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Effects of Freeze-Thaw Action and Composition on Compression Strength of WFS-FA-EPS Fills

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ABSTRACT: A frost-resistant earth fill was proposed by mixing waste foundry sand (WFS), fly ash (FA), expandable polystyrene (EPS) beads, Portland cement and water in proportions, which was known as WFS-FA-EPS fill. This study examined the unconfined compressive strength (UCS) weakening susceptibility of a range of WFS-FA-EPS specimens prepared at designated compositions which were exposed to freeze-thaw (F-T) cycling from 20 ºC to −15 ºC and up to 5 times. It was found that the inclusion of EPS reduced the unit weight of the fill materials by 20-40%. The majority of UCS loss was found suffered in the first F-T impact. Cement component clearly enhanced the anti-frost capability of materials. Components of EPS and FA also improved the F-T resistance of materials. Water was the main factor leading to F-T impairment, and should be prudentially added into the mixture. Inclusion of EPS beads was able to mitigate the frost impact by the means of reducing UCS loss. The optimal contents were 1.08% for EPS bead and 30% for FA.

INTRODUCTION

In the past two decades, waste foundry sand (WFS) has been widely reused as beneficial construction materials in civil engineering domain, e.g., cement concrete (Naik et al. 2003), asphalt concrete (Bakis et al. 2006), highway embankment (Abichou et al. 2004), earth fills (Deng and Tikalsky 2008), and hydraulic barrier (Abichou et al. 2004). This study was another attempt exploring a WFS-based earth fill incorporating expanded polystyrene (EPS) beads, which were used to reduce the weight and enhance the frost resistance of the earth fill.

The proposed earth fill was a mixture of WFS, fly ash (FA), EPS beads, cement and water in proportions, known as WFS-FA-EPS fill, which hardened into a material with an unconfined compressive strength (UCS) comparable to that of general compacted backfills. Relative to its low unit weight, the fill can be choice of construction material for backfilling situations where reduction in overburdens or lateral pressures was required (Tsuchida et al., 2001; Yoonze et al., 2004). The next merit was the frost sustainability of the material. The EPS bead inclusion may behave as buffering media in the matrix to attenuate frost impact (Jumikis 1977). The last attractive merit of the fill material was probably the beneficial reuse of solid waste materials, i.e., WFS and FA, which were the base materials and saved the cost retrieving feed materials.

This study was conducted to investigate the gain and loss of UCS of WFS-FA-EPS fills in conjunction with frost action and mixture compositions, which, perhaps, was one of the most critical properties of a fill placed in seasonable frozen regions.

MATERIALS AND METHODS

Materials

WFS samples were retrieved from a casting facility which used clay-based system sand to cast ferrous vehicle engines. Fig. 1 plots the gradation curve of WFS samples. Table 1 shows the physical properties of WFS samples. WFS sample was classified under the Unified Soil Classification System as SP (poor-graded sand).

FA was sampled from an electricity power plant, which discarded FA in wet. The physical properties are presented in Table 1. The gradation curve of the FA sample is presented in Fig. 1, which led to a classification of SW (well-graded).

EPS bead is a super light polymer foam, pre-puffed from polystyrene resin. The beads are white, uniform and spherical, sizing between 2-4 mm. The bulk unit weight of the beads (including the voids between beads) is 0.14 kN/m^3, which is only about 1% of the unit weight of a typical soil. Portland cement was used as a binding material for the mixture. Tap water was used to activate cement hydration.

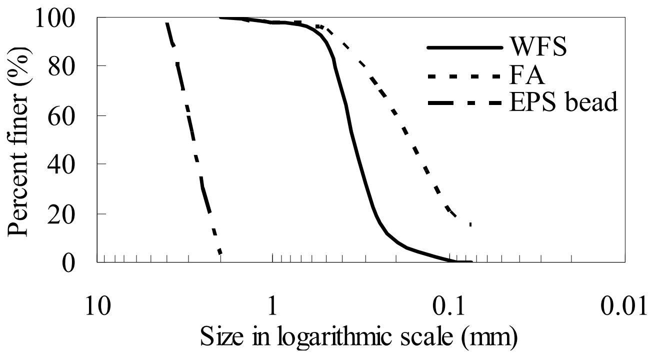

FIG. 1. Gradation curves of WFS, FA and EPS bead samples.

Table 1. Physical Properties of WFS, FA and EPS Beads Samples.

	Water Content (%)	Bulk Unit Weight (kN/m^3)	Specific Gravity	Dry Unit Weight (kN/m^3)		Void Ratio	
				Min.	Max.	Min.	Max.
WFS	1-5	12.5	2.50	12.6	15.8	0.59	0.99
FA	22.3	6.0	2.20	0.61	0.87	1.54	2.64
EPS	0	0.14	-	-	-	-	-

Testing Program

Thirteen series of WFS-FA-EPS mixtures (T1 to T13) were prepared in the laboratory. The mixing ratios are presented in Table 2. All composition were prescribed based on the dry weight of WFS component, and designated by varying the content of a single component, all other variable maintained constant. Water content was added based on the weight of the solid material in the matrix.

Table 2. Mixing Ratios of WFA-FA-WPS Mixtures.

Series	FA (%)	Cement (%)	EPS (%)	Water (%)	Unit Weight (kN/m^3)
T1-T3 and T6	30	6.15, 7.69, 11.54, 15.38	1.08	30	11.3-11.7
T4-T8	30	15.38	0, 0.62, 1.08, 1.54, 1.85	30	9.7-17.0
T6, T9 and T10	30	15.38	1.08	25, 30, 35	11.4-11.8
T6 and T11-T13	0, 13.04, 30, 52.94	15.38	1.08	30	11.2-12.3

A cylindrical specimen (50 mm in diameter and 100 mm in height) was prepared by using a steel tri-split mold, and cured in a chamber maintained at temperature of 20±2 ºC and relative humidity of 100%. UCS were tested on specimens cured through day 28, upon which the specimens were exposed to null, 1, 3 or 5 freeze-thaw (F-T) cycles.

F-T cycling was carried out by referring to the assembly and procedure specified in ASTM D5918-06. In this study, the freezing operation was configured as being unidirectional (upward), at fixed temperature (−15 °C at the bottom), at slow freezing rate (1.3 °C/h), being non-surcharged, and under (hydraulic) closed or open system.

A conventional strain rate controlled uniaxial compression apparatus was used to conduct UCS tests. The compression rate was 1.38 mm/min or 1.38% strain/min. The peak UCS value was observed. At least two specimens were prepared in each test.

RESULTS AND DICSUSSION

Unit Weight

The results of unit weight are summarized in Table 2. As expected, inclusion of EPS content decreased the unit weight of the mixture. For specimens prepared in series of T4-T8, every 1% inclusion of EPS content (up to 1.85%) led to 25-40% reduction in unit weight of the mixture, all other variable maintained constant. The minimum unit weight was 9.7 kN/m^3 for specimens prepared at EPS content of 1.85%. This was a significant improvement in terms of unit weight as the unit weight of a sandy soil was between 17-19 kN/m^3. Inclusion of FA content led to minor reduction in the unit weight of the mixture. A statistical regression data indicated that every 10% inclusion of FA content (up to 52.94%) led to 10-30% reduction in the unit weight of the mixture. Cement and water contents played marginal roles in affecting the unit weight.

Stress-Strain Relation

Fig. 2 presents the stress-strain relations of specimens prepared in series T10, cured through day 7 and 28, respectively, and exposed to null, one or three F-T cycles. The peak strength decreased if the specimens were exposed to F-T action. When the F-T action was conducted over 1 cycle, the strength decreased marginally (Fig. 2b), which indicated that the majority of strength loss due to repeated frost actions was suffered in the first F-T action. Following the first F-T action, the mixture would basically maintain post-action strength in the same order, or rarely lose clearly thereafter. Furthermore, the specimen exposed to 1 F-T cycle demonstrated similar stress-strain relation as the specimen exposed to 3 F-T cycles. It was thus presumed that the binding materials (e.g., cement hydrates) was impaired mainly in the first F-T action, and a minor impairment was suffered in the subsequent frost actions, if exposed. This indication would be further verified by additional test results in the next section.

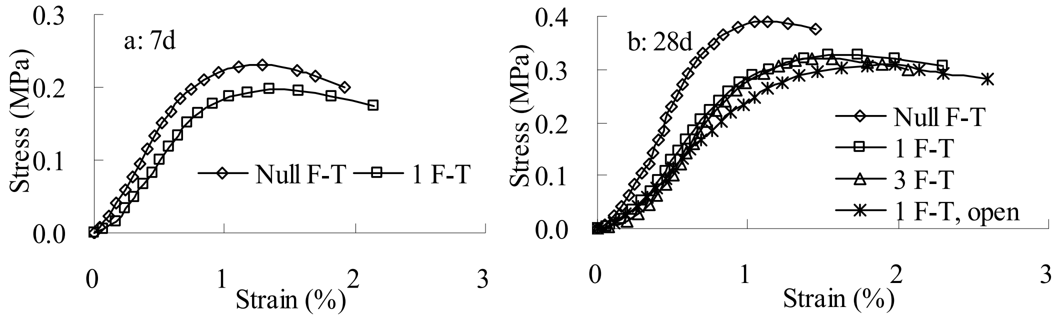

FIG. 2. Stress-strain relations before and after freeze-thaw (F-T) cycles.

The strain at the peak strength increased if the specimen was exposed to a F-T action, and the increase was clearer for the specimen cured through day 28 than that cured through day 7. The increase in strain could be due to the fissures resulted in F-T cycles. Freezing action converted water into ice, during which the mixture expanded, say by 10%. The additional volume took the form of numerous fissures in the mixture when thawing action reversed the conversion. Once loaded, these fissures led to the increase in strain. Fissures also led to initial tangent modulus decrease.

The stress-strain relation was further deteriorated for the specimen exposed to frost actions conducted under an open system (Fig. 2b). The strength parameters were moderately weakened. It was reasonable to interpret that the water migration led to such deterioration. Along with the freezing interface moving upward at a slow rate in the mixture during the freezing action, the water supply on the top had the tendency to migrate downward due to suction incurred by the thermal gradient (Jumikis 1977), which eventually increased the water content in the mixture. In this context, the F-T action impaired the matrix more than did under the closed system.

Effect of Cement Content

Fig. 3 shows the effect of cement content on the UCS of specimens prepared in series T1-T3 and T6, all other variable maintained constant. As expected, the increase of cement content led to a drastic increase in UCS. When the cement content ranges from 6.15% to 15.38%, the UCS gained from 0.12 MPa to 0.46 MPa, which fell within the UCS ranges of general compacted fills. Following the first F-T cycle, the UCS loss was 21.0%, 15.9%, 10.5% and 6.5 % for specimens prepared at cement content 6.15%, 7.69%, 11.54% and 15.38%, respectively. After 3 F-T cycles, the UCS loss increased marginally to 26.2%, 21.1%, 18.4% and 10.1%, respectively. The major UCS loss was suffered in the first F-T action out of 3 F-T cycles. That is, the binding materials (e.g., cement hydrates) were mainly impaired in the first F-T action, and the subsequent frost actions led to minor impairment of the fill materials.

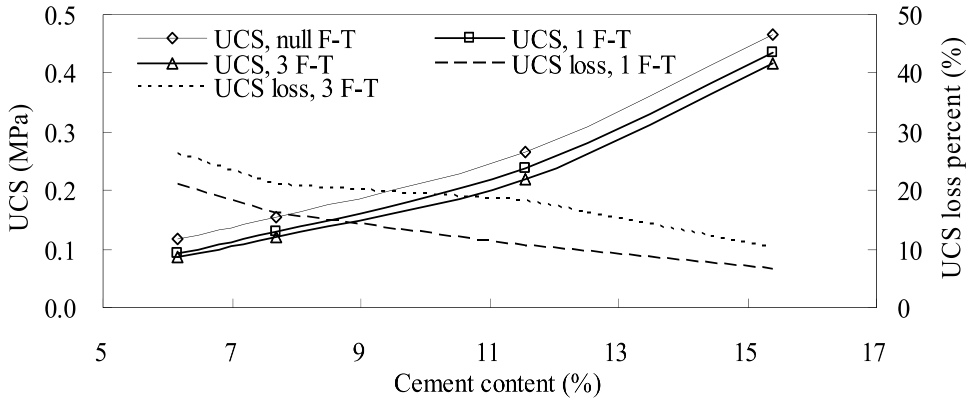

FIG. 3. UCS versus cement content.

The cement content also affected the UCS loss percentage, which estimated UCS loss due to F-T actions relative to the UCS of specimens without F-T exposures. The higher the cement content, the less the UCS loss percentage, and *vice versa*.

Effect of Expandable Polystyrene (EPS) Bead Content

Fig. 4 shows the effect of EPS content on the UCS of specimens prepared in series T4-T8, all other variable maintained constant. As seen, inclusion of EPS beads did temper the potential strength gain of the mixture. The UCS loss was positively associated with the EPS content. The more the EPS content, the more the UCS loss and the less the UCS values. The UCS ranges, however, reasonably fell within 0.4 to 0.6 MPa when the EPS contents ranged between 0.62% and 1.08%, which were still sufficiently high to be comparable to those of general compacted soils.

One of the merits including EPS into the WFS-FA-EPS matrix was to mitigate the F-T impairment. Along with the use and increase of the EPS content, the UCS loss percentage resulted in the first F-T impact decreased from 20.8% (null EPS) to the minimum 6.5% (at EPS content 1.08%) and to 9.3% (at EPS content 1.85%); the UCS loss percentage resulted in the first 3 F-T cycles decreased from 25.1% (null EPS) to the minimum 10.1% (at EPS content 1.08%) and to 18.1% (at EPS content 1.85%). The EPS content was consistently 1.08% at the bottom of the UCS loss percentage trends, which indicated that specimens prepared at EPS content 1.08% demonstrated favorable frost sustainability.

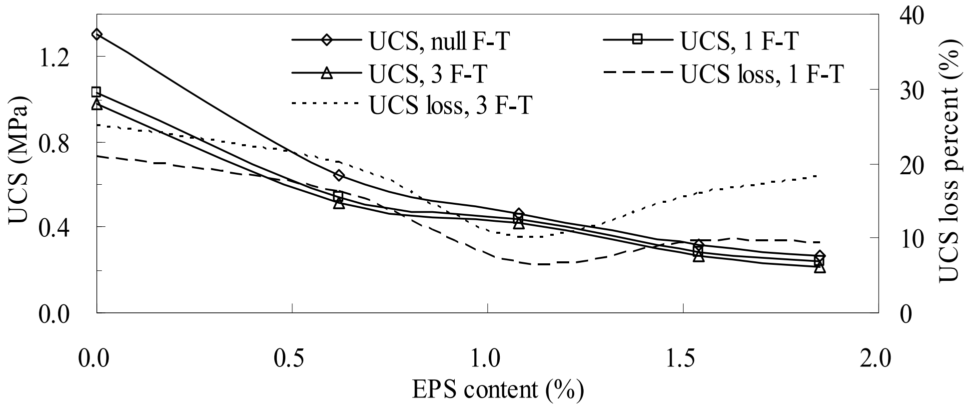

FIG. 4. UCS versus EPS bead content.

The majority of UCS loss percentage was suffered in the first F-T action, and the subsequent F-T actions (up to 3 cycles) led to minor relative loss of strength. The UCS loss percentages were 20.8%, 16.2%, 6.5%, 9.7% and 9.3% for the specimens prepared in series T4-T8, respectively, which were suffered in the first F-T action, and were 25.1%, 20.1%, 10.1%, 15.9% and 18.1% as the same, respectively, which were suffered in the first 3 F-T cycles. On average, around 70% UCS loss was suffered in the first F-T action, at least out of the first 3 F-T cycles.

There was an EPS content at which the WFS-FA-EFS mixture presented the reasonably optimal combination of critical properties, i.e., unit weight, UCS and F-T sustainability. In this context, EPS content of 1.08% (i.e., 45% in volume) seemed to be a reasonable choice, at which the specimen was 1.17 g/cm^3 in density, and 0.47 MPa for null F-T, 0.43 MPa for 1 F-T and 0.42 MPa for 3 F-T in UCS values, respectively.

Effect of Water Content

Fig. 5 shows the effect of water content on the UCS of specimens prepared in series T6 and T9-T10, all other variable maintained constant. Given water content of 30%, which was the optimal water content of the mixture, the specimen had the maximum UCS value out of the 3 series. The UCS loss percentage increased along with the increase of the water content. Given water content of 25%, the UCS loss percentages were 3.3% following the first F-T action, 6.3% following the first 3 F-T actions and 8.4% following the first 5 F-T actions, respectively. Given water content of 35%, the UCS loss percentages increased to 8.4% following the first F-T action, 15.1% following the first 3 F-T actions and 25.6% following the first 5 F-T actions, respectively.

The UCS loss in association with water content was interpreted by the freezing mechanism of water-granular matrix. Water is one of the necessities to trigger frost action and an internal factor impairing the structure of the matrix. More water volume means additional volume expansion upon freezing. The force during expansion may degrade the binding force of cement hydrates, which, apparently, led to UCS loss. Accordingly, it is suggested to control the water volume added to the mixture, given the water content required for cement hydration and mixture compaction.

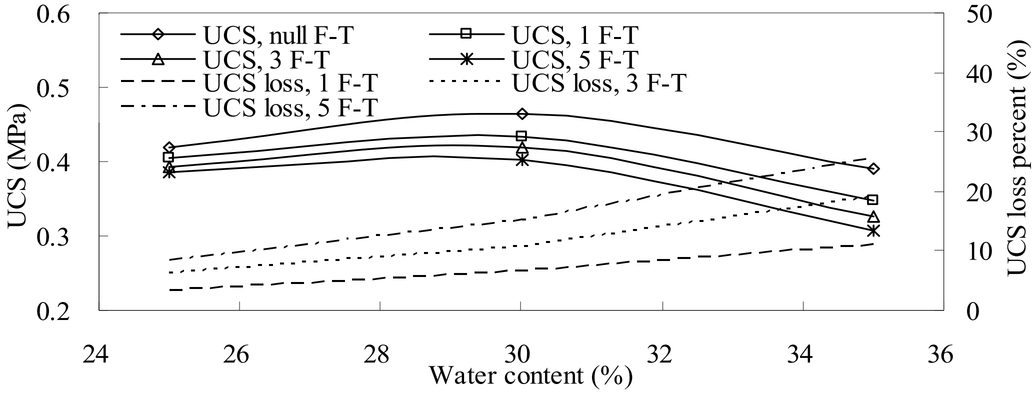

FIG. 5. UCS versus water content.

Effect of Fly Ash (FA) Content

Fig. 6 shows the effect of FA content on the UCS of specimens prepared in series T6 and T11-T13, all other variable maintained constant. Inclusion of FA mitigated the frost impairment. The specimens in series T11, which were prepared without FA content, suffered UCS loss percentage of 28.7% following the first F-T action and 42.8% following the first 3 F-T actions. In contrast, the specimens prepared with FA inclusion suffered UCS loss percentage of 6.5-16.1% following the first F-T action and 10.1-21.8% following the first 3 F-T action, respectively, which were well less than the respective percentages for specimens prepared without FA inclusion.

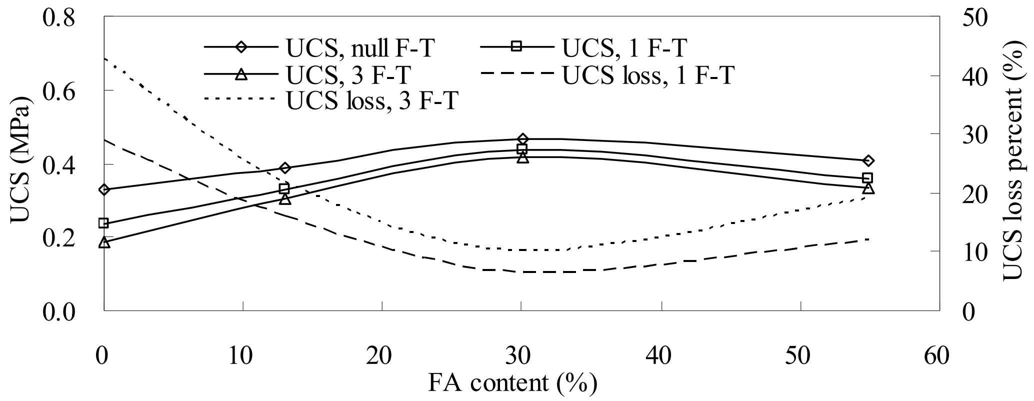

FIG. 6. UCS versus FA content.

The specimens prepared at 30% FA content consistently presented the maximum UCS and the least UCS loss percentage when exposed to null, 1 or 3 F-T cycles in this investigation, which suggests that the specimen prepared at 30% FA content and other variables prescribed as herein was a relatively weathering sustainable mixture in terms of UCS and frost resistance.

The enhancement in UCS and frost sustainability due to FA inclusion was probably associable with several mechanisms. Firstly, the cementitious materials contained in FA helped cement hydration processes and led to additional binding forces. Next, FA was less in unit weight than WFS, which means that less water volume in unit weight was required to prepare a specimen. The resulted water volume reduction mitigated the freezing expansion and thus the frost impairment to the specimen structure if exposed to F-T actions. The last, FA inclusion was able to improve the gradation of the mixture, leading to a well graded distribution in size and thus increasing the UCS gain.

CONCLUSIONS

For specimens prepared in all series, the unit weight was 20-40% less than that of general fill materials. The 28-day UCS values ranged from 0.11 to 1.30 MPa, which can be controlled to meet almost all the requirements for backfill materials. F-T cycling impaired the binding force of WFS-FA-EPA mixtures and led to the UCS loss of the cured specimen. The majority of the UPS loss was suffered in the first F-T action, at least out of the first 5 F-T cycles in this study. EPS inclusion was one of means effectively mitigating UCS loss. Water content was the essential leading to F-T impairment and should be controlled in making the mixture. In this study, the optimal contents were 30% for FA and 1.08% for EPS. Contents for cement and water should be determined in accordance with UCS requirements.

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