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Engineering properties of cement mortar with pond ash in South Korea as construction materials: from waste to concrete

Research Article

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Abstract: Among the wastes from coal combustion product, only fly ash is widely used for mineral mixture in concrete for its various advantages. However the other wastes including bottom ash, so called PA (pond ash) are limitedly reused for reclamation. In this paper, the engineering properties of domestic pond ash which has been used for reclamation are experimentally studied. For this, two reclamation sites (DH and TA) in South Korea are selected, and two domestic PAs are obtained. Cement mortar with two different w/c (water to cement) ratios and 3 different replacement ratios (0%, 30%, and 60%) of sand are prepared for the tests. For workability and physical properties of PA cement mortar, several tests like flow, setting time, and compressive strength are evaluated. Several durability tests including porosity measuring, freezing and thawing, chloride migration, and accelerated carbonation are also performed. Through the tests, PA (especially from DH area) in surface saturated condition is evaluated to have internal curing action which leads to reasonable strength development and durability performances. The results show a potential applicability of PA to concrete aggregate, which can reduce consuming natural resources and lead to active reutilization of coal product waste.

Keywords: Pond ash • Coal combustion • Cement mortar • Durability • Workability

1. Introduction

Due to thermal power generation from 1950, several countries including South Korea have been rapidly developed and coal still has been attractive as a source of power plant for its cost benefit, abundant deposits, and stable supply systems [1, 2]. However, CO_2 release from the power plant has become social and engineering issue for GREEN HOUSE EFFECT [3, 4]. In order to reduce CO_2 release, many researches have been focused on substitution of concrete which needs big fossil energy for manufacturing [5–8]. Active utilization of byproduct like fly ash (FA) and bottom ash (BA) in power plant is accordingly recommended. Coal ash is combustion byproduct in power plant and can be classified into 4 ashes for their formed type; FA, BA, EPA (electrical precipitator ash), and CA (cinder ash) [2]. FA is fine powder, formed from the mineral matter in coal, consisting of noncombustible matter in coal plus a small amount of carbon that remains from incomplete combustion. FA

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usually includes CA ash and EPA, and it amounts to 75–90% of total byproduct [9]. In Korea, reuse of FA went up to 67.9% in 2010 and showed 11% increase rate for the last 5 years. However BA shows only 40% of reuse for sub base material and more than 60% is treated for reclamation and landfill [2, 10], which is actually wasted. Since reuse of BA like reclamation or simple stack may cause additional soil contamination and insufficiency of natural resources like sand. Furthermore storage yard for PA reclamation is running short. Nowadays the problem of insufficient storage site has grown seriously. Active reuse of BA is strongly needed for aggregate or construction material. FA with pozzolanic reaction has been used for replacement of cement binder for its engineering advantages like reduction of hydration heat, long term strength development, high resistance to chloride attack, and improved workability [11–13]. 10–25% of BA has been recently applied for the replacement of fine aggregate. Several studies have been performed for its application to aggregate of low strength and filling concrete [9, 14–16]. BA is reported to have applicability for fine aggregate of concrete since it can make up for loss of crushed or sea sand during washing process and it has reasonable engineering properties [17].

Pond ash (PA) means stacked particles containing FA, BA and small soil particles in reclamation site. It has several limitations for direct use for fine aggregate of concrete. More than 40% of PA is wetted in reclamation site and sometimes it contains much chloride contents in reclamation site since it is almost located near to sea. Furthermore quality control of PA is difficult for concrete aggregate since it contains various particles and mineral ions [2]. In the previous research [18], comprehensive studies are performed for CCPs (Coal Combustion Products) but only the material of FA and BA are obtained and used from coal fired power plant.

In this paper, domestic PA from reclamation and landfill sites is studied for a feasible replacement of sand in cement mortar. Two selected PAs from different reclamation sites are prepared considering two replacement ratio of sand (30% and 60%). For evaluation of durability performance in hardened PA cement mortar, several tests like strength, freezing and thawing action, chloride migration, and accelerated carbonation are performed, and their results are compared with those from control cases (without PA mortar). The effect of water content on workability and performance of PA mortar is also evaluated. Evaluation and discussion of engineering properties in PA cement mortar are dealt with in this paper as a construction material.

2. Domestic PA as an aggregate for cement mortar

In South Korea, mainly two types of coal are used for power plant; domestic bituminous coal and imported anthracite. Bituminous coal is the only sufficient energy resource in South Korea but it generates much ash, amounts to 40–50% of raw coal, and low caloric power (4000 kcal/kg). On the other hand, anthracite imported from US and Canada generates only 15% of ash after combustion [2]. About 50% of anthracite is used for steel manufacturing and 30% for power plant for domestic electricity generation. For 10 accessible power plants, 2 reclamation sites (TA in West Sea and DH in East Sea) were selected. For each site, 2 holes were prepared and PAs containing FA, BA, and soil particles were excavated. For mortar mixing, excavated PA was washed and small particles were removed. Figure 1(a) shows the location of PA sampling (power plant), and Figure 1(b) and Figure 1(c) show boring test and PA extraction in reclamation site, respectively. Figure 2 shows the conventional acquisition process for FA and BA. The images of 50 times magnifying are shown in Figure 3 for 2 different types of PA.

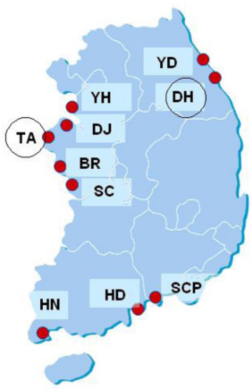
3. Experimental program

3.1. Materials

Two different PAs are prepared for this study. One is PA of anthracitic from DH and the other is bituminous coal from TA. Each PA is washed out for removal of chloride ion, soil particle, and dust before mixing. Granule size only within 0.15 mm–5.0 mm is selected through sieve process for fine aggregate. For binder, OPC (Ordinary Portland Cement) is used and its properties are listed in Table 1. The properties of PA and HWRA (High Water Reducing Agent) are listed in Table 2 and Table 3.

In Table 2, PA from DH has less Fe_2O_3 and more C components. Carbon in PA has hydrophobic surface, where chemical admixture like HWRA (High Water Reducing Agent) is absorbed in unburned carbon [19], so that reduction of workability and slump can be caused. PA usually has light weight and higher absorption ratio than normal sand. PA from DH (anthracitic coal) has higher absorption ratio of 6.32%. The aggregate with high absorption is reported to activate internal curing in surface saturated condition, [7, 12, 19–21]. The properties of standard sand are listed in Table 4.

(a)



(b)

(c)

Figure 1. Sampling location and PA from site.

3.2. Plan for mixing and durability tests

3.2.1. Mixing plan

For cement mortar mixing, two different w/c (water to cement) ratios and replacement ratios (30%, and 60%) are considered. The target flow for PA mortar with w/c 0.385 and 0.485 are 105±5 mm and 180±5 mm, respectively. Before mixing, sand and PA are controlled to be kept in

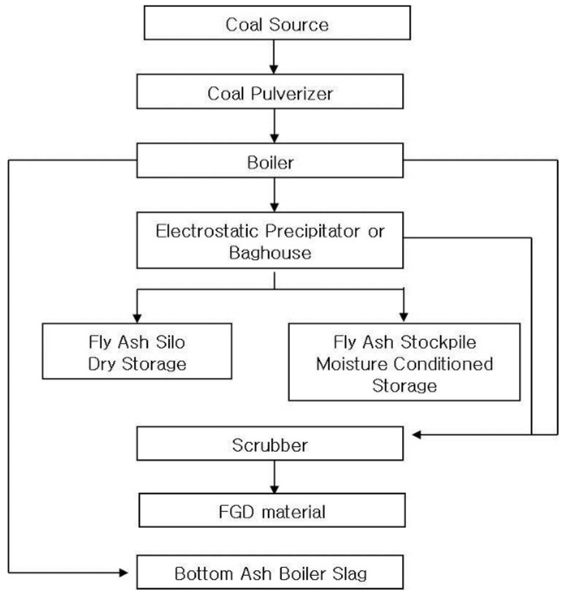


Figure 2. Conventional process for FA and BA [18].

surface saturated (SS) condition. Table 5 presents mix proportions for this test

3.2.2. Test for workability and durability

Flow, setting time, and compressive strength

Workability in cement mortar can be evaluated through flow test. Through this, variation of flow is evaluated with different replacement ratio of PA. Required amount HWRA for the target flow is also measured. Setting time of mortar is affected by residual carbon amount and absorbed free water [22, 23], so it is monitored. For strength test, cubic molds (50×50×50 mm) are prepared for compressive test. They are cured in submerged condition (23±2°C) and compressive strength is evaluated at 3, 7, 28 and 90 days based on the related standard.

Durability

Pores can be the main routes for deteriorating agents like chloride ion and carbon dioxide [24, 25]. For evaluation of porosity, MIP (Mercury Intrusion Porosimery) test is performed. Mortar samples with PA which have been cured for 28 days are crushed into small particles at the age of 28 days and are submerged into acetone for stopping hydration. After drying in oven (105°C) for 24 hours, porosity of each sample is measured. Chloride ingress is one of the most critical deteriorations for its direct effect on corrosion of steel [26, 27]. For

Table 1. Properties of cement.

Physical properties		Chemical component (%)							
Density (g/cm^3)	Blaine (cm^2/g)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	SO_3	Ig. loss
3.14	3.200	21.7	5.7	3.2	63.1	2.8	0.21	2.2	1.3

Table 2. Chemical and physical composition of domestic PA (weight %).

Chemical	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	ZrO_2	P_2O_5	C	LOI	Total
DH	53.47	28.25	3.65	1.99	0.72	0.65	2.88	1.2	0.03	0.1	6.90	0.27	99.84
TA	55.47	23.75	12.81	2.93	1.2	0.64	0.78	1.21	0.1	0.34	0.35	0.34	99.93

Physical	D_S [1)] (g/cm^3)	D_D [2)] (g/cm^3)	Unit weight (kg/m^3)	Absorption %	Solid Vol. (%)	Fineness Modulus
DH	2.27	2.12	1.315	6.32	59.4	2.88
TA	2.09	1.90	1.032	3.32	51.2	2.74

[1)] Surface saturated condition

[2)] Dried condition

(a) PA (Bituminous) from DH

(b) PA (Anthracitic) from TA

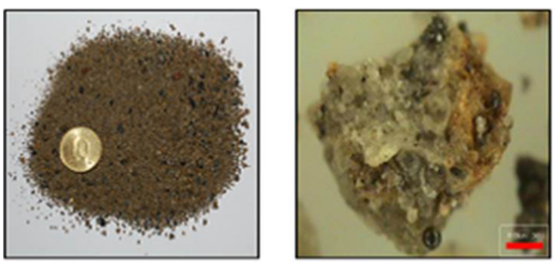


Figure 3. SEM image for different PA (unit length: 20 μm.

Table 3. Properties of HWRA.

Item	Color and condition	Mass contents (%)	Density (g/cm^3)	pH
High-range Water Reducing Agent (HWRA)	Dark brown liquid	41-45	1.15	7-9

Table 4. Properties of normal sand.

Item	Density (g/cm^3)	Absorption (%)	Unit weight (kg/m^3)	F.M.
Sand	2.58	0.72	2.640	2.57

evaluating resistance to chloride penetration, migration coefficient based on NT BUILD492 is evaluated. For this test, disk samples (10 cm of diameter × 5 cm of height) are prepared and 0.1N $AgNO_3$ indicator is used for colorimetric method [28]. Recently, carbonation in underground structure and urban cities are reported because of high CO_2 concentration. When CO_2 penetrates into concrete, $Ca(OH)_2$ is dissolved and $CaCO_3$ is formed through carbonic reaction [29, 30]. The carbonated area where pH of the pore water drops below 10.5 is vulnerable to steel corrosion due to loss of alkali, so accelerated carbonation test is performed for this matter. For measuring carbonation depth in PA cement mortar, 1% phenolphthalein indicator is used and it is measured for 8 weeks. Pores and related air amount are crucial to periodical freezing and thawing action [31]. Cubic samples with 50×50×50 mm are prepared and exposed to freezing in air and thawing in water. For 4 hours, 1 cycle from -18°C to +4°C is repeated. The compressive strength with

Table 5. Mix proportions.

Mix No.	w/c content (%)	PA content (%)	Unit weight (kg/cm^3) W	C	S	PA	HWRA ($C \times wt$ %) DH	TA	Target Flow (mm)
I-1		0			1249	0			
I-2	38.5	30	196.3	510	247	510		-	105±5
I-3		60			499	749			
I-4		0			1249	0			
I-5	48.5	30	247.3	510	874	374		-	180±5
I-6		60			499	749			
II-1		0			1249	0		-	
II-2	38.5	30	196.3	510	247	510	0.1	0.75	105±5
II-3		60			499	749	0.2	1.6	
II-4		0			1249	0		-	
II-5	48.5	30	247.3	510	874	374	0.1	0.8	180±5
II-6		60			499	749	0.1	1.7	

increasing cycle to 300 is evaluated and compared with control case. The test items and the referred standards are summarized in Table 6.

4. Evaluation of performance in PA cement mortar

4.1. Workability and strength

4.1.1. Flow test

From the previous researches [38], the increased capillary absorption in matrix with mixed BA and sand is affected not by the increased small particles due to added BA but by porous characteristics of BA. This is consistent with internal curing technique for HVFAC (High Volume Fly Ash Concrete) [12, 20]. The surface saturated porous aggregate in concrete can be the only source of inside water supply during hydration, which activates curing and provides much higher compressive strength than concrete with dry porous aggregate [39]. In the same workability (slump or flow), with increasing water content in porous BA in SS condition, the required water content for mixing can be reduced [40]. The variations of flow with different replacement ratio are shown in Figure 4. These results are for the cases without HWRA.

As shown in Figure 4, flow of DH (anthracitic) cement mortar shows little changes with replacement ratios, however, that from TA (bituminous coal) shows significant loss of flow with replacement ratio. PA mortar from DH has higher absorption ratio of 6.32% and this is fully saturated in mixing stage. Another influencing parameter to flow seems to be the shape of PA. PA from DH has clean and smooth surface compared with that from DH as shown in Figure 3. The ball bearing effect like fly ash [23] can help to resist flow loss with replacement.

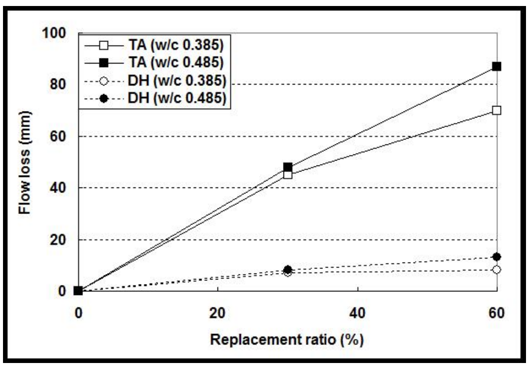


Figure 4. Variation of flow with different replacement ratio of PA.

Figure 5 shows the required HWRA for target flow for each PA cement mortar. It is evaluated that PA mortar from DH with high absorption ratio needs little HWRA since it already has fluid-ability through sufficient mixing water and smooth surface of PA.

Table 6. Test items and related references [32–37].

Test items		Referred method	Measuring period or timing
Workability and strength	Flow	KS L 5105 [32]	After Mixing
	Setting time	KS F 2436 [33]	After Mixing
	Compression	KS L 5105 [32]	3, 7, 28, 90 days
Durability	Porosity evaluation	Mercury intrusion porosimerty [34]	28 days
	Freezing and thawing Resistance	KS F 2456 [35]	0, 100, 200, 300 cycle after 28days
	Penetration Resistance of Chlorine Ion	NT Build 492 [36]	28 day
	Accelerated Carbonation	KS F 2584 [37]	7, 14, 21, 28, 42, 56 day measuring after 28 days

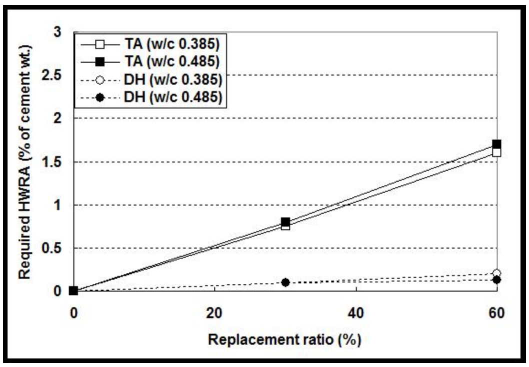


Figure 5. Required HWRA amount with different PA.

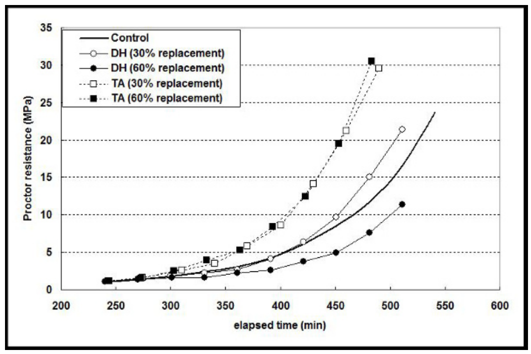


Figure 6. Proctor resistance with time.

4.1.2. Setting time

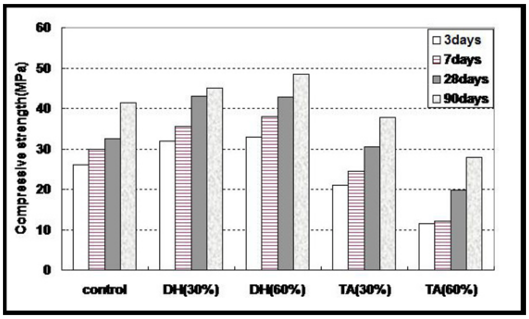
Young concrete with fly ash usually has retardation of hydration and delay of setting time due to the presence of SO_2^- ion from FA surface [23]. In this test, PA mortar with TA (bituminous) shows earlier setting time than results from DH (anthracitic) and control case. The mechanism of unburned carbon in mortar mixing is not clear but it is reported that the presence of unburned carbon causes absorption of chemical agent like HWRA [19]. The reason for earlier setting time in PA from TA can be explained as the amount of small particles and small mixing water. The passing weight ratio through 0.075 mm sieve is measured to be 1.2–1.8% for sand, 6.4–6.9% for PA from DH, and 14.7–17.9% for PA from TA. Despite of washing out, absorbed tiny particles around PA are added and this causes rapid hardening process. Figure 6 presents the variation of proctor penetration resistance with time.

4.1.3. Compressive strength

With lower w/c ratio, concrete usually has higher strength due to the more cement hydrates. As listed in Table 5, every mix proportion has the same cement content but different water content. Figure 7(a) shows the compressive strength in w/c 0.385 and Figure 7(b) shows those in w/c 0.485, where they have different strength behavior.

In Figure 7(a), TA mortar (bituminous) shows reduction of strength and this degradation is clear with higher replacement ratio. However, in the case of higher w/c ratio (0.478) in Figure 7(b), reasonable strength is measured with ages (in dot line box). The reason is thought to be the amount of mixing water that can be consumed for cement curing. PA mortar with TA has porous properties and irregularly angulated surface so that water is easily absorbed. It needs more mixing water due to large surface area and interlocking effect. In Figure 7(b) without HWRA, strength gaining is noticeable despite of higher

(a) Strength in w/c 0.385



(b) Strength in w/c 0.485

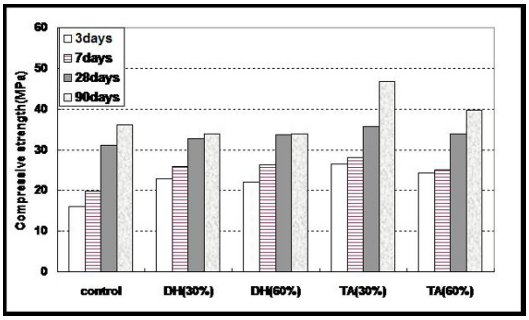


Figure 7. Compressive strength with different mix conditions (without HWRA).

w/c ratio. Due to the more mixing water, cement binder can be sufficiently cured. PA mortar of DH has little flow loss in Figure 3 so that strength reasonably increases with ages regardless of w/c ratio. The DH mortar with higher replacement ratio shows little strength gaining but not significant.

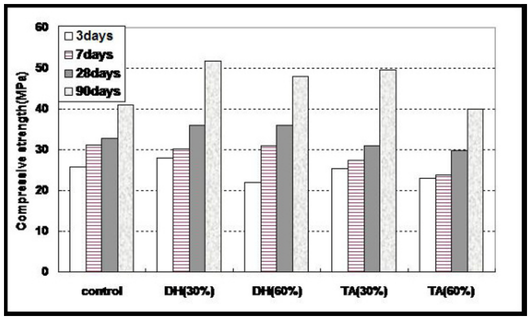
Figure 8(a) and Figure 8(b) present test results of strength in PA mortar with HWRA. Considering the results in Figure 7, strength loss due to the replacement of PA is not evaluated. DH mortar is evaluated to have more reasonable properties with higher strength. It is known that sufficient water inside is very efficient for both workability and strength development. PA size within 0.15–5 mm is used for mixing but residual little amount of FA around PA seems to be activated to some degree since strength in long term is measured to be high (Figure 8(a)).

4.2. Durability test and evaluation

4.2.1. MIP test

Porosities in the PA mortar without HWRA is measured through MIP at the age of 28 day. They are shown in Figure 9 including results in w/c 0.385 and 0.485. With

(a) Strength in w/c 0.385



(b) Strength in w/c 0.485

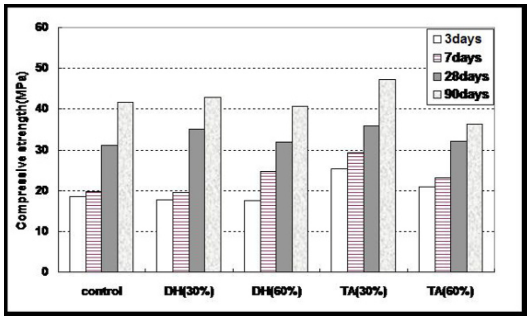


Figure 8. Compressive strength with different mix conditions (with HWRA).

increasing replacement of PA from TA, porosity increases. Porosities in DH mortar show lower results than those in control case (in the case of w/c 0.485). PA from DH with high absorption in SS condition causes little water absorption in binder matrix so that sufficient internal water is supplied for full curing of cement matrix, which leads dense pore structure. The use of smaller particles than standard sand may be another reason for dense structure in PA (DH) mortar through filling effect.

Porosities in control case are 10.74% for w/c 0.385 and 15.73% for w/c 0.485, respectively. In PA mortar, they are measured to 11.88–13.78% (from DH PA) and 15.27–21.56% (from TA PA). In DH mortar, lower porosities than those in TA mortar are measured and this can be similarly explained as strength development through sufficient supply of internal water. The mortar samples with TA show higher porosity than control case by 42.2–63.1% for w/c 0.385 and 16.9–39.6% for w/c 0.485. The reason for increasing porosity is relatively poor pore structure due to little water supply inside and irregular shape (not rounded shape) of PA.

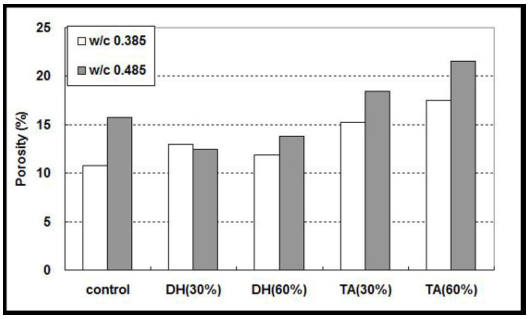


Figure 9. Porosity measurements in cement mortar without HWRA.

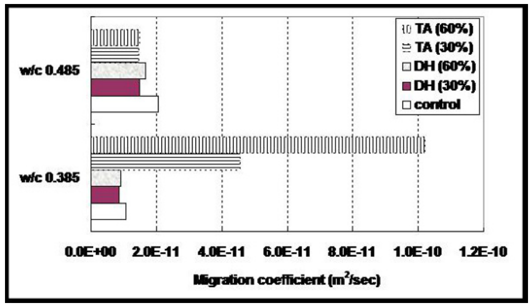
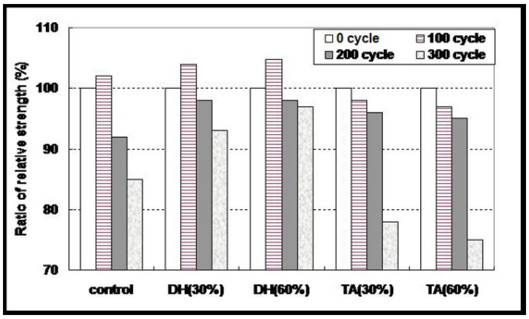


Figure 11. Migration coefficient in PA mortar without HWRA.

(a) w/c 0.385



(b) w/c 0.485

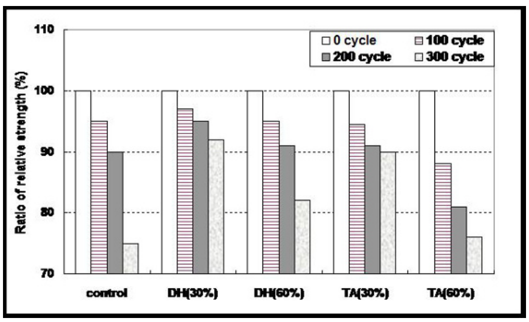


Figure 10. Relative strength ratio after freezing and thawing cycles (with HWRA).

4.2.2. Freezing and thawing test

In this test, relative compressive strength in PA mortar with HWRA is evaluated after specific cycles of freezing and thawing at the age of 28 days. The results are shown in Figure 10 with w/c 0.385 (a) and 0.485 (b).

When pore water in pore is frozen, the induced internal pressure causes micro cracks around pores and this leads degradation of cement binder [8, 41]. In all the cases, DH cement mortars show better resistance to freezing and thawing action.

4.2.3. Chloride migration test

Results from chloride migration test based on NT BUILD 492 are shown in Figure 11 for PA mortar without HWRA. Migration coefficients in control mortar are 1.06×10^{-11} m^2/sec for w/c 0.385 and 2.06×10^{-11} m^2/sec for w/c 0.485. The range of results from DH mortar is 8.71×10^{-12} m^2/sec 1.56×10^{-11} m^2/sec which shows reasonable resistance to chloride diffusion compared with control case. However those from TA mortar with w/c 0.385 show great increase in migration coefficients of 4.56×10^{-11} m^2/sec (30% replacement) and 1.02×10^{-10} m^2/sec (60% replacement). In the case of w/c 0.485, all PA mortar samples are shown to have equal or lower migration coefficients than control mortar. This is the same reason for the strength reduction in mortar of w/c 0.385 without HWRA in Figure 7. Insufficient curing water in the cement binder causes poor pore structure so that migration coefficients are measured to be dramatically higher in TA mortar (in dot line). Figure 12 shows the results in PA mortar with HWRA. Compared with Figure 11, migration coefficients increase little but no big difference in TA mortar is measured. Sufficient inter curing and addition of HWRA leads to improved migration coefficient in PA mortar with low w/c ratio.

4.2.4. Carbonation

The measured carbonation depth in PA cement mortar without HWRA is shown in Figure 13 where (a) and (b) are for w/c 0.385 and 0.485, respectively. Results from DH mortar after 56 exposed days are 6.74 mm, which has similar depth of control mortar with 6.60 mm. The effect of replacement amount seems to be little. In TA mortar with w/c 0.385 also has poor resistance

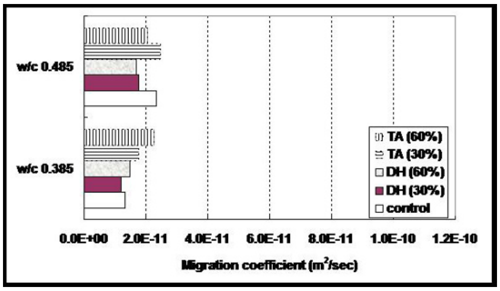
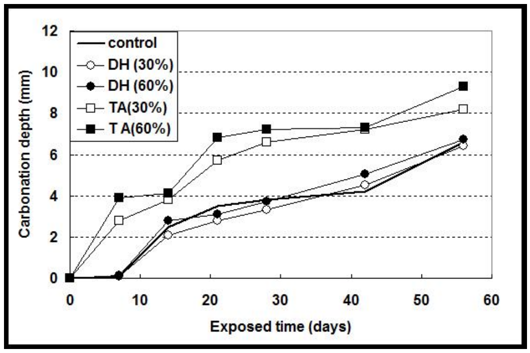


Figure 12. Migration coefficient in PA mortar with HWRA.

(a) w/c 0.385



(b) w/c 0.485

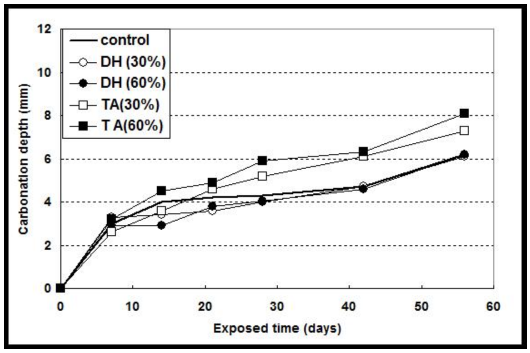


Figure 13. Carbonation depth in different PA mortar (without HWRA).

to carbonation since it has poor pore structure due to insufficient mixing water, which is consistent with results of strength and chloride migration. For convenient expression of carbonation behavior, carbonation depth can be assumed to be proportional to the square root of exposed time [42, 43]. In Table 7, regression results are listed with carbonation velocity. The more rapid carbonation velocities in TA mortar with insufficient mix content of w/c 0.385 are shaded in the Table 7.

Through a variety of tests regarding workability and durability performances, the characteristics and feasible applicability of domestic PA cement mortar are evaluated. PA from DH is evaluated to have more reasonable engineering properties for fine aggregate. However, it has several limitations of direct utilization for concrete aggregate. Before mixing, domestic PA should be under quality control like keeping higher absorption ratio and surface saturated condition. The small particle including unburned carbon should be removed through washout. The grading properties [44] can be improved through mixing 10–30% weight of ordinary sand. The results from this paper can help the reduction of consuming natural resources like sand and provide another active reutilization of domestic PA in reclamation site or landfill. The process of treating PA in this study can be summarized as Figure 14.

5. Conclusions

In this paper, engineering properties in cement mortar with domestic PA are evaluated and discussed. The conclusions from this study can be summarized as follows.

1. For workability evaluation, flows of mortar with domestic PA from TA region (bituminous) and DH region (anthracitic) are measured. Mortar with TA has lower flow due to porous characteristics of irregular angulated surface of PA. For the same target flow, bituminous PA from TA needs 7–13.5 time of HWRA. Anthracitic PA from DH has higher absorption ratio so that the mortar with surface saturated PA has little slump loss through sufficient internal supply of water and smooth surface of PA.

2. In the compressive strength test, TA cement mortar has significant reduction of strength without HWRA. It is because porous and angulated surface of PA with lower absorption ratio. In the TA mortar with higher w/c 0.485, higher strength is measured than that with w/c 0.385 without HWRA. The results that have better performances are evaluated in PA mortar with higher w/c ratio. In the same unit cement content are similarly repeated in the results of durability test such as freezing and thawing, chloride migration, and carbonation. This implies that sufficient water for hydration of PA cement mortar is necessary and internal curing through surface saturated PA is effective.

Table 7. Regression analysis for carbonation depth.

Type	w/c 0.385 (Ratio to control, %)		Type	w/c 0.485 (Ratio to control, %)	
	Carbonation velocity (mm^2/day)	Coefficient of determination		Carbonation velocity (mm^2/day)	Coefficient of determination
Control	0.7284 (100)	0.8479	Control	0.8438 (100)	0.9076
DH 30%	0.6881 (94.5)	0.8428	DH 30%	0.8038 (95.3)	0.9098
DH 60%	0.7609 (104.5)	0.8649	DH 60%	0.7951 (94.2)	0.9516
TA 30%	1.1362 (156.0)	0.9809	TA 30%	0.9709 (115.1)	0.9981
TA 60%	1.2609 (173.1)	0.9509	TA 60%	1.0739 (127.3)	0.9788

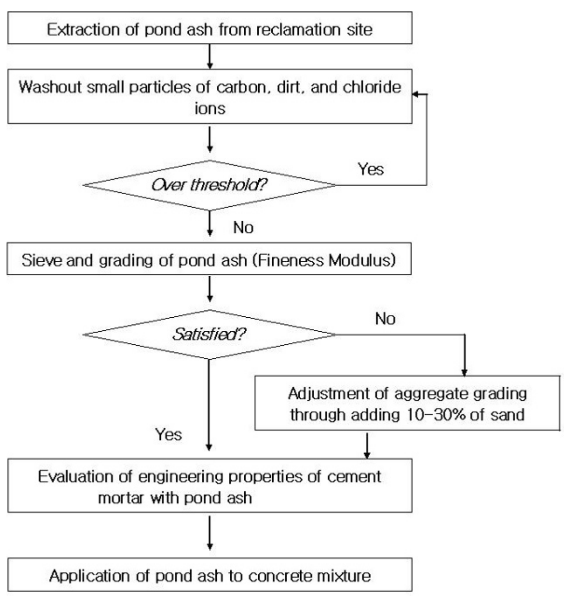


Figure 14. Process of PA for replacement of fine aggregate.

3. This paper shows feasibility of PA to construction material as fine aggregate. Through several tests, cement mortar with domestic PA (especially from DH region) is evaluated to have reasonable engineering properties through internal curing effect. Active use of PA can contribute to concrete industry through both reutilization of waste and reasonable engineering properties of concrete.

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