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A study of the plasticity of lightweight aggregate green bodies including bottom ash

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The plasticity of clay-based green bodies including bottom ash(BA) from power plants were investigated. The plasticity indices of clay-base green bodies using Atterberg limits were measured. The usefulness of plasticity indices was confirmed by mapping the applicable forming region and through the actual extrusion process. Possible forming compositions were examined using various contents of water, bottom ash, stone dust, and sewage sludge. The relationship between the properties of aggregates and plasticity of green bodies was also investigated. Suitable compositions for forming aggregates by the extrusion method can be found by measuring the plasticity indices of green bodies and a map of the plasticity indices was matched with the results of actual extrusion process. The properties of aggregates were greatly influenced not only by the raw materials but also by the plasticity of green bodies.

Key words: Bottom ash, Atterberg limits, Plasticity index, Plastic limit, Liquid limit, Aggregates.

Introduction

A rapid expansion of cities for living and industrial areas eventually requires a greater electricity supply; therefore, coal fired power plants are constructed for many electricity demands because the cost of electricity generation by coal is still cheaper than by other methods. As a matter of course, the more coal fired power plants constructed, the more coal ash including bottom ash is produced. The annual production of bottom ash from coal fired power plants in Korea is estimated at 1.2 million tons which is 15-20% of the total ash produced from coal firing [1].

Unlike fly ash, bottom ash is mostly reclaimed at the sea side area because the chemical and physical properties of bottom ash are generally not as good as those of fly ash. The reclamation of bottom ash gives much trouble to the sea side ecology and bionomics, and power plants have to seek other reclamation areas because of the saturation of bottom ash in the existing reclamation areas [2, 3].

Atterberg limits provides important data to classify as well as to estimate the physical and mechanical properties of clay. The Atterberg limit is a dynamical experimental method and was first proposed by the Swedish scientist Atterberg in 1911; thereafter, experimental procedures and devices were revised by Casagrade and it was finally recommended as an official test method for plasticity of clay by ASTM [3, 4].

The Atterberg limits of green bodies including bottom ash were measured and maps of plasticity and liquid limits of specimens were produced to anticipate a high limit of bottom ash content for making lightweight aggregates [5-7]. This research study will be helpful to increase the recycling rate of bottom ash by providing the optimum compositions for forming aggregates which are applicable to the actual production process.

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Experimental

Ordinary red clay, dredged soil, bottom ash, fly ash, stone sludge, and sewage sludge were used as raw materials for making lightweight aggregates. The compositions of the raw materials are listed in Table 1. Each raw material was milled by a ball mill(raw materials went through No. 40 sieve after ball milling) or pin mill. The sieved raw materials were dried with a drying oven for 24 hours. The compositions of the lightweight aggregates were varied by 20% by weight. The average particle size and specific surface area of the raw materials are listed in Table 2.

A specially designed mold and bench press were used for extruding green bodies with different compositions. These experiments were performed to anticipate the state of green bodies which will come from the extruder in the actual ceramic process for the production of lightweight aggregates. The green bodies which came out of the mold were classified by the degree of cracking. The specific gravity and absorption rate were measured after sintering in the electric furnace.

Plasticity indices were measured using Atterberg limits which can be used as a reference for determining the degree of plasticity of green bodies. As almost all of the clay materials are used in a plastic state, the significant parameters

Table 1. Chemical compositions of raw materials (wt%)

	Ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	ZrO_2	P_2O_5	Cr_2O_3	MnO	C
Clay	11.00	57.69	19.02	7.05	0.20	1.04	0.09	2.53	0.92	-	0.17	-	0.22	-
Dredged soil	5.23	67.6	15.8	3.99	0.74	1.07	2.32	2.24	0.87		0.04		0.02	
Bottom ash	4.07	45.54	18.59	8.07	2.17	0.78	0.18	0.51	1.33	0.33	0.24	0.01	0.05	18.05
Fly ash	1.51	60.04	14.98	2.02	0.36	0.31	0.21	0.57	0.72		0.15			18.97
Stone ash	3.57	66.74	14.89	2.30	1.96	1.05	3.81	5.22	0.28	-	0.11	-	-	-
Sewage sludge	93.42	3.12	1.35	0.58	0.39	0.12	0.07	0.17	0.05	-	0.64	-	-	-

Table 2. The average particle size and specific surface area

	Bottom Ash	Fly Ash	Dredged Soil	Clay
Average diameter (μm)	76.20	56.12	22.05	28.05
Specific Surface area (m^2g^{-1})	0.256	0.547	0.775	1.192

include two of the Atterberg limits(the liquid limit, LL, and plastic limit, PL); and the plasticity index(PI) [4, 5]. LL defines the moisture content above which the material acts as a fluid, and below which it acts as a plastic substance. PL is defined as the moisture content below which the material ceases to behave as a plastic material and becomes friable or crumbly. Only the clay pastes, whose moisture contents lie within the Atterberg limits, can be shaped [6]. PI was measured by means of Atterberg's consistency limits (CNR UNI 10014): plastic limit(W_p), liquid limit(W_l) and plasticity index($PI = W_p - W_l$). Both the LL and PL test methods were followed by the procedures of ASTM D-423-66 and D-4318 [4]. The details of these measurement are also shown in many references [6, 7].

The aggregates with the same compositions as the specimens for the PI measurements were made and the relationship between PI and the specific gravities and absorption rates of green bodies were examined.

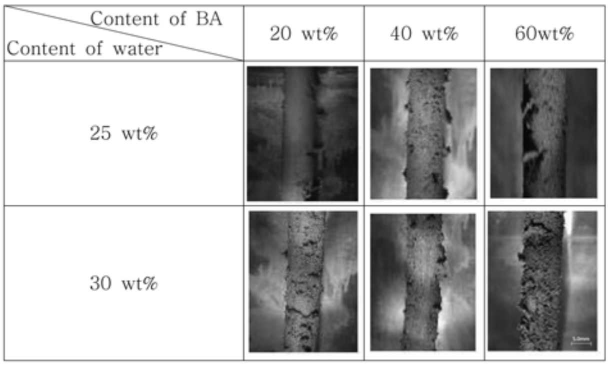

Fig. 1. Optical images of green bodies extruded by the press. Green bodies showed very different surface conditions by having different plasticities at various water and bottom ash contents.

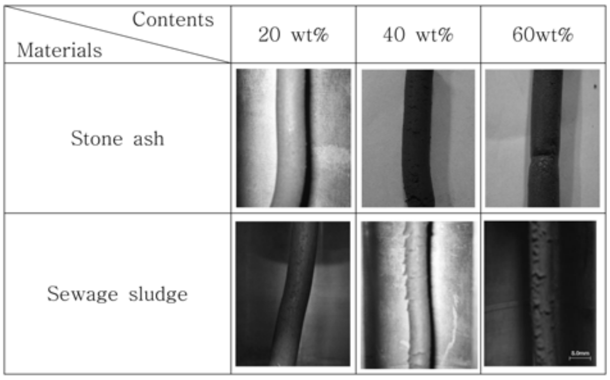

Fig. 2. Optical images of green bodies extruded by the press. Green bodies showed different surface conditions in having different plasticities at various stone ash and sewage sludge contents. The contents of water and bottom ash were fixed at 25 wt% and 20 wt%, respectively.

Results and Discussion

Fig. 1 shows optical images of green bodies extruded from the mold by the press. As shown in Fig. 1, more surface cracks were seen on the surfaces of green bodies with 30 wt% water than ones with 25 wt% water. From the above result, it is concluded that the optimum water content of a green body was 25 wt% which was also used in the case of the extruding process in the actual production line. The number of cracks increased and the length of specimens decreased with an increase in the content of bottom ash. Here, the length of a specimen is defined as the maximum length of the green body extruded by the press without total separation or break down by gravity.

Extrusion forming was performed with various stone ash contents while the contents of water and bottom ash were fixed at 25 wt% and 20 wt%, respectively. (Fig. 2) Although the length of the specimen decreased with an increase in the content of stone ash, the number of surface cracks on the specimen with addition of stone ash was less than that on the specimens with bottom ash only. However, when we added sewage sludge there was little difference in the number of cracks on the specimens before and after the addition of sewage sludge.

The aggregate specimens were made by hand 8 mm in diameter after extrusion forming and sintered at 1100-1200 °C. Fig. 3 shows the specific gravities of sintered specimens according to the contents of water and bottom ash at various sintering temperatures from 1100 °C to 1200 °C. The symbols BA and W in the inlet of each figure mean bottom ash and water contents, respectively. The number in the abscissa means the degree of cracks on the green body surface. The higher the number the more cracks on the surface. Fig. 4 shows the absorption rate of sintered specimens according to the contents of water and bottom ash

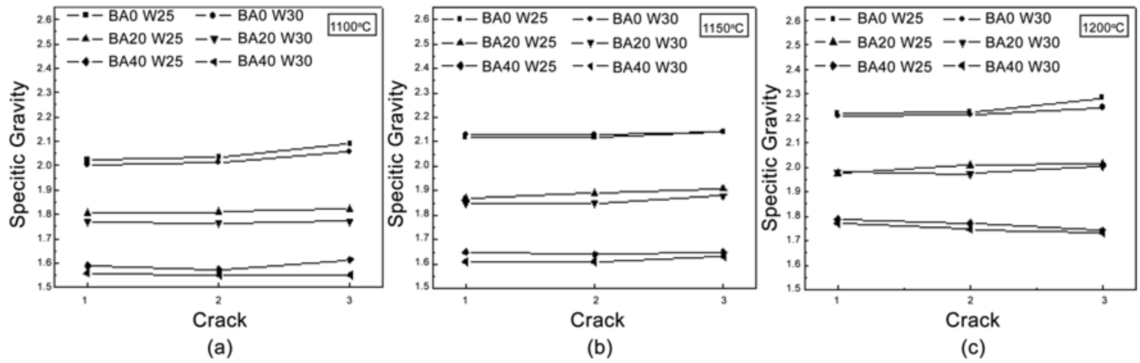

Fig. 3. Specific gravities according to the contents of water and bottom ash sintered at (a) 1100 °C, (b) 1150 °C, and (c) 1200 °C, where BA and W in the inlet means bottom ash and water contents, respectively. The number in the abscissa means the degree of cracks on the green body surface. The higher the number the more cracks on the surface.

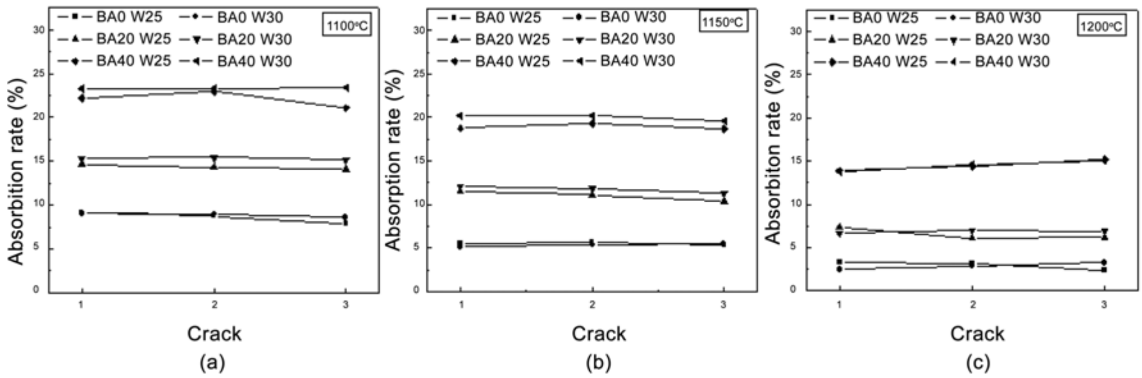

Fig. 4. Absorption rate of the sintered specimens according to the contents of water and bottom ash. (a) 1100 °C, (b) 1150 °C, and (c) 1200 °C.

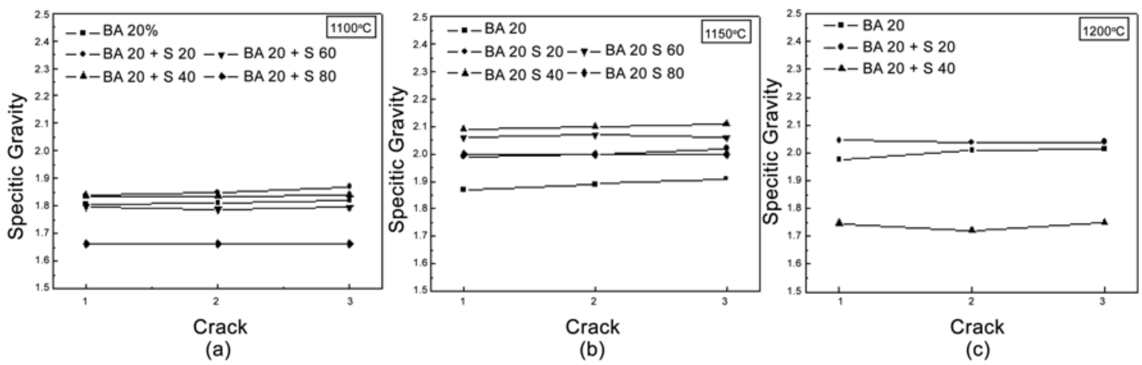

Fig. 5. Specific gravities of sintered specimens according to the content of stone ash at various sintering temperatures from 1100 °C to 1200 °C when the contents of water and bottom ash were fixed at 20wt% and 25wt%, respectively. All symbols and numbers have the same meaning as in Fig. 3.

at various sintering temperatures from 1100 °C to 1200 °C. From Fig. 3, the specific gravity tends to decrease with a decrease in the water content, with a decrease in the bottom ash content and with a decrease in the sintering temperature. However, the water absorption rate tend to decrease with a decrease in the bottom ash content and with an increase in the sintering temperature. Only small changes in both the specific gravity and absorption rate according to the number of cracks on the specimen surfaces could be observed.

Fig. 5 shows the specific gravities of sintered specimens according to the contents of stone ash at various sintering temperatures from 1100 °C to 1200 °C when the contents of water and bottom ash were fixed at 20 wt% and 25 wt%, respectively. All symbols and numbers have the same meaning as in Fig. 3. The specific gravity of the BA20 + S40 specimens increased up to 1150 °C; however, it decreased at 1200 °C because the compositions in the stone ash worked as bloating materials [1]. Fig. 6 shows the absorption rate of sintered specimens according to the contents of stone ash at various sintering temperatures from 1100 °C to 1200 °C when the contents of water and bottom ash were fixed at 20 wt% and 25 wt%, respectively. The absorption rate of all the specimens tends to decrease with an increase in the sintering temperature and content of stone ash. It is suggested

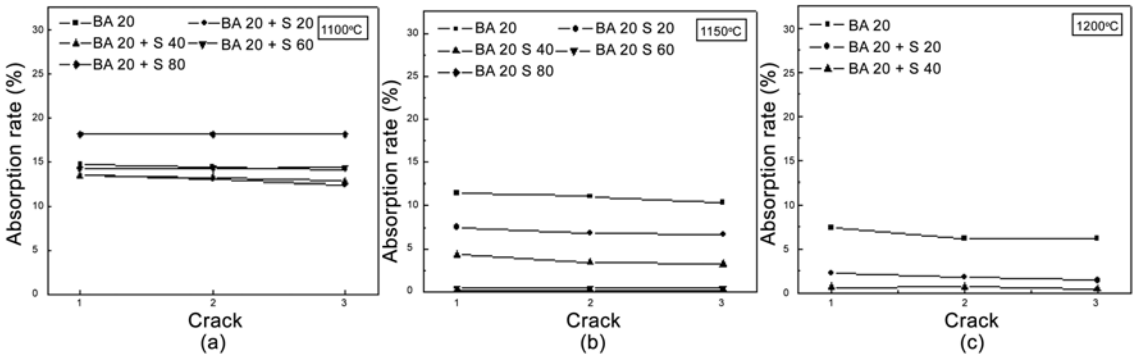

Fig. 6. Absorption rates of sintered specimens according to the content of stone ash at various sintering temperatures from 1100 °C to 1200 °C when the contents of water and bottom ash were fixed at 20 wt% and 25 wt%, respectively.

that the amounts of Na_2O and K_2O in the stone ash (Table 1) reduced the melting temperature of the aggregates and the liquid phases formed on the surfaces of aggregates blocked the open pores. This is the reason why the absorption rates were decreased with an increase in the temperature and content of stone ash. In Fig. 5 and Fig. 6, the number of specimens are different at each temperature. The reason is that the specimens with high contents of stone ash were much too bloated to measure the physical properties. Some of them totally collapsed during the sintering process. Therefore, some of the data are missing in these figures.

Atterberg limits were introduced to digitize the degree of plasticity of green bodies. The measured plasticity indices (PI) are shown on the left-side of Fig. 7 and Fig. 8. In these figures, the plasticity indices of clay bodies are given with various bottom ash and fly ash contents when using normal red clay and soils dredged from the sea shore. The differences of plasticity indices between clay and dredged

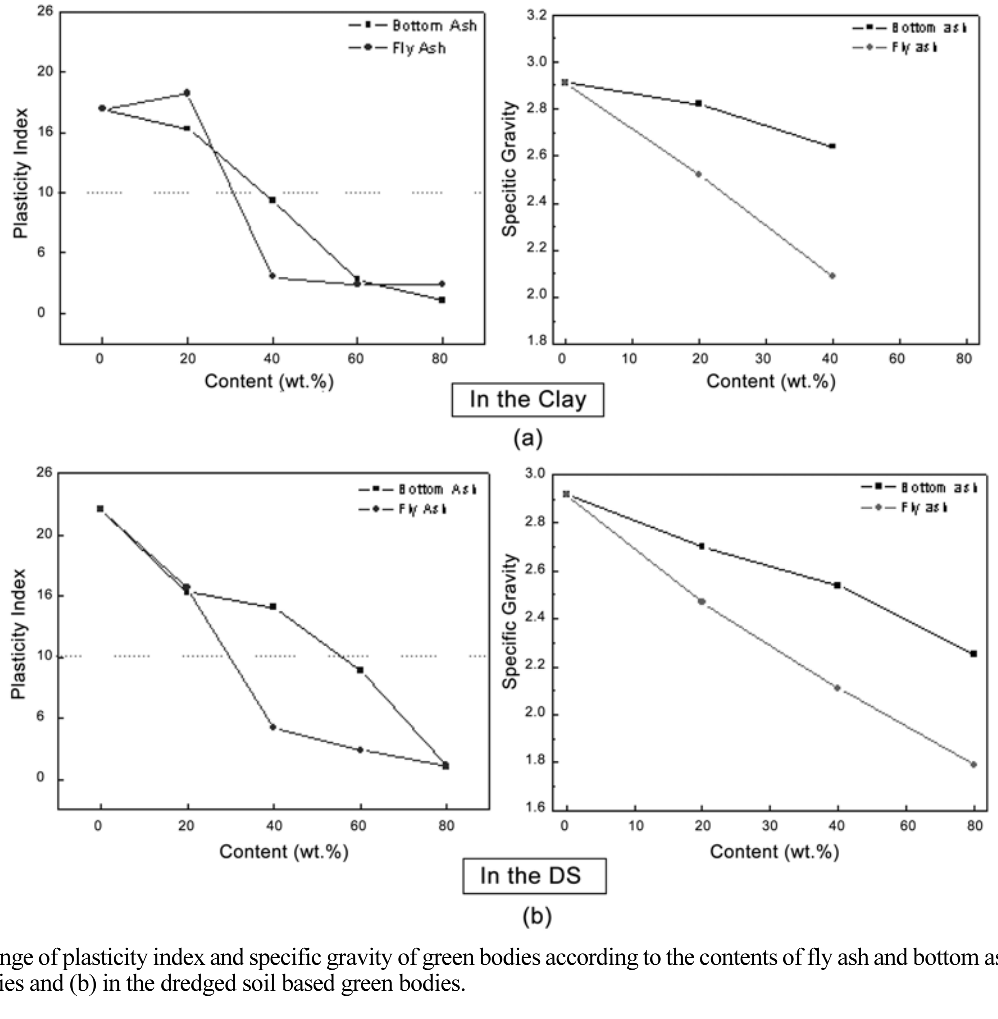

Fig. 7. The change of plasticity index and specific gravity of green bodies according to the contents of fly ash and bottom ash. (a) in the clay based green bodies and (b) in the dredged soil based green bodies.

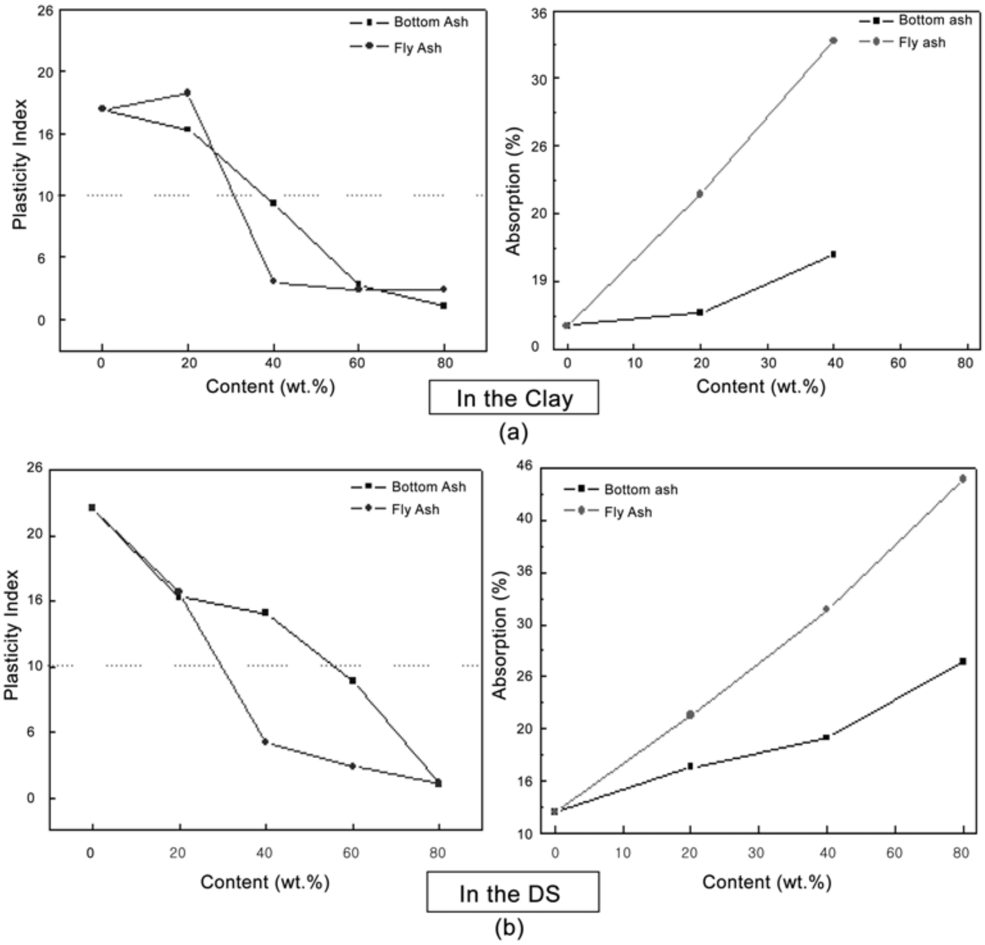

Fig. 8. The change of plasticity index and absorption rate of green bodies according to the contents of fly ash and bottom ash. (a) in the clay based green bodies and (b) in the dredged soil based green bodies.

soil as well as bottom ash and fly ash are clearly seen in Fig. 7. The plasticity indices of both bottom ash and fly ash with dredged soils were higher that those with normal red clays. This phenomenon can be explained by the finer size of dredged soils than that of normal clay as shown in Table 2. Generally speaking, plasticity indices of green bodies containing bottom ash were higher than those of ones containing fly ash. In both cases of fly ash and bottom ash containing bodies, the plasticity indices were decreased with an increase in the contents of both fly ash and bottom ash. From the result of plasticity index measurements, the maximum contents of fly ash and bottom ash in the green bodies were up to 40 wt% for forming without a problem. If the plasticity index of a green body is more than 10, the green body is considered as having a good plasticity so that it is good for forming aggregates [8, 9].

As shown in the left-side of Fig. 9 and Fig. 10, the plasticity index of green bodies having dredged soils was higher than those of green bodies having clay when the contents of bottom ash was fixed by 20 wt%. The plasticity index of a green body having stone ash was higher than that with sewage sludge because all the organic components which can help in forming in the sewage sludge were completely dried out in the drying process.

In both stone ash and sewage sludge cases, the plasticity index of green bodies was decreased with an increase in the contents of the additions. It was determined that the optimum additions for both materials was about 20 wt% when using with dredged soils.

The relationship between the properties of green bodies and the plasticity index was confirmed by making real aggregates with extruder. The results are shown from Fig. 7 to Fig. 10.

Fig. 7 shows the changes of specific gravities as well as plasticity indices according to the contents of fly ash and bottom ash in both the clay and dredged soil based green bodies. In both cases, plasticity indices and specific gravities were decreased with an increase in the ash content. Generally speaking, the plasticity indices of dredged soil based green bodies were higher than those of clay based ones. The plasticity index was above 10 which means the green body has a good plasticity for extrusion when the green body contains up to 40 wt% of bottom ash in the dredged soil.

Fig. 8 shows the changes of absorption rates as well as plasticity indices according to the contents of fly ash and bottom ash in both the clay and dredged soil based green bodies. The absorption rates were rapidly increased

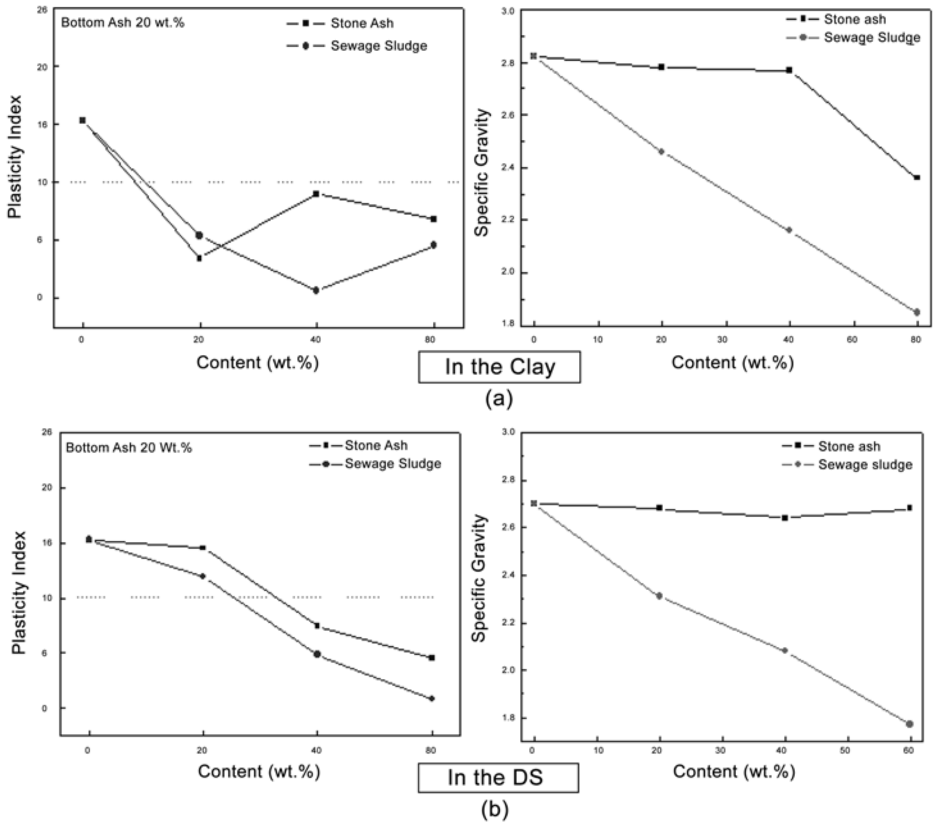

Fig. 9. The change of plasticity index and specific gravity of green bodies according to the contents of stone ash and sewage sludge. (a) in the clay based green bodies and (b) in the dredged soil based green bodies.

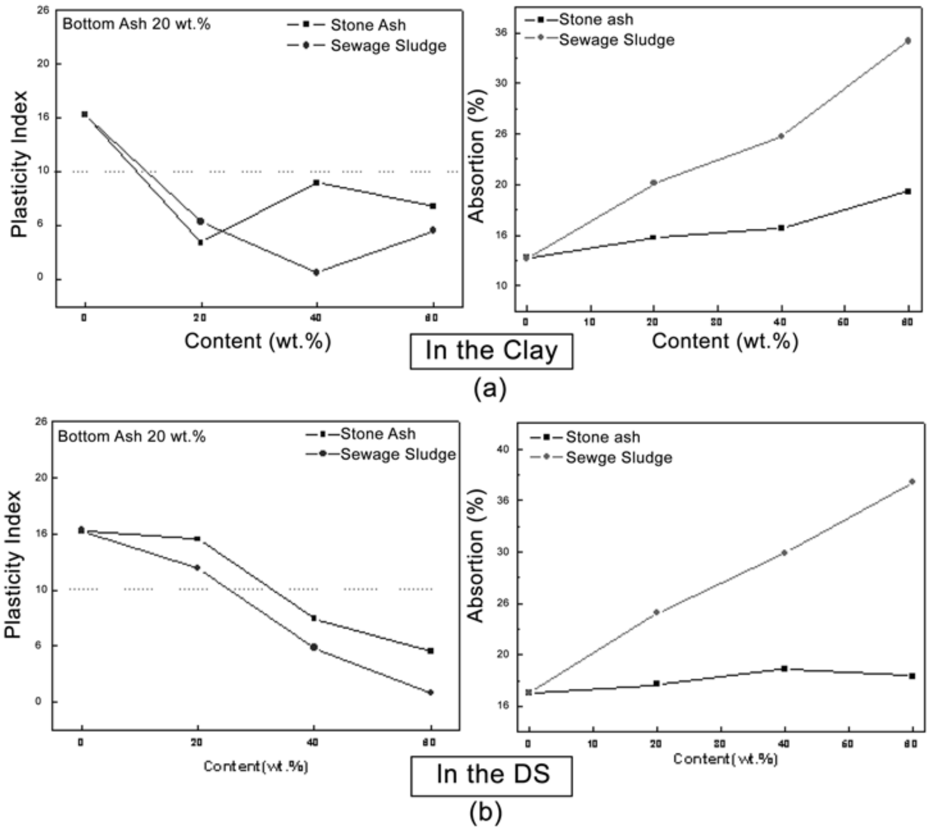

Fig. 10. The change of plasticity index and absorption rate of green bodies according to the contents of stone ash and sewage sludge. (a) in the clay based green bodies and (b) in the dredged soil based green bodies.

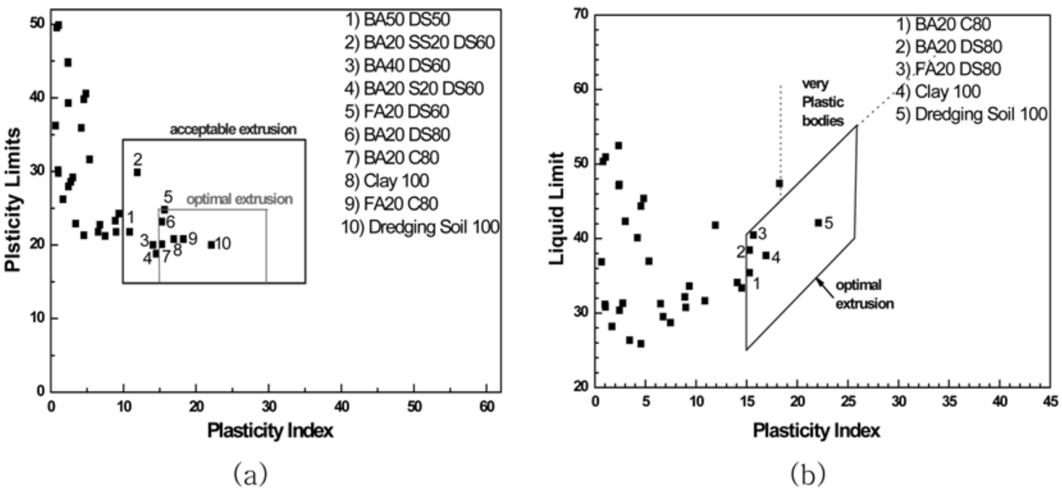

Fig. 11. Optimal and acceptable extrusion areas. (a) plasticity index vs. plastic limits and (b) plasticity index vs. liquid limits.

with an increase in the ash contents, especially in the fly ash case. It can be concluded that bottom ash is the better raw material for making a lightweight aggregate from the plasticity index and absorption rate point-of-view.

Fig. 9 presents the changes of specific gravities as well as plasticity indices according to the contents of stone ash and sewage sludge in both the clay and dredged soil based green bodies. In both cases, the plasticity indices and specific gravities tend to decrease with an increase in the contents of both stone ash and sewage sludge. The plasticity indices of dredged soil based green bodies were much higher than those of clay based ones in both cases. The plasticity index was above 10 only when the green body contains up to 20 wt% of both stone ash and sewage sludge in the dredged soil. The specific gravities of green bodies containing sewage sludge were decreased rapidly with an increase in the content of sewage sludge.

Fig. 10 shows the changes of absorption rates as well as plasticity indices according to the contents of stone ash and sewage sludge in both the clay and dredged soil based green bodies. The increasing rate of absorption rate in the case of sewage sludge was far greater than that in the case of stone ash with an increase in their contents. It can be concluded that both stone ash and sewage sludge can be used as raw materials up to 20 wt% with dredged soil for making aggregates without forming problems. However, it is expected that the aggregates with stone ash will have a lower absorption rate compared to the ones with sewage sludge.

By comparing from Fig. 7 to Fig. 10, the properties of aggregates were greatly influenced not only by the raw materials but also by the plasticity of the green bodies. Those with a higher plasticity index showed the better properties, that is, a lower absorption rate and a higher specific gravity.

The compositions for suitable forming aggregates were found by using the plasticity index, liquid limit, and plastic limit. As shown in Fig. 11, the compositions in the box can be used for forming aggregates by an extruder in the actual forming process and the results were all well matched with those from previously published extruder experiments [10, 11]. The green bodies of some compositions showed good extruding characteristics from the plastic limit point-of-view; however, the plasticity of these was not good from the liquid limit point-of-view [11]. Because the optimum water content exists between the plasticity limit and liquid limit, there will be no problem in forming if the green bodies are satisfying either the plasticity limit or the liquid limit [12].

Conclusions

The plasticity index was studied with green bodies containing clay and various waste materials by using the Atterberg limits and an extrusion method for effective recycling of bottom ash produced from coal fired power plants.

1) The optimum water content of a green body containing bottom ash was 25 wt% which could be used in an extruding process for mass production.

2) The number of cracks increased and the length of specimens decreased with increasing contents of bottom ash.

3) The specific gravities of sintered specimens were decreased with a decrease in the water content, with a decrease in the bottom ash and stone ash contents, and with a decrease in the sintering temperature.

4) The water absorption rate of sintered specimens tend to decrease with a decrease in the bottom ash content and with an increase in the sintering temperature.

5) The maximum content of fly ash and bottom ash in the green bodies were up to 40 wt% for forming without any problem.

6) The plasticity index of green bodies having dredged soils was higher than those of green bodies having other materials such as stone ash or sewage sludge.

7) The properties of aggregates were greatly influenced not only by the raw materials but also by the plasticity of the green bodies.

8) Suitable aggregate compositions for extrusion forming can be easily determined with minimum effort by the measurement of plastic and liquid limits.

9) From the results of property measurements of sintered aggregates, a higher plasticity index showed the better properties, that is, a lower absorption rate and a higher specific gravity. Therefore, there is a strong relationship between the plasticity index and properties of aggregates.

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