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Research Note

Effects of petrochemical wastes incinerator ash powder instead of Portland cement on the properties of concrete

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Abstract. Petrochemical wastes incinerator ash is generated from industries in which the landfill is the last step for their flowing. This research was performed for waste management of ash and its possible large-scale utilization in making concrete. An experimental investigation carried out to evaluate the mechanical properties of concrete mixtures in which Portland cement type II was partially replaced with Petrochemical Complex Incinerator Ash Powder (PCIAP). The cement was replaced with various amounts of PCIAP, i.e. 5%, 10%, 15%, 20%, and 25%. Tests were performed on the properties of fresh concrete as well as hardened concrete. Compressive, splitting tensile and flexural strengths, and modulus of elasticity were determined in 7, 28, and 90 days. Test results indicated that by using PCIAP as partial replacement of cement, stabilization, solidification, and neutralization treatment processes for the industrial wastes management were carried out, and the test results of the mixture M-2 (5% PCIAP) indicated that it can be used to make concrete which is lighter than normal concrete and heavier than structural lightweight aggregate concrete.

1. Introduction

Some products of petrochemical industries include raw plastics. Different units of these industries generate wastes with high toxic compounds. Some petrochemical industries use incineration system to optimize their wastes since it reduces the volume of waste tremendously and destroys the toxic compounds of wastes. Petrochemical Complex Incinerator Ash (PCIA) is obtained after incineration of petrochemical wastes. PCIA is ground to ease its reaction with Portland cement and is termed as Petrochemical Complex Incinerator Ash Powder (PCIAP). It has inherent pernicious effects, which is why it disposes in landfills. Since cement production causes environmental costs such as use of natural resources, air pollution, and energy consumption, research on the possible use of PCIAP as a cement substitution seems beneficial and necessary. Most common methods of waste management include neutralization, Stabilization, and Solidification (S/S). Neutralization is a method that a reactor, such as

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cement, Pozzolan, lime, improved clay, organic thermo set, thermo plastic, organic polymer, and silicate, decreases toxic properties of contaminants and immobilizes the contaminants [1]. Solidification is a method that sticks a polluted media with a reagent, changes contaminants' physical properties, and constitutes a solid substance. Also, stabilization is a method that decreases the mobility of contaminants with a chemical reaction [2]. Partial substitution of PCIAP for cement in concrete results in its neutralization and S/S as well.

Over the past few years, utilization of bottom ash or incinerator ash as partial substitution of aggregates [3], as an aggregate substitution in asphalt mixes [4,5], as a substitute for cement [6,7], as a substitution for natural aggregates in structural grade concrete [8,9], as an aggregate replacement in highway and roads construction [10,11], and as a soil stabilizing agent [12] has been the subject of several investigations. S/S is an effective technology to treat hazardous wastes according to United States Environmental Protection Agency [13] in low-level radioactive waste [14] in variety of industrial wastes [14] and in contaminants that include metals [15].

Juric et al. [7] reported that bottom ash can be used as a substitution forcement in concrete for the sake of SiO_2 and CaO inclusion. Forteza et al. [16] concluded that engineering properties of bottom ash are like natural aggregates, and they can be used in road construction. Cement is a common binder in S/S technology and cement solidification is mainly used for inorganic contaminants [15]. Also, wastes trap within gel structure and calcium hydroxide trap in pores [17]. Pecqueur et al. [18] indicated that the use of Municipal Solid Waste Incinerator (MSWI) bottom ash as embankments in road construction may cause pavement cracking and expansion due to chemical reaction, but it is solvable with Portland cement up to 70%.

Ferraris et al. [19] reported that vitrified bottom ashes can be used as filler instead of cement up to 20% and as a substitute for natural aggregate up to 75% vol. Kikuchi [20] demonstrated that Municipal Solid Waste Incinerator Ash (MSWIA) can partially be replaced with the cement as raw materials up to 50%. Saikia et al. [21] indicated that raw municipal solid waste incineration fly ash-based clinkers are more reactive than the washed Municipal Solid Waste (MSW) ash based clinkers. Use of incinerator fly ash as substitution of cement in concrete was studied by Taha et al. [6]. They indicated that concretes made by incinerator fly ash achieved low compressive strength at the ages of 3 to 6 months; however, the specimens attained higher compressive strength after six months due to increasing pozzolanic reaction with the passage of time. S/S is recognized as the best demonstrated available technology in treating hazardous wastes [22]. Pan et al. [23] indicated that cement production can be a feasible substitution for MSWIA management and does not have any impact on the compressive strength of the clinker. Other researchers reported that low amounts of bottom ash can be used in kilns as a raw material since it includes chloride [24,25]. Use of MSWI fly ash as a raw material in sintering sulphoaluminate cement clinker was studied by Shi et al. [26]. They reported that although sulphoaluminate cement have higher compressive strength in early ages, it improves smoothly at later ages. It is also proved that concrete incorporating Fly Ash (FA) exhibits either similar or enhanced performance in comparison to Portland cement [6].

Utilization of MSWI ash in concrete [27] and in cement and mortar [28] was also reviewed. Municipal solid waste incineration fly ash was examined for different applications in concrete [29,30]. Kula et al. [31] reported that fly ash and coal bottom ash can be used as a high volume cement replacement in the production of concrete. MSWI ash or bottom ash was used for different applications; for instance, as raw materials for clinker production [32] and for cement production [20,21,23,33], as aggregates in non-structural concrete [34], as controlled low-strength materials in trench construction [35] and in the production of polymer concrete [36], as aggregates in road construction and in concrete [16,37,38], as in the form of glass-like as natural aggregates in mortar and concrete [19], in tile production [39], and in glass ceramic products [40].

Fly ash and other waste materials have been reported recently which are considered as one of remarkable materials that have shown a good potential in enhancing the strength and thermal properties of cementitious materials. However, the effects of PCIAP on the performance and properties of cement-based materials have been neglected in previous research studies. This research investigates the possibility of using PCIAP as cement substitution in concrete to treat it with methods of S/S and neutralization, as this material has substantial economic and environmental benefits. To reach this goal, engineering properties of the concrete mixtures made with PCIAP are tested. This study also attempts to answer the question of whether or not PCIAP creates drawbacks as well as advantages in concrete.

2. Experimental program

2.1. Materials

Portland cement type II was used according to ASTM C150 [41]. Physical properties and also chemical compositions of cement are given in Tables 1 and 2, respectively [42]. PCIA was obtained by the burning of petrochemical wastes. The physical properties and

Table 1. Physical properties of Portland cement [42].

Physical test	Results obtained	ASTM C150 (type II cement)
Air content of mortar, volume (%)	5.54	12 max
Fineness: specific surface (air permeability test) (m^2/kg)	281	280 min
Autoclave expansion (%)	0.4	0.80 max
Vicat time of setting (min)		
Initial	128	45 min
Final	235	375 max
Compressive strength (MPa)		
1 days	14.5	—
3 days	20.3	10.3 min
7 days	29.2	17.2 min
28 days	41	—
Specific gravity	3.39	—

Table 2. Chemical compositions of Portland cement [42].

Constituent	Results obtained	ASTM C150 (type II cement)
SiO_2 (%)	21.10	20.0 min
Al_2O_3 (%)	4.79	6.0 max
Fe_2O_3 (%)	3.80	6.0 max
CaO (%)	63.09	—
MgO (%)	3.00	6.0 max
SO_3 (%)	1.93	3.0 max
Na_2O (%)	0.20	—
K_2O (%)	0.81	—
LOI (%)	1.24	3 max
IR (%)	0.63	0.75 max
C_3S (%)	48.32	—
C_2S (%)	24.05	—
C_3A, (%)	6.27	8 max
C_4AF (%)	11.58	—
Free CaO (%)	1.22	—

chemical compositions of PCIAP are given in Tables 3 and 4, respectively [42]. Natural sand was used as a fine aggregate (regular sand) with a maximum size of 4.8 mm and was tested to satisfy the requirements of ASTM C33 [43]. Coarse aggregates with the maximum size of 25 mm were used in this research. Aggregate properties are shown in Table 5 [42].

Table 4. Chemical composition of PCIAP [42].

PCIAP	Value (%)	PCIAP	Value (ppm)	PCIAP	Value (ppm)
SiO_2	18.25	Cl	772	Zr	71
Al_2O_3	5.43	Ba	150	Y	4
Fe_2O_3	27.95	Sr	299	Rb	22
CaO	16.21	Cu	80	Co	1
Na_2O	1.28	Zn	1543	As	61
K_2O	0.89	Pb	35	U	1
MgO	1.37	Ni	110	Th	2
TiO_2	0.546	Cr	175	Mo	46
MnO	0.079	V	57	Ga	6
P_2O_5	9.444	Ce	4	Nb	3
SO_3	2.765	La	1		
L.O.I	15.19	W	3		

2.2. Mixture proportions

According to ACI Standard Specifications 211.1 [44], mixture proportions of control specimen without PCIAP were designed to achieve a 28-day cube compressive strength of 36.5 MPa. Also, five mixtures were prepared with different amounts of PCIAP. The percentage of PCIAP was varied between 5 and 25% by weight of the cement. The water to binder ratio (w/b) was kept constant at 0.5 for all mixtures. Detailed mix proportions of the concretes are given in

Table 3. Physical properties of PCIAP [42].

Property	PCIAP	Portland cement type II
Specific gravity (gr/cm^3)	2.63	3.39
Fineness: specific surface (air permeability test) (m^2/kg)	288	281

Table 5. Physical properties of coarse aggregates and regular sand [42].

Property	Coarse aggregate (25 mm)	Regular sand (fine aggregate)	ASTM C33
Specific gravity	2.7	2.6	—
Unit weight (kg/m^3)	1670	1760	—
Absorption (%)	0.5	0.7	—
Fineness modulus	—	2.4	2.3-3.1
Clay lumps and friable particles (%)	—	0.4	3 max
Materials finer than 75 μm (%)	—	0.8	3 max
Total moisture content (%)	1	5	—

Table 6. Mixture proportions of concrete mixtures containing PCIAP [42].

Mixture no.	M-1	M-2	M-3	M-4	M-5	M-6
Cement (kg/m^3)	362	343.9	325.8	307.7	289.6	271.5
PWIAP (%)	0	5	10	15	20	25
PWIAP (kg/m^3)	0	18.1	36.2	54.3	72.4	90.5
Water (kg/m^3)	181	181	181	181	181	181
W/C	0.5	0.5	0.5	0.5	0.5	0.5
Sand (4.8 mm) (kg/m^3)	705	705	705	705	705	705
Coarse aggregate (25 mm) (kg/m^3)	1197	11.97	11.97	1197	1197	1197

Table 6. Concrete mixes were prepared in power-driven revolving-type drum mixers with a capacity of 0.25 m^3.

2.3. Preparation and casting of test specimens

Fresh concrete was cast into $150 \times 150 \times 150$ mm cubes for compressive strength test, 150×300 mm cylinders for splitting-tensile strength and modulus of elasticity tests, and $101.4 \times 101.4 \times 508$ mm prismatic molds for flexural strength test. The specimens were compacted using a tamping rod to exclude the air bubbles from the concrete. In order to minimize the moisture loss, the samples were covered. Subsequently, the test samples were placed in the casting room with a temperature of 23°C. Eventually, the specimens were demolded 24 hours after casting and cured in water at 23 ± 3°C until they were tested.

2.4. Test procedure

Slump test was performed according to the ASTM Standard Specifications C143 [45]. Hardened specimens were tested at 7-, 28-, and 90-day ages in accordance with the ASTM Standard Specifications C39, C642, C496, C469, and C293 [46-50].

3. Results and discussions

3.1. Slump test

The slump test results of the fresh concrete used to determine the effects of the PCIAP on the consistency are given in Figure 1. According to Figure 1, the slump value of the fresh concrete for concrete mixtures with PCIAP was higher than control mixture. Concrete mixtures with PCIAP had an increase of slump value in comparison with control mixture (see Figure 2). It is perceived that the PCIAP increases the slump value of the fresh concrete and the fluidity. This is probably due to Fe_2O_3 content present in PCIAP or due to the decrease of binder value in concrete, in which increasing the fluidity of the fresh concrete is effective.

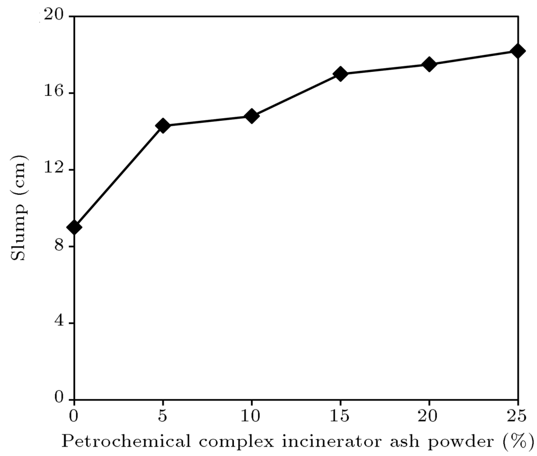

Figure 1. The effect of the PCIAP on the slump behavior.

3.2. Compressive strength

Compressive strength of concrete mixtures made with and without PCIAP was measured at age of 7, 28, and 90 days of curing. The results are shown in Figure 3 [42]. According to Figure 3, compressive strength of concrete mixtures with PCIAP was lower

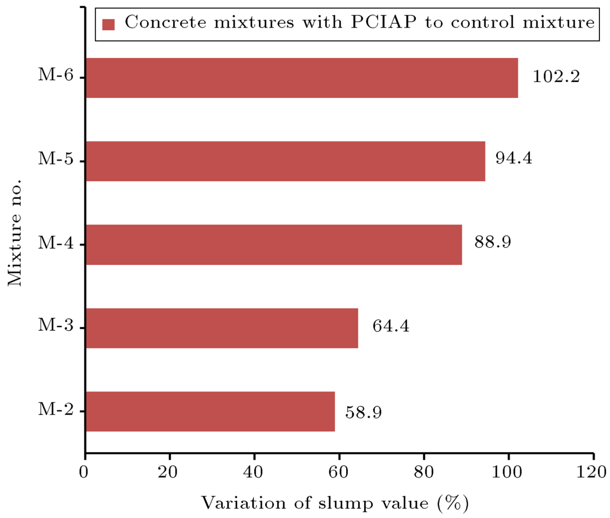

Figure 2. A comparison of slump value variation.

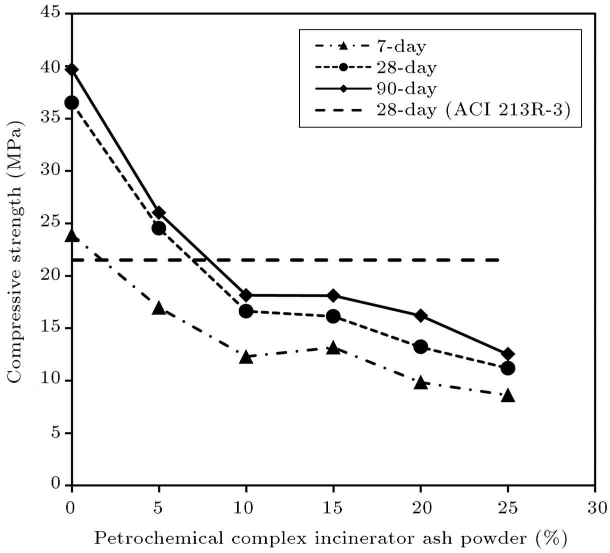

Figure 3. Compressive strength in relation to PCIAP and curing age [42].

than control mixture (without PCIAP). It could be due to the presence of Fe_2O_3 in PCIAP, but compressive strength of concrete mixtures increased with age. In Figure 4, at 28 days, percentage decrease in compressive strength of concrete mixtures made with PCIAP was more than that of control mixture. According to Figure 4, with the age of 28 to 90 days, percentage increase in compressive strength of concrete mixtures made with PCIAP was more than that of control mixture except mixture M-2, which is certainly by virtue of increasing the pozzolanic reaction with time. Taha et al. [6] indicated similar results, as they reported that concretes made with incinerator fly ash achieved low compressive strength at ages of 3 to 6 months, but it achieved high compressive strength later than 6 months due to an increase in pozzolanic reaction with time. According to ACI classifications

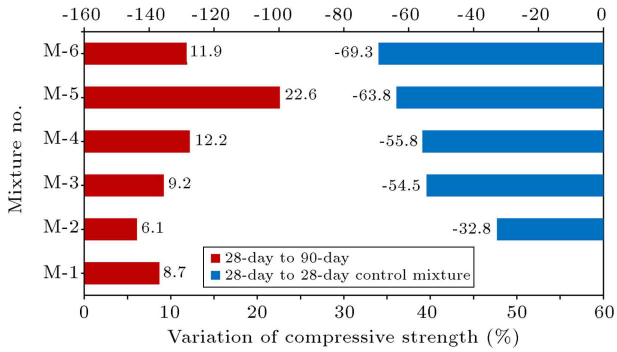

Figure 4. Multiple comparisons of compressive strength variation.

[51], structural lightweight aggregate concrete (LWAC) is concrete in which its air-dry unit weight at 28 days is usually in the range of 1440 to 1900 kg/m^3, and it has a minimum compressive cylindrical strength of 17.2 MPa at 28 days. According to UNESCO [52], compressive strength of cylindrical specimen was converted to cube specimen. At 28-day age, compressive cubic strength of mixture M-2 was 24.5 MPa, higher than the ACI 213R-87 [51] allowable limits [42].

3.3. Splitting-tensile strength

The splitting-tensile strength of concrete mixtures was determined at 7, 28, and 90 days of curing. The results are shown in Figure 5. Splitting tensile strength of concrete mixtures increased with age. As can be seen in Figure 6, at 28-day age, concrete mixtures with PCIAP had a decrease of splitting-tensile strength in comparison with control mixture. At 90-day age, all concrete mixtures had an increase of splitting-tensile strength in comparison with 28-day strength (see Figure 6). At 90-day age, there was a marginal increase in splitting-tensile strength of mixture M-2 in comparison with control mixture. Also, there was a

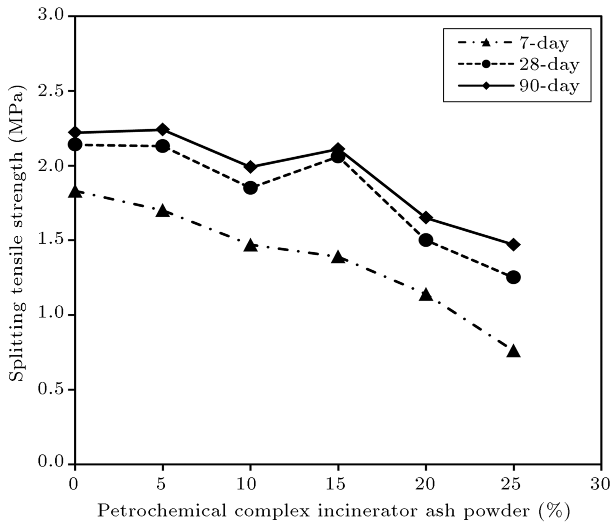

Figure 5. Splitting-tensiling strength in relation to PCIAP and curing age.

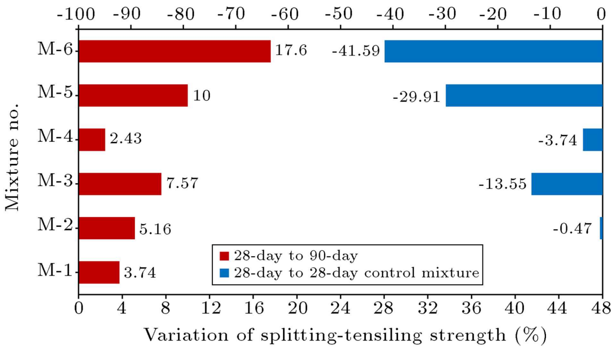

Figure 6. Multiple comparisons of splitting-tensiling strength variation.

slight increase in splitting-tensile strength of mixture M-4 in comparison with mixture M-3 at 28 and 90 days. According to the results, 5% PCIAP replacement can be considered as the optimum percentage of the PCIAP. The mixtures containing more than 5% PCIAP had splitting-tensile strength lower than the control mixture.

3.4. Flexural strength

Flexural strength of concrete mixtures made with and without PCIAP was determined at ages of 7, 28, and 90 days. The flexural strength test results of concrete mixtures are shown in Figure 7. At 28-day age, concrete mixtures with PCIAP had a decrease of flexural strength in comparison with control mixture. As can be clearly seen from Figure 7, it is evident that flexural strength of samples increased with the age. There is a decrease in flexural strength of concrete mixtures by fostering the content of PCIAP at 28-day age in comparison with control mixture (see Figure 8), such as compressive and splitting tensile strengths. At 90-day age, all concrete mixtures had an increase of flexural strength in comparison with 28-day strength

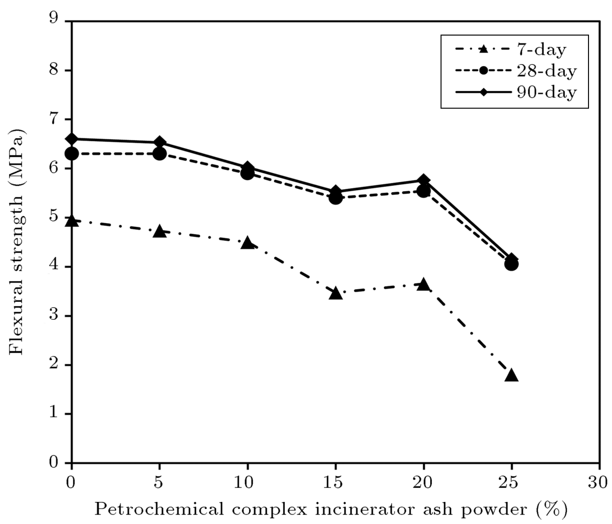

Figure 7. Flexural strength in relation to PCIAP and curing age.

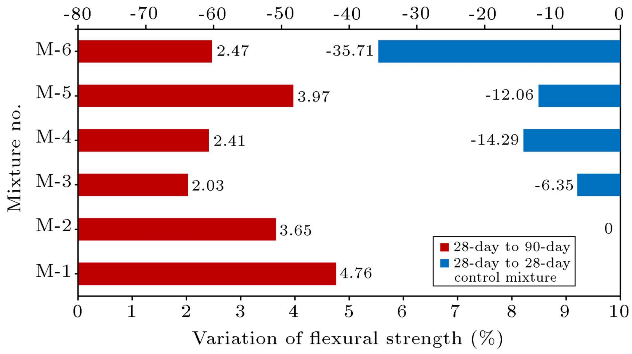

Figure 8. Multiple comparisons of flexural strength variation.

(see Figure 8). At 7, 28, and 90 days, there was a marginal increase in flexural strength of mixture M-5 in comparison with mixture M-4. At 28 and 90 days, flexural strength of concrete mixtures decreased with the increase in PCIAP content in comparison with mixture M-1, such as compressive strength.

3.5. Modulus of elasticity

The modulus of elasticity was determined according to ASTM C469 [49]. This test method covered determination of chord modulus of elasticity (Young's). The modulus of elasticity (E) was calculated according to the equation suggested by ASTM C469. The formula appears in Eq. (1):

$$E = (S_2 - S_1)/(\varepsilon_2 - 0.000050), \quad (1)$$

where E is chord modulus of elasticity in psi, S_2 is stress corresponding to 40% of ultimate load in psi, S_1 is stress corresponding to longitudinal strain, ε_1, of 50 millionths, psi, and ε_2 is longitudinal strain produced by stress, S_2. Modulus of elasticity of concrete mixtures was determined at 7, 28, and 90 days, and the results are plotted in Figure 9. At 28-day age,

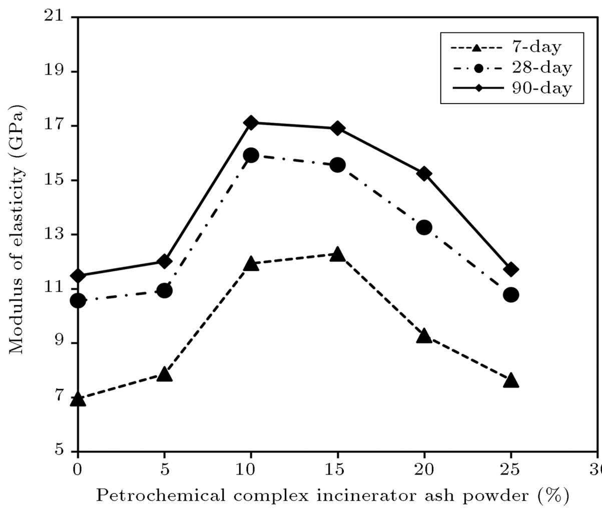

Figure 9. Modulus of elasticity in relation to PCIAP content and curing.

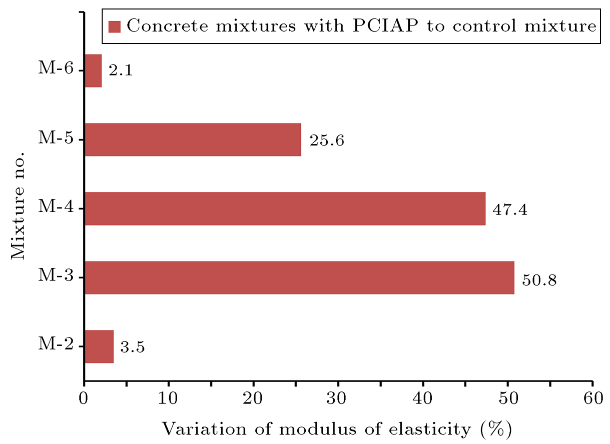

Figure 10. A comparison of modulus of elasticity variation.

concrete mixtures incorporating PCIAP demonstrated an increase in modulus of elasticity compared with the control mixture (see Figure 10). It is also evident that modulus of elasticity of all mixtures increased with the age. At 7, 28, and 90 days, modulus of elasticity of concrete mixtures increased with the increase of PCIAP content in comparison with control mixture. In this study, the 10% PCIAP replacement can be considered as the optimum percentage of the PCIAP.

3.6. Water absorption

The water absorption test was performed for each concrete mixture at of 7-, 28-, and 90-day age. From each mixture, three cubical samples were weighed and submerged for an hour, then taken out from the water and weighed again. Later, the samples were kept dry for two days. Again, the samples were weighed and submerged for a day, after which they were taken out and the weights of the samples were measured. The water absorption values of the samples with and without the PCIAP are provided in Figure 11. At 28-day age, there was an increase in water absorption of concrete mixtures with the inclusion of PCIAP as partial replacement of Portland cement type II (see Figure 11). Also, at 7 and 90 days, there were similar results such as those at 28 days. Also, water absorption of concrete mixtures also increased with age. These may be explained as the consumption of PCIAP increases the void in the concrete. This investigation indicated an enhancement in water absorption of concrete mixtures made with PCIAP.

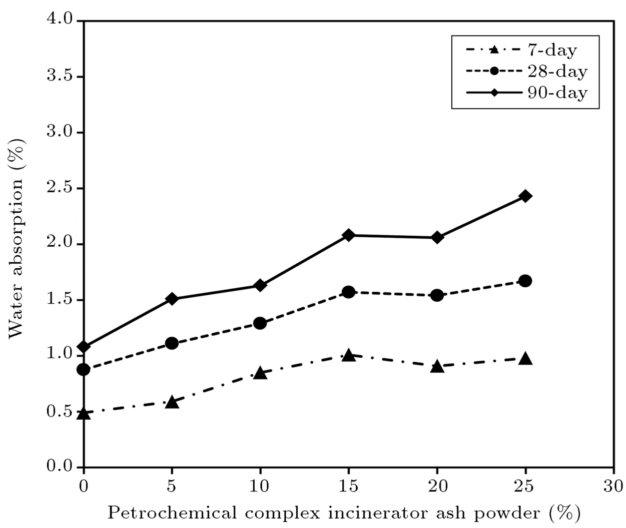

Figure 11. Effect of PCIAP content on water absorption.

3.7. Unit weight

The unit weight test results of concrete mixtures are shown in Figure 12. At 28-day age, there was a decrease in unit weight of concretes mixtures with the inclusion of PCIAP as partial replacement of Portland cement type II (Figure 12). At 28-day age, unit weight of concrete mixtures decreased with the increase in PCIAP content in comparison with control mixture (see Figure 13). This could be due to the lower specific gravity of the PCIAP in comparison with Portland cement type II. This investigation

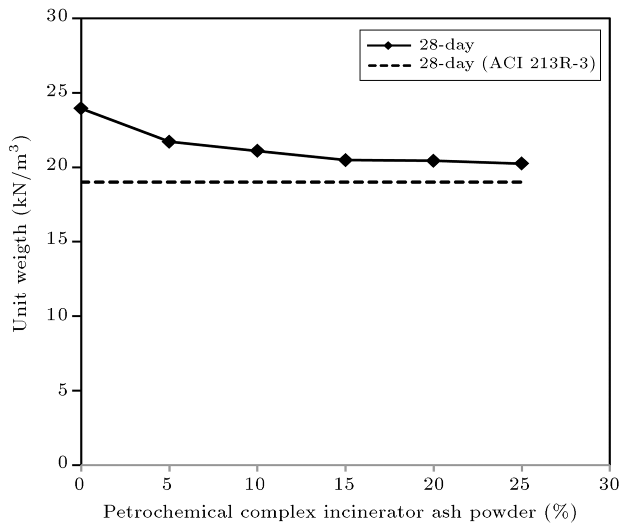

Figure 12. Unit weight versus PCIAP content.

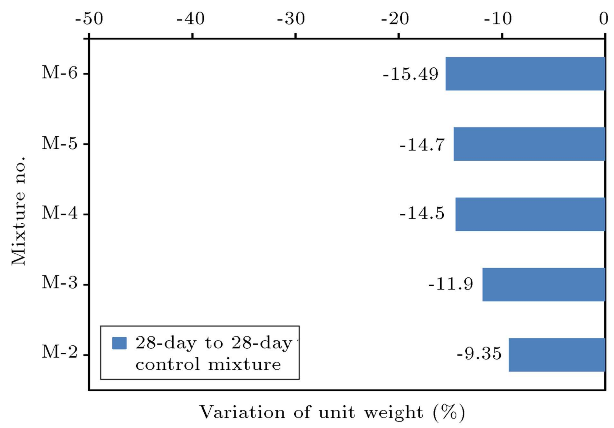

Figure 13. A comparison of unit weight variation.

indicated that concrete mixtures made with PCIAP were lighter than control mixture. According to ACI 213R-87 [51], structural LWAC has a maximum air-dry unit weight of 1900 kg/m^3 at 28 days (see Figure 12). Unit weights of concrete mixture with the inclusion of PCIAP were higher than the ACI code allowable limits, but were lower than normal concrete.

4. Conclusions

The following conclusions can be drawn based on the present investigation:

1. Compressive strength, flexural strength, and unit weight of concrete mixtures decreased with the increase in PCIAP contents in comparison with control mixture;
2. In splitting-tensile strength, the 5% amount of replacement of PCIAP could be the optimum percentage of the PCIAP. The mixtures containing more than 5% PCIAP had splitting-tensile strength lower than the control mixture;
3. By modulus of elasticity assessment, it can be concluded that 10% replacement of PCIAP is the optimum percentage;
4. Water absorption, fluidity, and slump value of the fresh concrete were boosted in PCIAP-containing mixtures;
5. The test results proved that 5% PCIAP can be used as cement substitution in concrete which was lighter than normal concrete and heavier than structural LWAC. Also, the compressive strength was higher than ACI 213R-87 estimated compressive strength value for 28-day age;
6. Using PCIAP as cement substitution in concrete resulted in the process of S/S and neutralization to eliminate the adverse environmental impacts;
7. It can be inferred from the results that concrete mixture containing 5% PCIAP has many benefits, such as reduction in contaminations of cement production, dead loads, energy consumption; the reduction occurs using the natural resources for cement production and costs elimination of treatment, burial, and transportation of PCIAP.

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