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Engineering Performance Evaluation of Mortar with EOS (Electric arc furnace Oxidizing Slag) as fine aggregate

Seung Jun Kwon [1], Han-Seung Lee[2], Hee-Seob Lim[1*],

[1] *Department of Civil Engineering, Hannam University, Daejeon, Korea*

[2] *Department of Architecture, Hanyang University, Ansan, Gyeonggi-do, Korea*

Abstract

Recently many researches of EOS (Electric Arc Furnace Oxidizing Slag) on application to construction industry have been carried out with increasing its production and limited reclamation site. EOS can be used as a fine aggregate for construction material, however, its engineering properties vary with the manufacturing process and producing district, causing a quality differences in material performance. In the work, EOS is obtained from steel manufacturing plants in South Korea and the engineering properties are evaluated for EOS and the cement mortar with EOS, respectively. From the tests, EOS is mainly made up of CaO, SiO_2, and FeO with 18.2% of larnite which has a crystal structure of β-C_2S with similar cement mineral. EOS mortar shows an increasing compressive strength with more EOS content, which is affected by a considerable amount of larnite (β-C2S) in EOS. The EOS based mortar with ERS (Electric Arc Furnace Reduction Slag) shows unsatisfactory results over the criteria for rate of change, which implies that more consideration must be taken for the usage of the mixed ERS and EOS for cement mortar due to swelling effect of ERS on dimensional stability.

Keywords: Steel slag, EOS (Electric Arc Furnace Oxidizing Slag), ERS (Electric Arc Furnace Reduction Slag), Cement mortar, Length change rate

1. Introduction

Steel production has increased continuously over the years with industrial developments. In 2009, global steel production was reported to be 1.25 billion tons, but increased to 1.6 billion tons in 2015 [1]. As of 2015, Korea was producing 70 million tons of steel annually, ranking the 5th in the world for steel production and the 1st for steel product consumption per person. Typically, approximately 130~300 kg of slag is produced for every 1 ton of steel [2] so that more than 400 million tons of steel slag is produced globally, with Korea accounting for approximately 24 million tons. Blast furnace slag, a high value construction material, has been efficiently utilized through recycling of byproduct but still used for road asphalt, embankments, and simple reclamation due to unstable substances. These include free CaO and MgO, which cause volume expansion in cementitious material. In the previous researches, EOS (Electric Arc Furnace Oxidizing Slag) was reported to contain smaller amounts of these unstable materials [3] and used for aggregates for road construction in some countries [4].

Further, many studies are being performed for a feasible use of EOS as a fine aggregate for concrete with shortages of natural aggregates. It was evaluated that the addition of EOS to concrete showed an increase in strength of concrete [5–7] but was still pointed out that the particle grading of EOS as a fine aggregate is uneven due to the crushing process employed during EOS production [8]. The researches on durability evaluation were also performed for EOS concrete, which showed improved durability performance compared to normal concrete [9–11]. In the previous works, chloride penetration tests performed on EOS concrete and improved resistance to chloride ingress was evaluated [12]. The fundamental studies on physical and chemical characteristics of EOS were investigated considering production processes as well [13], indicating that the quality of concrete or mortar with EOS varies with used EOS which has different engineering properties with treat process and product region.

In the present work, the physical and chemical properties of EOS from South Korea are investigated firstly, and the engineering properties in cement mortar containing EOS for fine aggregate are evaluated with several tests like compressive strength, pore characteristics, and length change measurements. Its applicable feasibility to construction material is discussed with evaluation of engineering properties.

2. Fundamnental properties of EOS as fine aggregate for construction material

2.1 Electric furnace slag

Electric furnace slag is an industrial by-product which is produced during the smelting process of scrap iron using electricity for molten steel. It can be categorized into two classes, oxidizing and reducing slag, depending on how the impurities are removed during the steel production, resulting furnace oxidizing slag-EOS and electric arc furnace reduction slag-ERS, respectively. When electric furnace slag is produced, small amounts of free CaO and free MgO are generated in the form of unstable products and these can cause cracks in concrete when incorporated into concrete [14]. EOS has a large content of Fe but contains small amounts of unstable by-products. Hence, it has significant potential for use as a concrete material. On the other hand, ERS has a higher concentration of unstable by-products, which makes its limitedly application to construction material. In the open-air storage yard, EOS is often mixed with ERS and this make quality control of EOS difficult.

2.2 Korean Industrial Standard (KS) F 4571 [15]

In 2007, Korean Industrial Standards (KS) specifications were proposed for the use of EOS as a fine aggregate for concrete. These specifications were amended in 2012 for including the use of EOS as a coarse aggregate but it has been used very limitedly due to high transportation costs since EOS has been mainly produced in limited locations in Korea. Table 1 lists the physical properties and chemical compositions for EOS in the KS specification.

Table 1. Chemical composition of EOS per KS F 4571 specification

Parameter		Value
Chemical constituent	CaO	Concentration not more than 40.0%
	MgO	Concentration not more than 10.0%
	FeO	Concentration not more than 50.0%
	Basicity	Not more than 2.0
Absorption (%)		Not more than 2.0
Density (kg/cm^3)		3.1~4.5

3. Experimrntal program for EOS aggregate

3.1 Evaluation of EOS properties as fine aggregate

EOS samples were obtained from steel companies (region-Dangjin, H company), and their properties were evaluated for use feasibility as a fine aggregate. The tests included sieve analysis test referred to KS F 2502 [16], and density/ absorption rate test in KS F 2504[17]. They are adopted to determine the physical properties of EOS samples. In addition, pH measurements and X-ray diffraction (XRD) analysis were performed to evaluate the chemical properties of EOS samples.

3.2 Evaluation of mortar mixed with EOS aggregate

3.2.1 Outline of test program for cement mortar with EOS and ERS

Cement mortar was prepared using EOS aggregate. Table 2 lists the mixing proportions in accordance with the KS L ISO 679 standard [18]. For the samples of EOS mortar test, EOS content was set as 0%, 50%, and 100%. In addition, MIP (Mercury Intrusion Porosimetry) test was performed for pore distribution evaluation on the mortar samples. For the compressive strength evaluation, the test specimens with 40× 40 × 160 mm were prepared. The pore characteristics and strength were evaluated at 3 days, 7 days, and 28 days.

Rate of length change tests were also performed on for cement mortar with EOS and ERS. Free CaO amount in binder plays an important role in volume swelling, so that CaO measurement was carried out. In table 2, mixing proportions for cement mortar were listed with several replacement ratios of EOS and ERS.

Table 2. Mixing proportions used to produce mortar samples

	W/C (%)	Unit weight (kg/cm^3)				
		Cement	Water	Sand	EOS	ERS
OPC				1350	-	-
EOS50				675	908.5	-

EOS100	50	450	225	-	1,817	-
EOS9/ERS1				-	1635	182
EOS8/ERS2				-	1453	364

EOS50: 50% EOS is used as the fine aggregate, with the remaining 50% being sand.

EOS100: 100% EOS is used as the fine aggregate.

EOS9/ERS1: 90% EOS and 10% ERS are used as the fine aggregate.

EOS8/ERS2: 80% EOS and 20% ERS are used as the fine aggregate.

3.2.2 MIP measurements

MIP was used to measure pore distribution and porosity in the hardened mortar samples. The measurements were performed using a Micromeritics Auto Pore IV 9505 analyzer at a maximum pressure of 33,000 psi (228 MPa). The test particles were extracted from the center of the test mortar specimen. This particle size was approximately 5 mm and subsequently immersed in an acetone solution for 24 hours, then dried for 2 hours before measurement.

3.2.3 Rate of length change test

The test for length change was performed referred to KS L 5107 [19] which covers sample preparation and determination of the volume change due to CaO and MgO in the sample. The expandability of the EOS mortar evaluated by replacing EOS with ERS from 10% and 20.0%, which contains swelling components as listed in Table 1. The test sample with dimensions of 25.4 × 25.4 × 254 mm was cut and cured for 24 hours at 20 °C. The initial length of the test sample was measured, then it was placed in autoclave and the temperature of the autoclave was elevated to the state that the steam pressure reached 2 ± 0.07 MPa after 45~75 min. The heat was turned off after 3 hours, once the pressure had reached 2 ± 0.07 MPa. After 90 min, the autoclave was allowed to cool, so that the pressure decreased to less than 0.07 MPa. The ventilation valve was opened for decreasing the inside pressure to atmospheric pressure. Next the test piece was immediately immersed in water heated to over 90 °C , then cold water was added around the test sample and it was cooled at 23 °C for 15 min. After its surface was dried, the length was measured. The process was repeated after 12 , 24 , 36 , and 48 hours to determine the rate of length change.

3.2.4 Measurement of free CaO content

The ethylene glycol method defined in ASTM STP 985 [20] was used to measure the free CaO content in EOS sample. The ethylene glycol method can quickly and quantitatively analyze small amounts of free CaO in cement, so that it has been widely adopted in the previous researches [21, 22]. For the test, a sample was first extracted based on the KS F 2501 (aggregate sample extraction method) [23]. The sample was dried for 1 hour in a dryer at 80 °C and crushed in a disk mill for powder type with 100 μm. In the case of the ethylene glycol method, the mixing rate must be adjusted based on the concentrations of the materials, that is to say, test sample should be 1 g if the free CaO content is within 3%. First, 1 g of the sample was extracted considering the free CaO content in each material. The sample was then placed in a 100-mL Erlenmeyer flask, and 50 mL of ethylene glycol was added. The sample was mixed with the ethylene glycol for 30 minutes using a water bath heated to 60 °C. The treated sample was then suction-filtered using two sheets of No. 5B filter paper in a Buchner funnel, and the sample remaining in the flask was washed using 30 mL of ethylene glycol. The filtrate was placed in an absorbent Erlenmeyer flask, and approximately 2~3 drops of Bromocresol green solution were added. Subsequently, a standard N/10-HCl solution was added to the flask, and the free CaO content was determined based on the consumption rate of the solution.

4. Results and discussion

4.1 Evaluation of EOS properties

4.1.1 Physical properties and chemical composition

Figure 1 shows the particle distribution curves of the EOS and washed sand samples used in the present work. Table 3 and Table 4 show the physical and chemical (XRF measurement result) properties of the materials used, respectively. The FMs (Fineness Modulus) of the EOS and washed sand samples were evaluated to 2.71 and 2.76, respectively, which shows similar level of FM. Their chemical compositions vary considerably. The main components of EOS are CaO (26.1%) and Fe_2O_3 (36.8%) and its density is 3.58 kg/cm^3. On the other hand, the primary component of the washed sand sample was SiO_2 (86.2%) with 2.59 kg/cm^3 of density.

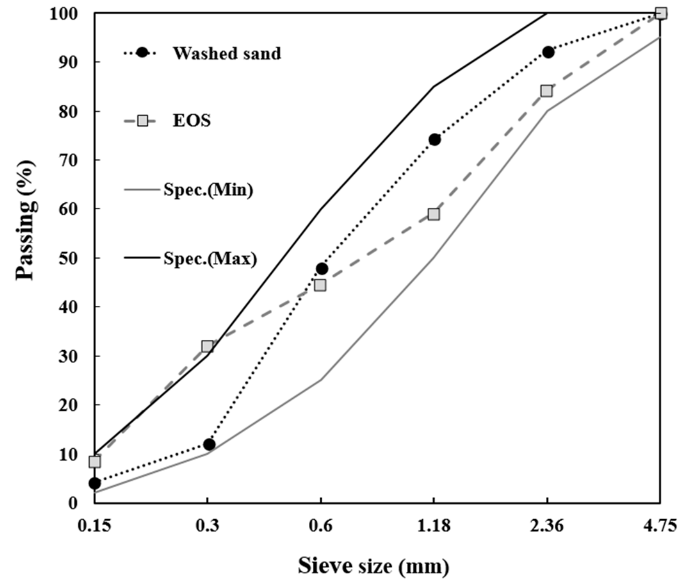


Fig. 1 Grading curves for fine aggregates used in the present study.

Table 3. Physical properties of fine aggregates used in the present study

Parameter		Washed sand	EOS
Density (kg/cm^3)	KS F 2504	2.59	3.58
Fineness modulus	KS F 2502	2.76	2.71
Absorption (%)	KS F 2504	1.56	1.72

Table 4. Chemical compositions of cement, EOS, and washed sand samples (%)

	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	MnO	Other
Cement	62.6	21.9	4.8	2.6	3.4	-	4.7
EOS	26.1	15.5	11.9	3.4	36.8	6	0.3
Sand	0.5	86.2	5.8	0.2	0.5	-	6.8

4.1.2 pH measurements

To determine the rate of change in pH with addition of EOS and washed sand, 10 g of each material was mixed with 20 mL of distilled water, and a pH meter was used to measure the initial pH value. The mixture was then stirred at 100 rpm at 20 °C and pH was measured after 30 minutes, 1 hour, 2 hour, and 3 hours. Figure 2 shows the stirrer used for the pH measurements and the results of the pH measurements for the EOS and washed sand samples are shown in Figure 3. It is observed that, in the EOS sample, the pH increases from 6.7 to 10.1 after 30 min. of stirring with almost constant pH thereafter. On the other hand, in the washed sand, the pH increases slightly after 30 min. and keeps constant to 3 hours. EOS sample is highly alkaline due to the presence of soluble calcium salts which can emit Ca^+ ions in solution.

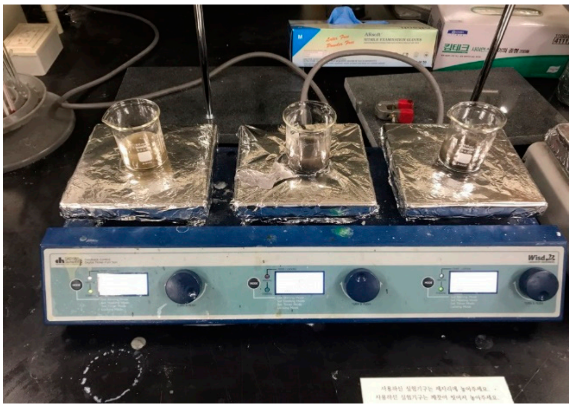


Fig. 2. Experimental setup with magnetic stirrer

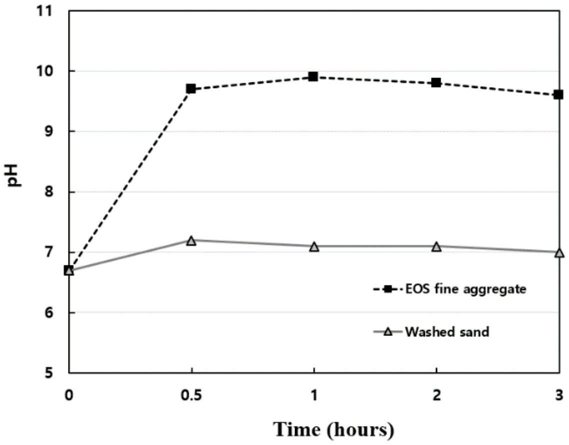


Fig. 3. Results of pH measurement

4.1.3 XRD analysis results

Figure 4 shows the XRD analysis results for the EOS sample. It is found that the EOS sample contains 30.2 % of monticellite ($MgCa(SiO_2)$), 23.9% of magnesium iron aluminum oxide, 21.8% of wustite (FeO), 18,2% of larnite ($Ca_2(SiO_4)$), 3.3% of quartz (SiO_2), and 2.5% of hercynite ($AlFeO_4$). Its main components are CaO, SiO_2, and FeO, with a large amount of larnite, which has the crystal structure of β-C_2S, the main mineral of cement, also being present.

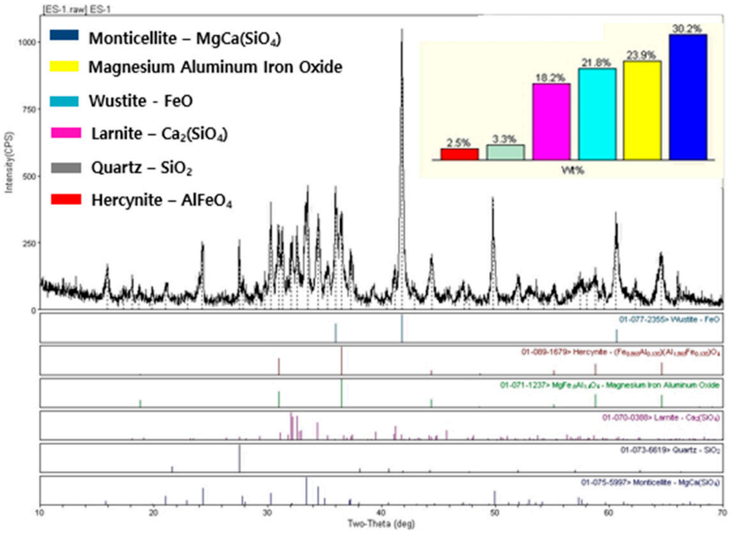


Fig. 4. Results of XRD analysis of EOS sample.

4.2 Evaluation of mortar with EOS

4.2.1 Compression strength

Figure 5 shows the compression strength test results of mortar with different EOS contents with ages. As the amount of EOS increases, the compression strength also increases. The strength of OPC at 28 days is 59 MPa, while that of EOS50 is 62 MPa and that of EOS100 is 66 MPa. It shows that the strength of EOS50 is approximately 5 MPa higher than that of OPC at 3 days, 3 MPa higher at 7 days, and 2 MPa higher at 28 days. In the comparison with EOS100, the strength of EOS100 was 8 MPa higher than that of OPC at 3 and 7 days, and 7 MPa higher at

28 days.

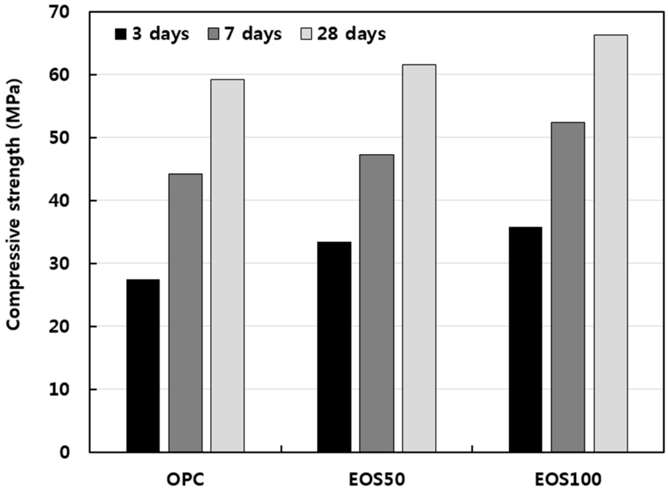
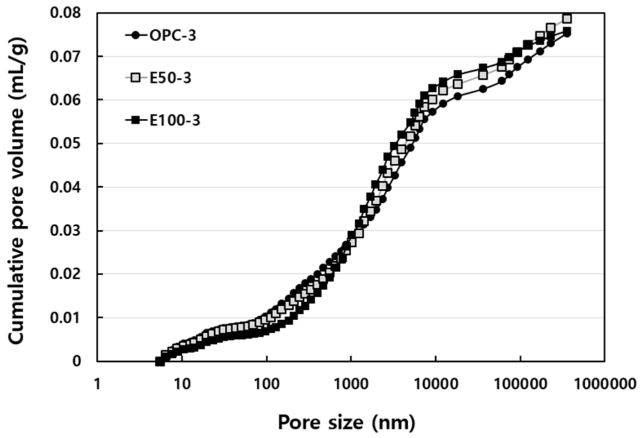


Fig. 5 Compressive strengths of mortar samples.

4.2.2 MIP measurements

Figures 6, 7, and 8 show the cumulative pore volumes of the mortar samples with ages. Usually the cumulative pore volume decreases with aging due to hydration. EOS50 has a higher pore volume at 3 days than OPC, however, it was lower than that of OPC after 7 days. EOS100 exhibits a low cumulative pore volume overall, which shows porosity decreases with an increase in the EOS content. Figure 9 compares the cumulative pore volume and compression strength in mortar samples. The decrease in the cumulative pore volume is evaluated with increasing compression strength, which is typical relationship between porosity and strength development.



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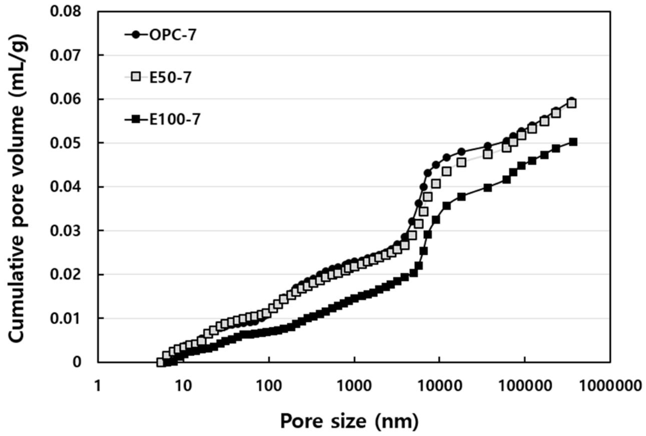
205 Fig 6. MIP results at 3 days.



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207 Fig 7. MIPs results at 7 days.

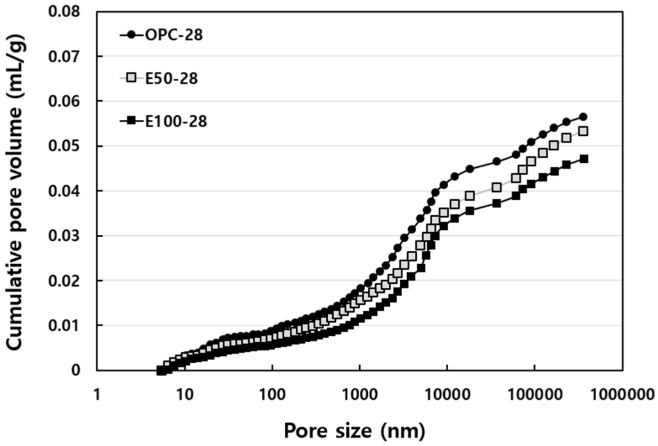

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Fig 8. MIP results at 28 days.

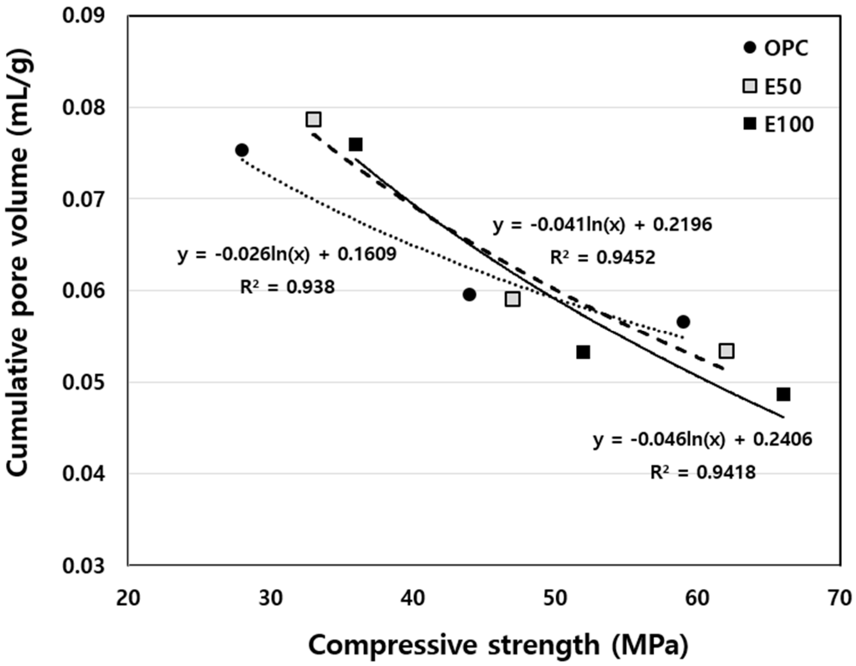

Fig. 9. Relationship between cumulative pore volume and compressive strength.

4.2.3 Rate of length change

Figure 10 shows the results of the rate of length change measurements for mortar. The rate of length change for OPC and EOS is measured to be less than 0.1%, which shows satisfactory results with the requirements in the KS Specification. While the rates of length change for EOS9/ERS1 and EOS8/ERS2 at 24 hours satisfy the standard, those after 36 hours are greater than 0.1% of expansion. The expansion increases with increasing ERS amount. It is thought that the excessive expansion is attributable to the free CaO present in ERS. In Table 5, the basicity (CaO/SiO_2) and free CaO content are summarized. The amount of free CaO in EOS is 0.491%, while it increases to 0.560% and 0.700% in EOS9/ERS1 and EOS8/ERS2, respectively. The basicity is approximately 3.08 for ERS, 2.08 for EOS9/ERS1, and 2.36 for

EOS8/ERS2. In the mixed conditions (EOS9:ERS1, EOS8:ERS2), the basicity results does not meet with the requirement in KS standard which is below 2.0. The free CaO content which causes swelling has a critical effect on the rate of length change.

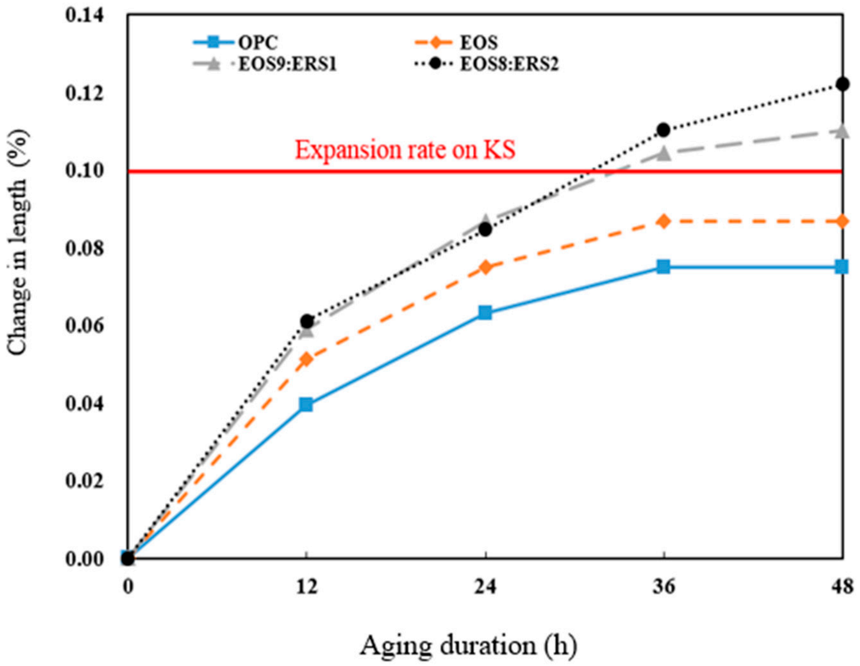

Fig. 10. Results of rate of length change measurements for mortar when using autoclave.

Table 5. Results of basicity and free CaO content measurements.

Sample	CaO/SiO_2	Free CaO
EOS	1.68	0.491
ERS	3.08	1.738
EOS9/ERS1	2.08	0.560
EOS8/ERS2	2.36	0.700

5. Conclusions

In the work, the engineering performance in EOS and cement mortar containing EOS is evaluated for utilization as fine aggregate. The conclusions on the study can be summarized as follows:

1. The XRD analysis of EOS sample shows that its primary components are CaO, SiO_2, and FeO. It also contains 18.2% larnite, which has a crystal structure of β-C_2S with similar mineral of cement. Moreover, pH measurement shows that EOS sample has high-alkality. This provides a soluble calcium salts causing a large number of Ca^+ ions given the chemical properties of the EOS.

2. For cement mortar with EOS, the tests on compressive strength and porosity are performed. It reveals that cumulative pore volume decreases and the compressive strength increases as more addition of EOS as the fine aggregate. The changes in the compression strength and cumulative pore volume vary with ages. EOS contains a greater proportion of fine particles than sand, which can be the reason for the lower porosity due to packing effect. The change in the compressive strength with ages in the EOS mortar is much affected by the large amount of larnite (β-C_2S) present in the EOS.

3. The mortars with EOS and washed sand as their fine aggregates satisfy the rate of length change requirement below 0.1% in the KS Specification. However, all the results from the mortar containing ERS show higher changing rate over 0.1% after 36 hours. The expansion of the samples is attributed to the free CaO present in ERS. The free CaO contents of the EOS9/ERS1 and EOS8/ERS2 mortars are 0.56% and 0.70% respectively, while their basicity values (CaO/SiO_2) are 2.09 and 2.36, respectively. The values fall outside 2.0 of the acceptable limits in the KS specifications. The results

suggest that more consideration must be taken for the usage of mixed ERS and EOS as a fine aggregate.

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