Feasibility Study of Precoated Binder-Type Electric Arc Furnace Oxidizing Slags as Aggregates for Cement Mortar

Wei-Ting Lin, Andīna Sprince, Marek Hebda, Gábor Mucsi, An Cheng, and Huang-Hsing Pan

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1 Introduction

Cement and civil engineering industry is a critical infrastructure industry. With the goal of net-zero carbon emissions, research issues such as using aggregates and carbon emissions from cement are complex and urgent industry transformation

W.-T. Lin (✉) · A. Cheng
Department of Civil Engineering, National Ilan University, Yilan, Taiwan
e-mail: wtlin@niu.edu.tw

A. Sprince
Institute of Civil Engineering, Faculty of Civil and Mechanical Engineering, Riga Technical University, Riga, Latvia

M. Hebda
Department of Materials Engineering, Faculty of Materials Engineering and Physics, Cracow University of Technology, Kraków, Poland

G. Mucsi
Institute of Raw Materials Preparation and Environmental Technologies, University of Miskolc, Miskolc, Hungary

H.-H. Pan
Department of Civil Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan

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challenges. The cement and concrete industry is now the world's largest producer of carbon emissions. To achieve the goal of net zero carbon emissions by 2050, researchers, engineers, and the industry have invested heavily in research and development of materials and equipment and other strategies to reduce carbon emissions and indirectly reduce the payments of carbon tax [1, 2]. As the global steel industry has continued to flourish in recent years, steel has become an indispensable and significant industrial material. In particular, the increased demand in engineering fields, such as high-rise buildings and bridges, has strengthened the utilization of steel materials. Recycled steel waste has increased as reinforced steel and steel materials have been produced at higher rates [3, 4]. Over the past few years, electric arc furnace oxidizing slag (EAFOS) has become the primary recycling material due to the recycling industry's requirements. For a long time, EAFOS reuse has troubled the relevant engineering units. The industry strongly advocates that resources should be recycled and reused, and how to use EAFOS is the research focus at this stage [5, 6]. The EAFOS waste was a typical solid waste with high iron content and hardness, making it unsuitable for grinding into powder for reuse. Reprocessing EAFOS also led to high production costs. This treatment option contributed significantly to alleviating the shortage of natural aggregates by using crushed EAFOS as a direct substitute for aggregates [7, 8]. However, using EAFOS instead of natural aggregation has led to problems with expansion and cracks on the surface of the concrete because of the effect of free calcium oxide (f-CaO) or magnesium oxide (f-MgO) [9]. Therefore, the development of stabilization technology to replace natural aggregates with EAFOS is an essential task at this stage.

The use of EAFOS as aggregates was subject to the requirement of volume stability. In the past, alkali-activated technology was used as the test procedure for the stabilization of EAFOS [10, 11]. Although using such alkali-activation technology to reuse EAFOS was feasible, practical application required the addition of chemical agents, which also increased the cost. It was found in the literature that EAFOS should be able to be successfully used in cement mortars to replace fine aggregates in combination with other industrial by-products such as copper slag and coal bottom ash [12, 13]. Past studies have shown that recycled aggregates have the potential to be precoated to enhance recyclability and adaptability [14, 15]. The same precoated technology can be applied directly to EAFOS, verifying its feasibility and achieving EAFOS stabilization. In this study, EAFOS was selected as an industrial by-product to replace the natural aggregates and to improve the recycling efficiency of the waste. The paste mixing process provided EAFOS with a precoated layer of cement, ground granulated blast furnace slag (GGBS), or fly ash. It verified the most suitable precoated material and the best aggregate replacement ratio for precoated EAFOS. The volumetric stability of the precoated EAFOS mortar has also been continuously verified to verify the stabilizing effect of this solution on EAFOS particles.

2 Test Programs

2.1 Materials

The precoated materials used in this study consisted of Portland Type I cement, GGBS, and fly ash. The specific gravities of the three precoated materials were 3.15, 2.88, and 2.72, respectively. The fineness of the three precoated materials was 3690 cm^2/g, 5850 cm^2/g, and 10,500 cm^2/g, respectively. EAFOS was sourced from Tung Ho Steel Enterprise Corporation in Taiwan. EAFOS conducted tests in the range of fine aggregate gradations to replace the natural aggregates in the mortar specimens. EAFOS had a modulus of fineness of 3.90, water absorption of 3.80%, and a specific gravity of 3.60. Results of the EAFOS sieve analysis tests are shown in Fig. 1. It was found that EAFOS aggregates were significantly coarser than fine aggregates, and their grading curves deviated from ASTM requirements. Subsequent tests were performed to improve the particle size distribution of EAFOS using paste-precoated technology.

2.2 Paste-Precoated Method

Three types of binders (cement, GGBS, and fly ash) were used as paste-precoated materials in this test. Different water-to-binder ratios (w/b) were used as variables. The test procedure was to mix the paste-precoated materials into a paste specimen at a specified w/b. And the next procedure was to mix the paste with EAFOS using a mixer for 5 min to perform the subsequent procedures. The precoated EAFOS was then allowed to cure in the air for 7 days and tested by sieve analysis. The test procedure is to set the No. 4 (4.75 mm) sieve passing rate to 85% of the paste-precoated group, which was regarded as the test group that met the requirements. The test variables included two parameters, namely the amount of paste-precoated (20%, 25%, 30%, 35%, and 40%) and w/b (0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50).

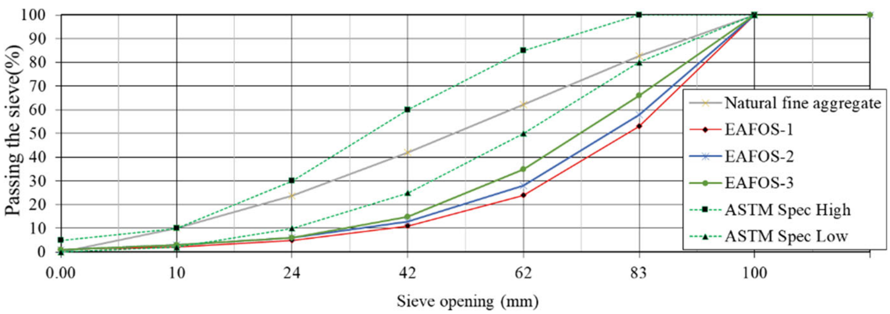

Fig. 1 Results of the EAFOS sieve analysis tests

Table 1 Mix design of control group (kg/m^3)

Water	Cement	Fine aggregates
288.1	523.8	1440.5

2.3 Mix Design

The mix design for the control group is shown in Table 1, and the w/b was fixed at 0.55. EAFOS was used to replace 10–50% of fine aggregates in 10% increments. The ratio of cement to aggregates was 1:2.75.

2.4 Testing Methods

The sieve analysis of natural fine aggregates and EAFOS particles was carried out according to ASTM C136 specification. The specific gravity and water absorption of natural fine aggregates and EAFOS particles were tested with reference to the ASTM C128 specification. The compressive strength tests of mortar specimens were conducted by referring to ASTM C109. The specimen size for compressive strength was 50 × 50 × 50 mm. The dry shrinkage tests of mortar were conducted with reference to ASTM C596, and the size of the specimen was 25 × 25 × 285 mm. The measurement of length change was mainly based on the observed value on the first day as the zero point (reference point), and the measurement values for each age were the observed values. Scanning electron microscope (SEM) observations were conducted in accordance with the recommended procedures of the ASTM C1723 specification. The specimens were selected after compressive strength tests from broken specimen fragments (size less than 3 × 3 × 10 mm).

3 Results and Discussion

3.1 Precoated Properties of EAFOS Particles

EAFOS was mixed with three types of binder using the paste precoated technique and cured for 7 days, and the test groups that passed 85% through a No. 4 sieve (4.75 mm) are listed below. For the cement group, the passing percentages were 83%, 89%, and 86% for the precoated EAFOS with a paste amount of 30% and w/b of 0.35, 0.30, and 0.25, respectively. Aggregates with 35% and 40% paste content showed a less than 15% passing percentage. This means that the EAFOS particles in the fine grades have jumped to the coarse grades due to excessive precoated pastes. For the GGBS group, the passing percentages were 86% and 87% for the precoated EAFOS with a paste amount of 30% and w/b of 0.35 and 0.30, respectively. The same trend was observed in the GGBS group. When the amount of precoated was

Table 2 Specific gravity and water absorption of different types of precoated EAFOS

Indicators	Precoated EAFOS					
	–	Cement	GGBS	GGBS	Fly ash	Fly ash
Parameters for w/b and precoated amount	–	0.35	0.35	0.30	0.40	0.35
	–	30%	30%	30%	40%	40%
Specific gravity	3.60	3.30	3.20	3.28	3.29	3.25
Absorption (%)	3.80	8.80	7.53	4.82	3.39	3.01

20% and 25%, although its passing percentage met the requirement of more than 85%. It can be observed from the external observation of the precoated EAFOS particles that there is insufficient precoated paste. For the fly ash group, the passing percentages were 92% and 92% for the precoated EAFOS with a paste amount of 40% and w/b of 0.40 and 0.45, respectively. Insufficient precoated pastes were also observed in groups with less than 35% precoated content. From the relevant studies, it can be found that these surface coatings were beneficial to forming surface hydration layers on the EAFOS particles to achieve the effect of particle stabilization [16, 17].

Table 2 summarizes the specific gravity and water absorption of EAFOS particles, cement-precoated, fly ash-precoated, and GGBS-precoated EAFOS (curing at room temperature for 7 days). The lower specific gravity of the coated particles compared to the EAFOS particles demonstrates the lower weight for the same volume. The GGBS and fly ash precoated group had a lower specific gravity than the cement group (cement had a higher specific gravity of 3.15 compared to the two binders). In addition, the water absorption of the coated particles was higher than that of the original EAFOS particles. The cement group had the highest water absorption. On the contrary, the GGBS and fly ash groups showed significantly lower water absorption than the cement group. It was evident that the pozzolanic reaction led to an increase in compactness and a decrease in water absorption. Such a trend is consistent with the findings of previous studies [18, 19].

3.2 Compressive Strength

Development curves of EAFOS utilization against compressive strengths for non-precoated group are shown in Fig. 2. The compressive strength was negatively affected by EAFOS doping without paste precoated, and the strength began to decrease significantly at 40% replacement. In addition to being coarser than natural fine aggregates, EAFOS aggregates are distributed in approximate section grades. Large amounts of EAFOS resulted in grain size grades deviating from ASTM specifications. This significantly reduced the strength of the mortar. For the cement-precoated group, a precoated amount of 30% with a w/b of 0.35 was used as a parameter. The development of compressive strength with the corresponding

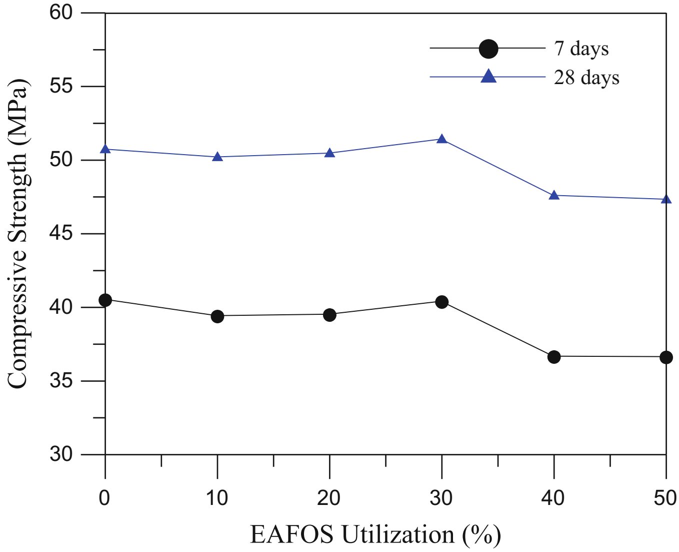

Fig. 2 Development of EAFOS utilization against compressive strengths (non-precoated)

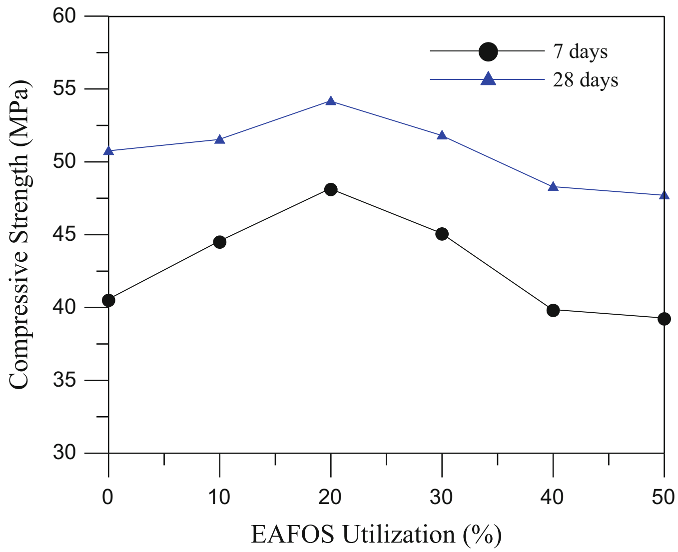

Fig. 3 Development of EAFOS utilization against compressive strengths (cement-precoated)

EAFOS replacement is shown in Fig. 3. Cement-precoated specimens increased their compressive strength, with the maximum compression strength of 20% EAFOS being substituted. Compressive strength has also increased significantly with the

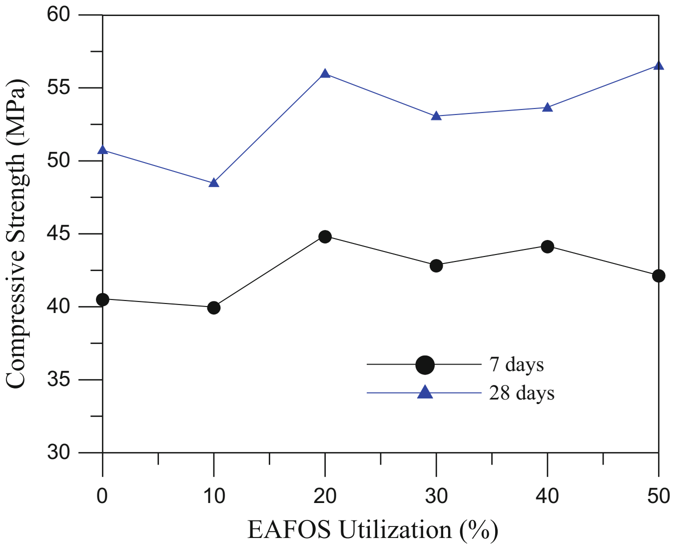

Fig. 4 Development of EAFOS utilization against compressive strengths (GGBS-precoated)

increase in EAFOS replacement. It is clear that the paste-precoated technology contributed to the improved suitability of EAFOS aggregates. Prior to the production of mortar specimens, the paste precoated EAFOS aggregates were allowed to cure for 7 days. To further increase the strength of the specimens, it is recommended to increase the curing time to 28 days.

For the GGBS-precoated group, a precoated amount of 30% with a w/b of 0.30 was used as a parameter. The development of compressive strength with the corresponding EAFOS replacement is shown in Fig. 4. GGBS was slightly more potent than the cement group, and the optimum substitution was also 20%. The maximum strength of the GGBS group (20% EAFOS) was up to 55.92 MPa. Under the same curing conditions, GGBS had a better pozzolanic reaction and a better interfacial transition zone between aggregates and pastes. There was an improvement in the compactness of the paste and an increase in strength [16]. For the fly ash-precoated group, a precoated amount of 40% with a w/b of 0.35 was used as a parameter. The development of compressive strength with the corresponding EAFOS replacement is shown in Fig. 5. Because of the high fluidity of fly ash, a precoated amount of 40% was required. The fly ash-coated specimens were not significantly stronger due to the long curing times required for fly ash to develop the reactive properties required for pozzolanic materials. The maximum strength (47.97 MPa) of the fly ash-precoated specimens was achieved with 30% EAFOS replacement. In conclusion, coated EAFOS particles helped to increase the compressive strength of the mortar. GGBS as paste-precoated materials provided superior compressive strength. Compared to previous findings [8, 20], such paste-

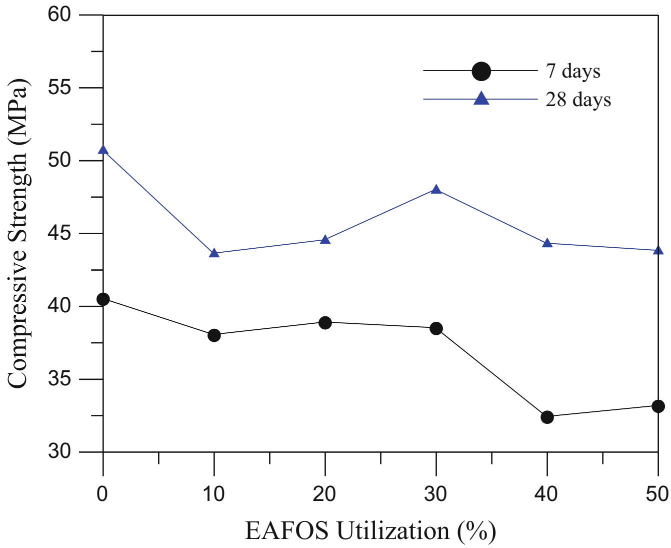

Fig. 5 Development of EAFOS utilization against compressive strengths (fly ash-precoated)

precoated technology provided an effective solution for replacing aggregates with EAFOS and offered superior compressive strength and a cost-effective treatment process.

3.3 Length Variations

Length variations of mortar specimens with different precoated methods are illustrated in Fig. 6. The w/b of cement, GGBS, and fly ash paste-precoated materials were 0.35, 0.30, and 0.35, respectively, for 20% EAFOS replacement (based on better strength considerations). Observing the length variations within 28 days, it was found that the length variations of the paste-precoated materials were similar to those of the un-precoated specimens. The precoated method contributed to the control of the expansion behavior of the specimens. Compared with the results of compressive strength, the paste-coating method is favorable for increasing strength and utilization. This treatment solution contributed to the high-volume reuse of EAFOS and achieved industrial waste reuse efficiency. The appearance of the specimens immersed in 90-degree water for 28 days after demolding is shown in Fig. 7. From the appearance of the specimens, it can be found that there were no abnormalities such as cracking and swelling in the various proportions.

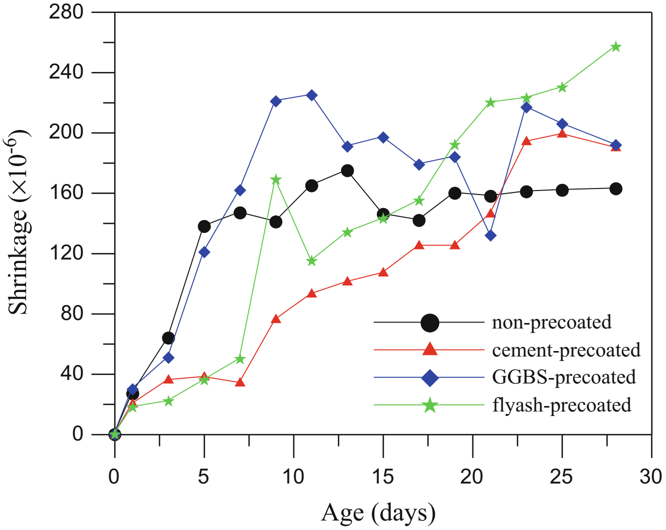

Fig. 6 Length variations of mortar specimens with different precoated methods

Fig. 7 Appearance of specimens immersed in water at 90° for 28 days

3.4 *SEM Observations*

SEM photographs of the three paste-precoated materials are shown in Figs. 8, 9, and 10. The w/b of cement paste-precoated materials was 0.35, GGBS paste-precoated materials was 0.30, and fly ash paste-precoated materials was 0.35. The replacement rate of EAFOS was fixed at 30%. Significant inter-crystalline gaps were found in the microstructure of cement paste-precoated materials. AFt and calcium hydroxide were also observed, and hydrates filled the remaining voids. The microstructure of

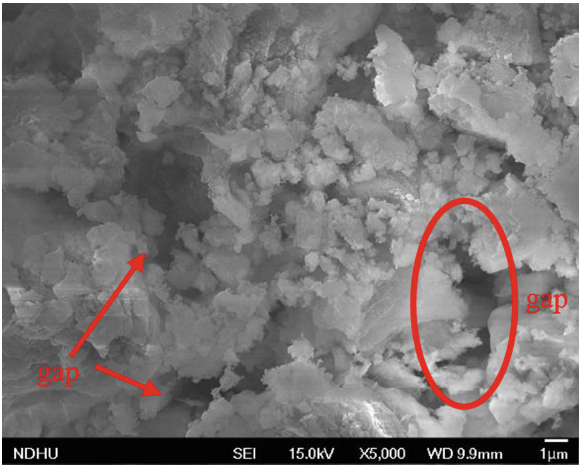

Fig. 8 SEM photo for cement-precoated specimen

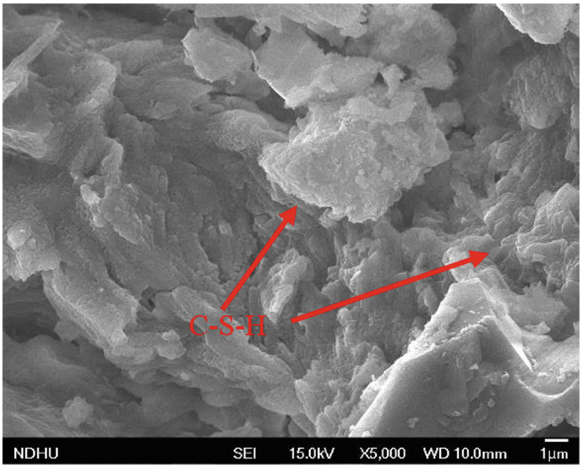

Fig. 9 SEM photo for GGBS-precoated specimen

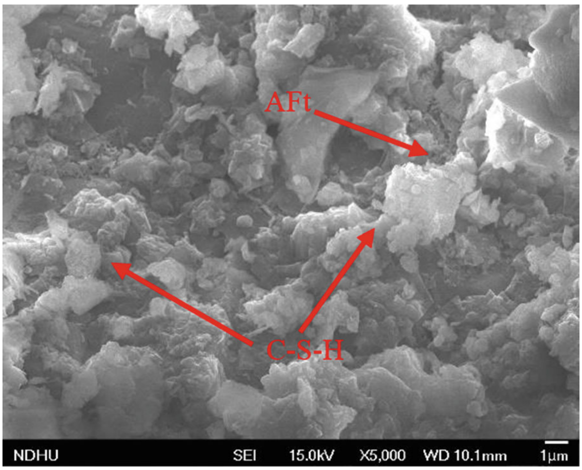

Fig. 10 SEM photo for fly ash-precoated specimen

GGBS paste-precoated materials had fewer pores than cement paste-precoated materials, the surface was significantly smoother and denser, and the amount of AFt and sodium hydroxide was reduced considerably. This is the main reason that GGBS paste-precoated materials possess better compressive strength than other compositions. The microstructure of the fly ash paste-precoated materials showed noticeable unreacted fly ash particles, AFt and calcium hydroxide, with smaller gaps between the crystals and a smoother surface. The surface had fine hydrates but required continuous curing to facilitate hydration reaction.

4 Conclusions

The results are summarized as follows:

1. The compressive strength of natural aggregates replaced by uncoated EAFOS in mortar specimens did not increase significantly with increasing amounts of aggregate. Strength began to deteriorate at 30% replacement.
2. The paste-precoated method benefited the compressive strength of EAFOS mortars, and the optimum replacement was between 20% and 30%. The precoated specimens also maintained excellent volume stability.
3. Among the three paste-precoated materials, GGBS-precoated showed the highest compressive strength (55.92 MPa at 20% EAFOS replacement).
4. The paste-precoated method should pay attention to the amount of precoated and the w/b of the binders; the optimal amount of precoated was 30–40%, and the w/b was 0.30 ~ 0.35.
5. This paste-precoated technology provided an effective solution for replacing aggregates with EAFOS and offered superior compressive strength and a cost-effective treatment process.

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