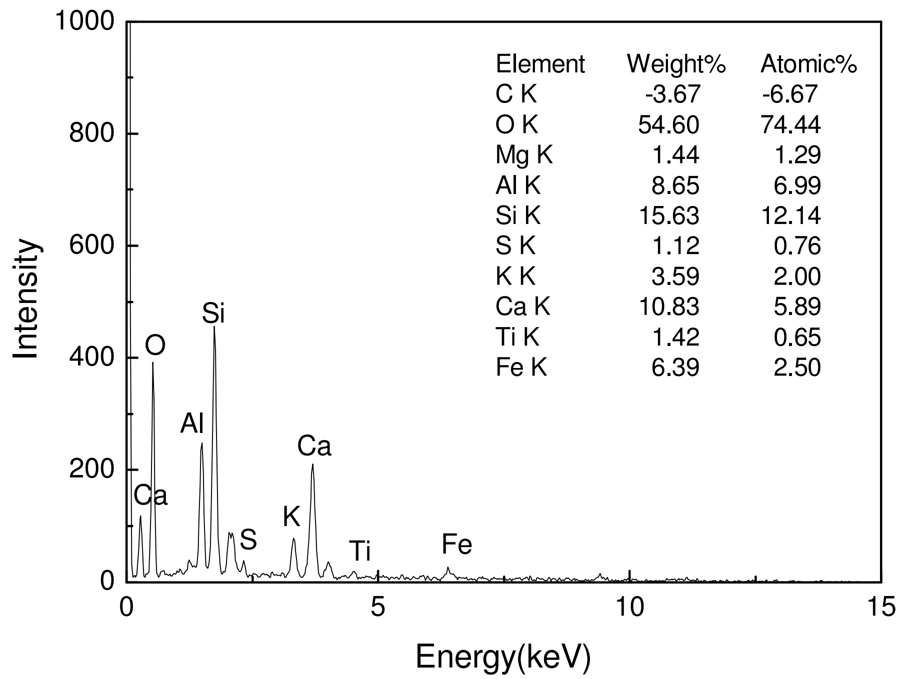
Table 3 shows the standard migration values by the method of Administration for Toxic Substances and Wastes and the results of leaching tests on our specimens. The values for the test pieces were lower than the standard values or not detected. These results indicate that the use of coal ashes as a construction material should present no migration problem, and they can therefore be used as an eco-friendly alternative aggregate.

Freezing-thawing and wetting-drying resistance

Figure 9 displays the relationship of cement content and loss rate of fly- and bottom-ash soil mixtures according to the freezing-thawing and wetting-drying cycle. As the cement content was increased, the loss rate was reduced, and the loss rate was increased in the smaller specimens. Moreover, a greater loss rate was observed in the wetting-drying test than in the freezing-thawing test; this was likely because the moisture filling the gaps underwent repeated vaporization and the occurrence of contraction and because expansion had a greater effect on the loss rate than the frequent changes in temperature.



(a) Cement 4%



(b) Cement 10%

Figure 7. The results of the EDS analysis according of the specimen cured for 28 days.

With the exclusion of the specimen S50, with the greatest loss rate, the two types of specimens both displayed great differences in loss rates, ranging from 4 to 8%; noting that the loss rate was smaller in 8 to 10% cement

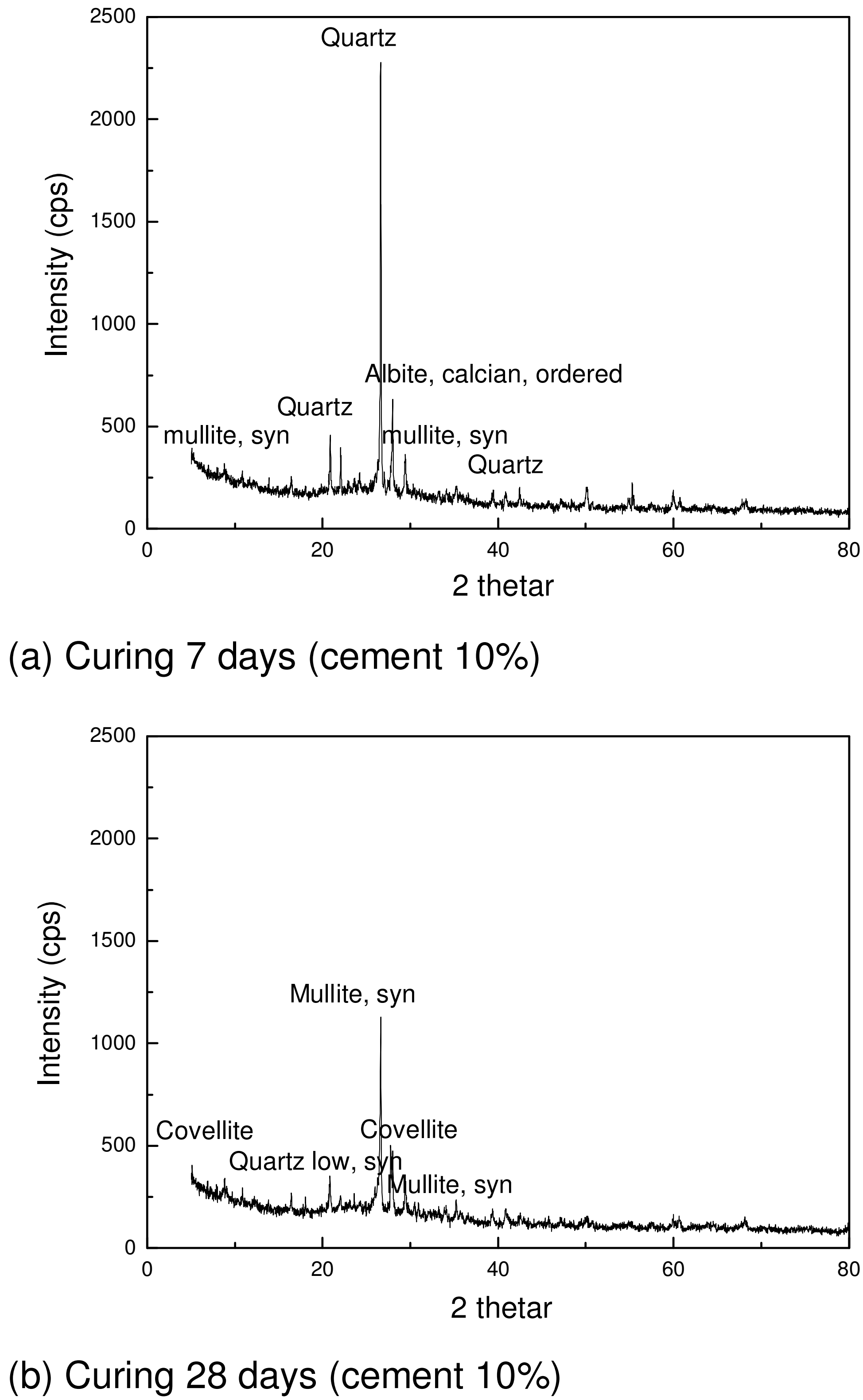
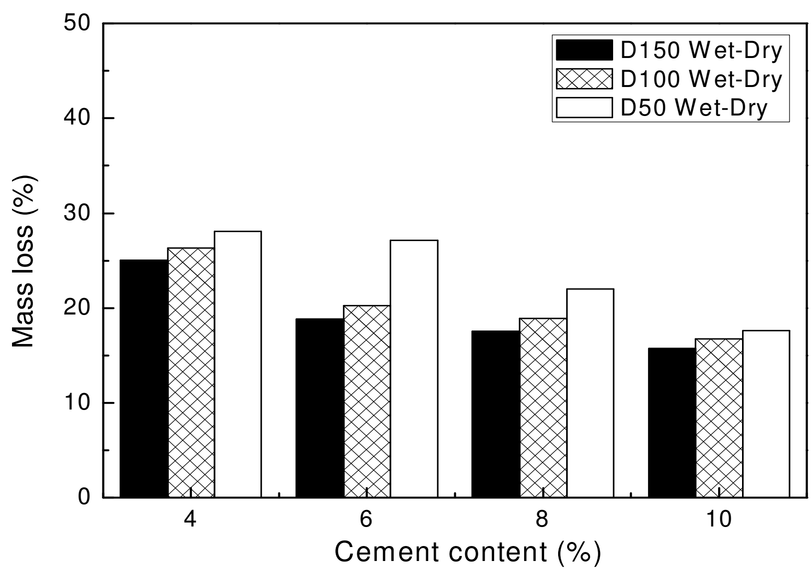


Figure 8. The results of the XRD analysis.

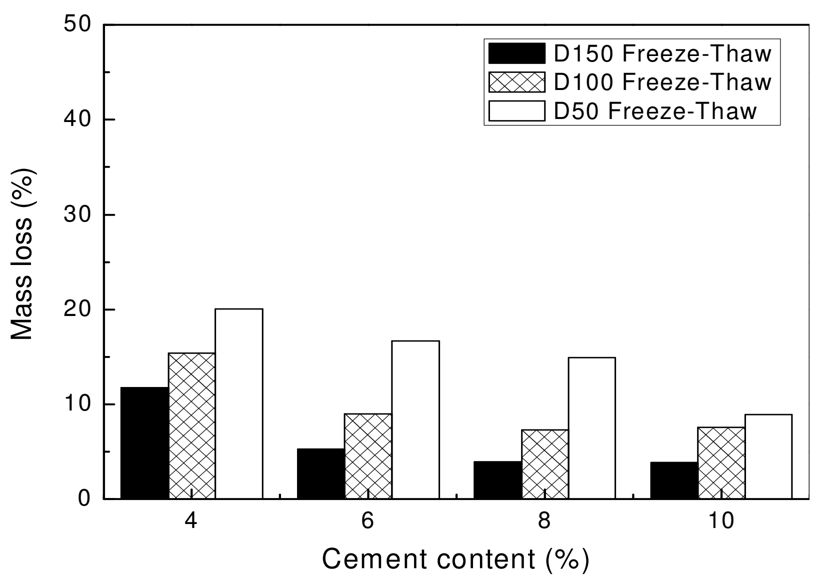
mixtures, when producing construction material a minimum of 8% cement should be used to provide resistance against freezing-thawing and wetting-drying losses.

Table 3. The results of the leaching tests.

Sample	Cd (ppm)	As (ppm)	Cu (ppm)	Pb (ppm)
base Value	0.3	1.5	3.0	3.0
Bottom Ash	0.001	N.D.	0.021	0.003
Cement 4%	N.D.	N.D.	0.005	0.001
Cement 6%	N.D.	N.D.	0.003	0.001
Cement 8%	N.D.	N.D.	0.003	0.001
Cement 10%	N.D.	N.D.	0.001	0.001



(a) The results of Wet-dry test



(b) The results of Freeze-thaw test

Figure 9. The relationship of cement content and loss rate of fly- and bottom-ash soil mixtures.

Conclusion

To evaluate the utilization of fly- and bottom-ashes in soil mixtures containing cement, we analyzed the engineering and environmental properties of the products, including the unconfined compression strength test, tensile strength test, micro-structure analysis, leaching test, freezing-thawing and wetting-drying resistance analysis. The main conclusions are as follows.

1. The strength increased according to the cement contents and the strength rate of increase also increased with specimen size. Moreover, on Day 7, the majority of specimens displayed 82 to 96% of the strength at Day 28, confirming the possibility of using fly- and bottom-ash soil mixtures after 7 days.
2. The micro-structural analysis of the fly- and bottom-ash soil mixtures revealed that the hydration products increased with cement content. The results of the leaching test gave values that were lower than the standard values or undetectable.
3. The results of the freezing-thawing test and the wetting-drying test showed that the freezing-thawing resistance of the mixtures was greater. Moreover, the loss rate was related to the cement content; the content over 8% was judged to maintain the appropriate wetting-drying and freezing-thawing resistance for future utilization as a construction material.
4. On the whole, the engineering and environmental test results of the fly- and bottom-ash soil mixtures show that they present great recycling possibilities for use as an eco-friendly alternative aggregate, and, when considering economic feasibility, 8% was judged to be most appropriate cement content.

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