Development of Lightweight Roadside Safety Barriers using Foaming Admixture: Phase I—Properties of Flue Gas Desulfurization (FGD) Cellular Concrete

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Synopsis: The roadside safety barrier is a protective barrier that is erected around a racetrack or in the middle of a dual-lane highway in order to reduce the severity of accidents. Recently, interest in portable roadside safety barriers has heightened the interest in the development of a low-cost and high-performance alternative to the conventional safety barrier system. A study has been undertaken to characterize fresh and hardened properties of flue gas desulfurization (FGD) cellular concrete (CC) using foaming admixture towards the development of a lightweight roadside safety barrier. Test results indicate that FGD CC using a foaming admixture can be effectively used in manufacturing lightweight roadside safety barriers.

Keywords: cellular concrete; flue gas desulfurization (FGD) material; foaming admixture

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INTRODUCTION

Existing roadside safety devices such as safety barrier, lighting columns, signs, etc are designed to maximize safety performance and minimize cost. However, there are rooms for further safety advances where as a variety of safety and security barriers for directing traffic have been developed. These developments include steel panel systems, sand-filled barrels, and heavy concrete barriers[1]. The steel system is relatively effective for passenger cars but may not be capable of containing heavy trucks and similar vehicular traffic. In addition, the leaching of zinc from steel systems is a source of heavy metal environmental pollution. The sand-filled barrel is inexpensive but it requires extensive maintenance and can be cumbersome to install or replace. The heavy concrete barrier, capable of containing the heavier trucks but is less effective for smaller vehicles including motor cyclists may cause an increase in the number of injury accidents. Furthermore, its weight requires special lifting equipment to install or replace. Therefore, roadside safety systems can stand further improvement in the level of safety in terms of reducing injuries, lowering impact on the environment during its life-cycle, reliability, durability, maintenance and cost-effectiveness.

When a collision occurs, a safety barrier should absorb most of the collision energy when crushed. The barrier acts as a cushion, bringing the vehicle to a stop minimizing the hazard to the passengers[2]. It is important to consider the energy absorption capability of the barrier in order to minimize the incidence of juries. It is advantageous in this regard to use cellular concrete for roadside safety barriers. Cellular concrete (CC) is a mixture of cement, fine sand, water and foaming admixture, which once hardened results in a strong, lightweight concrete containing millions of evenly distributed, consistently sized air bubbles or cells[3]. These air bubbles are highly suitable for absorbing collision energy as well as sound. Furthermore, its lightweight modular design offers an excellent portability. Components can be transported easily without special heavy lifting equipment, simplifying installation. Maintenance can be minimal and clean-up simplified. In addition, flue gas desulfurization (FGD) material, a by-product resulting from a chemical process to remove sulfur oxides (SO_x) resulting from the combustion of fossil fuels in coal-burning power plants, was used as a cost-saving component in the safety barrier mixtures.

The present study was aimed to characterize fresh and hardened properties of FGD CC lightweight roadside safety barrier construction. The experimental study included comprehensive laboratory experiments related to water to cementitious material ratio and air content on fresh and harden properties of FGD CC.

EXPERIMENTAL PROGRAM

Materials

Materials used in this study included an ASTM Type I Portland cement, ASTM Class F fly ash, and flue gas desulfurization (FGD) material. FGD material, a by-product resulting from the combustion of fossil fuels in coal-burning power plants, is a mixture of hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$, gypsum), calcium sulfite ($CaSO_3$), and fly ash. The FGD material is being used in a growing number of applications. Uses of FGD material include concrete products, flowable fill, road base construction, wallboard manufacture, and embankment construction, etc. According to the American Coal Ash Association (ACAA) 2003 coal combustion product use survey, about 31 million tons of FGD materials were produced in 2003 year in the US. Only 8.7 million tons of these materials were used in commercial applications. Even though the utilization of FGD material has considerably increased during the last 10 years, these materials have the potential to be utilized in a variety of applications. To develop a cost effective safety barrier, FGD materials was used as a major component in the mixture. The chemical and physical properties of the cement, fly ash, and FGD material are given in Table 1.

A natural river sand meeting the specification of ASTM C 33 was used in the mixture. The sand had an absorption capacity of 0.8%, a relative density of 2.61, and a fineness modulus of 2.77.

Mixture Proportions

Test mixtures were prepared under laboratory conditions. The forming admixture was diluted with water at a ratio of 1 to 40 (by volume) and then aerated under pressure to form the foam. To evaluate the effect of air content and unit weight on fresh and hardened properties of FGD CC, tests were conducted on FGD CC mixtures with varying air contents, unit weight, and water to cementitious material ratio (w/cm). The mixture proportions are given in Table 2.

Specimen Preparation

Cellular concrete mixing was carried out in the laboratory using a rotary drum mixer which is tilted at an angle of 15° from horizontal level. As there is no standard for cellular concrete preparation, the mixing was carried out following the sequence: The dry materials such as cement, fly ash, sand, or FGD materials were first placed into the mixer and dry-mixed for 30 seconds. Three quarters of the specified water was then added to the mixer over a period of 3 minutes. After a minute rest period, the remaining water was added and mixing continued for an additional 2 minutes or until a homogeneous mortar with no lumps of cement was obtained. The foam was produced by the foam generator and was added to the mixture over a 2 minutes period until all foam was uniformly distributed in the mix. The schematic mixing procedure is given in Fig. 1.

Test Procedures

Table 3 lists testing factors and relevant standards for each testing method. The fresh properties (wet density, flowability, bleeding, and setting time) for all the CC mixtures were tested immediately after mixing.

Cylindrical specimens of 75mm x 150mm (diameter x length) were prepared for compressive strength testing. Immediately after casting, the test specimens were covered to prevent moisture evaporation and placed in a moist-curing room at 23°C; demolding was carried out 3 days after sample preparation. After demolding, the specimens were stored again at 23°C and 100% relative humidity room until tested. The compressive strength was tested at ages 3, 14, 28, 56, 91 days.

The Vacuum saturation method (similar with ASTM C 642) developed by Day and Marsh[4] was used for determining the absorption and the porosity (volume of permeable pore space) of CC mixtures. After 28 days curing at 23°C and 100% relative humidity room, specimens were dried in an oven at 100 ± 5°C until constant weight had been achieved. After removing each specimen from the oven, the mass of oven-dried sample was measured. The specimens were immediately transferred to the desiccator filled with de-aired, distilled water, and vacuumed for at least 24 hours. The apparent mass of the sample in water after immersion and vacuuming was determined. Finally, the mass in air of saturated sample was determined by removing surface moisture with a towel. The absorption and porosity was calculated using Eq. (1) and Eq. (2), respectively:

$$A = \frac{\left(W_{sd} - W_{od}\right)}{W_{od}} \times 100 \qquad \text{Eq. (1)}$$

$$P = \frac{\left(W_{sd} - W_{od}\right)}{\left(W_{sd} - W_{water}\right)} \times 100 \qquad \text{Eq. (2)}$$

Where, $A =$ absorption after immersion and vacuuming (%); $P =$ vacuum saturation porosity (%); W_{sd} = weight of surface-dry sample in air after immersion and vacuuming; W_{od} = weight of oven-dried sample in air; and W_{water} = apparent weight of sample in water after immersion and vacuuming.

The energy (potential energy) absorbed by the specimen during impact was measured using a vertical drop method. Fig. 2 shows the vertical drop test set-up. Cylindrical specimens of 75mm x 150mm were mounted to a rigid backing plate and impacted with the face of a cylindrical hammer with a diameter of 75mm. The drop hammer with weight of 8.17kg was dropped from a height of 1.52m to produce an impact velocity of 5.47m/s on to the specimens. The potential energy was calculated from the following equation. Taken together, the dynamic impact force for each mixture was calculated.

$$PE = W(h+s) \qquad \text{Eq. (3)}$$

$$F_{dyn} = f_{cr} A_{cr} = \frac{W(h+s)}{s} \qquad \text{Eq. (4)}$$

Where, $PE =$ potential energy; $W =$ impact object weight; $h =$ drop height; $s =$ stopping distance; F_{dyn} = dynamic impact force; f_{cr} = specimen crush strength; and A_{cr} = crushed impact area.

TEST RESULTS AND DISCUSSION

Fresh Properties

Flowability of cellular concrete was assessed in terms of slump-flow spread test (Fig. 3). The slump-flow test is a measure of deformability relative to the diameter of the sample after a collapse has been obtained[5]. The slump-flow value indicates deformability as well as the capability of the material to be placed under its own weight with little or no vibration. The characteristics of the flowability include high deformability, good segregation resistance, and filling forms without vibration. The flowability is related to slump, air content, setting time, and compressive strength at various ages. The relative flow area (Γ_m) was calculated using Eq. (5). A larger value of Γ_m indicates higher deformability.

$$\Gamma_m = \frac{\left(d_1 \cdot d_2 - d_0^2\right)}{d_0^2} \qquad \text{Eq. (5)}$$

Where, d_1 and d_2 = measured flow diameter; and d_0 = slump cone diameter (bottom)

The Γ_m for all the mixtures ranged from 0.27 to 0.55 (Table 4). As air content and w/cm increased, the Γ_m increased. Cement factor [CF–sacks of cement in a full batch (50 kg of cement per sack)] also affects the Γ_m of cellular concrete. The Γ_m value of the mixture containing higher CF was lower than those of mixture with low CF at the same air content and water to cement ratio. For instance, the Γ_m of mixture B-50FGD-7 was 0.47, whereas that of mixture B-50FGD-3 was 0.55.

Bleeding and subsidence are important characteristics in the cellular concrete mixture. High bleeding can either delay hardening of CC mixture or contribute to the formation of a weak surface layer. Furthermore, when CC mixtures are placed, evaporation of the bleed water often results in deterioration of the bubble system and subsidence of the CC mixture. Subsidence (also called settlement shrinkage) refers to the vertical shrinkage of fresh cementitious materials before initial set[6]. It is caused by bleeding, air voids rising to the surface, and chemical shrinkage. Excessive subsidence can also be caused by a lack of consolidation of the fresh concrete. Early volume changes in the concrete (within 24 hours) can influence crack formation in hardened concrete. Fig. 4 represents the bleeding and subsidence measured for each of the ten mixtures. It was noted that bleeding and subsidence are directly related to the air content (amount of foaming agent), w/cm, and CF. As the air content and w/cm increased, the bleeding and subsidence values increased. However, at high CF levels, the values of both bleeding and subsidence were reduced.

The standard test method ASTM C 403/C403M-99[7] was used to measure the setting time of C.C. mixture which is the time required for the penetration resistance of each mixture to reach 3.45 MPa (500 psi). Setting time of the mixtures ranged from approximately 6.6 to 11.1 hours (Fig. 5). FGD CC mixture exhibited a significant retardation in setting while the mixture not containing FGD material had the shortest setting time. For example, the time of setting of mixture 0.4-50Plain-5 was 6.6 hours while the setting time of mixture 0.4-30FGD-5 was 10.4 hours. When FGD material content was reduced (as indicated by air content increased from 30 to 70), the reduction in setting time was observed. The results confirm that presence of FGD material in the cement system causes prolonged setting. Őlmez and Erdem[8] reported that delayed hydration of cement system containing FGD material results from the formation of impermeable layers composed of products forming between the calcium hydroxide and impurities from FGD material. Increasing w/cm also retards the setting time of CC. Interestingly, when CF increased, the setting time of CC was accelerated. It is obvious that the major factors affecting the setting time of FGD CC are FGD content, CF, and w/cm. Therefore, if lightweight roadside safety barriers need a quick set FGD CC, it is required to optimize these factors to make the mixture without retarding setting time.

Hardened Properties

Dry density, water absorption, and porosity of CC mixtures were measured at 28 days (Table 4). The density of all mixtures ranged from 524 to 1520 kg/m^3. Inclusion of FGD material caused a decrease in density of the CC mixture relative to the control plain mixture not containing FGD material. For example, at the same air content, mixture 0.5-50Plain-5 without containing FGD material exhibited the density of 1113 kg/m^3, whereas mixture 0.5-50FGD-5 with FGD material showed the density of 978 kg/m^3.

Generally speaking, density, water absorption, and porosity are related to each other. With decrease in density and increase in porosity, the water absorption increases. The water absorption of CC mixture with FGD material was larger than that of the mixture without FGD material. The water absorption values ranged from 6.99% to 37.67%. The water absorption of C.C. mixtures is plotted as a function of dry density in Figure 6. There is a good relationship between water absorption and dry density. It is obvious that the mixtures with lower densities absorb significantly higher percentage of water than those with higher densities. It is also apparent that the mixture with higher w/cm and lower CF has a trend of increased absorption and decreased density. This property needs further investigation because it is connected to durability in service. For instance, when the CC samples are exposed to wet and sulphate environmental conditions the proportion of water-soluble sulfates inside the CC sample, especially magnesium, sodium, and potassium sulfates can lead to efflorescence. Furthermore, the CC sample may show poor resistance to external sulfate attack.

The porosities varied from 23.74% to 40.93%. The highest porosity, of 40.93% was for mixture 0.4-70FGD-5 with a w/cm of 0.50, CF of 5, and 70% air content (as indicated by the lowest FGD content). The porosity of mixtures containing FGD material is marginally higher than that of mixtures not containing FGD material. As reported in other investigation[9], the porosity of CC mixture was reduced with increasing CF (increasing cement content). This was probably attributed to the increased formation of calcium-silicate-hydrate (C-S-H) phases from the hydration reactions with increasing cement content. The relatively strong relationship between the porosity and the dry density of CC was found in Fig. 7.

The porosity of CC is the sum of macro and micro pores within the concrete. The porosity of CC depends on combination of pore of different sizes (capillary pore and gel pore), uniformity of pore distribution, the continuity of the pore system, and other factors. The relationship between porosity and water absorption are shown in Fig. 8. An increase in the porosity (as indicated by a reduction in dry density) leads to an increase in water absorption. Although linear regression analysis indicates a correlation coefficient of 0.74 for CC between porosity and water absorption, higher porosity does not necessarily result in higher water absorption. As previously mentioned, it should be noted that absorption is based on the volume of the open accessible to water (the water content of the saturated paste expressed as a percentage of its weight), not on all factors to affect the porosity.

The compressive strength of cellular concrete mainly depends on its density, but characteristics of the cementitious constituents may play a role as well. Fig. 9 provides compressive strength development of different CC mixtures. As expected, mixtures containing FGD material leads to low compressive strength at early age due to the role of delayed hydration of FGD material. Furthermore all mixtures containing fly ash shows slower strength development for all curing period because fly ash takes more than 14 to 28 days to make any significant contribution to strength development.

Fig. 10 presents the relationship between compressive strength at 28 days and 91 days as a function of porosity. There is an exponential relationship between the strength and the porosity. The linear regression analyses indicate that a correlation coefficient at 91 days for a given the porosity is slightly higher than that at 28 days. In spite of a little variation, this result confirms the fact that the compressive strength of cellular concrete is primarily a function of the porosity regardless of ages[10].

As previously mentioned, safety barrier should absorb most of the collision energy when a car collision occurs. The barrier acts as a cushion, bring the vehicle to a stop minimizing the hazard to the passengers. It is important to evaluate how much the energy can be absorbed in the safety barrier design. The energy absorbed by the specimen is shown in Fig. 11. Three tests were run on each mixture, and the data shown in the chart represents the values calculated from the average of all tests. As expected, mixtures containing a large amount of air leads to high-energy absorption regardless of water to cementitious material ratio and cement factor. Fig. 12 presents the relationship between the energy absorption and the porosity. As relationship between strength and porosity stated above, energy absorption may be a function of the porosity, though higher porosity does not necessarily result in higher energy absorption.

CONCLUSIONS

Most of flue gas desulfurization (FGD) material from coal combustion power plant have been land-fill or have limited use in construction applications because of their inherent chemical and physical properties. A laboratory test program was conducted to evaluate the potential use of FGD material to develop lightweight roadside safety barriers using foaming admixture. Prior to manufacturing the safety barrier, the fresh and hardened properties of FGD cellular concrete (CC) using foaming agent was investigated. Test results indicate that FGD CC can accommodate FGD material to manufacture the lightweight roadside safety barrier. Based on the test results, the following conclusion can be drawn.

- As air content and water to cementitious material ratio (w/cm) increase and cement factor (CF) decreases, flowability, bleeding, and subsidence of FGD C.C. increase.
- As the amount of FGD material increases and CF decreases, the setting time increases.
- The mixtures with higher w/cm and lower CF have a trend of increased absorption and decreased density.
- The porosity of CC mixtures generally increased with increasing FGD content and w/cm while it was reduced with increasing CF.
- The mixtures containing FGD material have lower early compressive strength due to the delayed hydration.
- FGD CC shows an exponential between the compressive strength and the porosity.

- The mixture containing high air content has higher energy absorption than that of low air content.

From test results, FGD cellular concrete may be used to develop lightweight roadside safety barriers, but the use of FGD material in portland cement-based mixtures raises the question of sulphate attack with may affect durability. With respect to the sulphate attack caused by FGD material, high volume fly ash based-mixtures using low calcium fly ash were designed in this study because the use of low calcium fly ash can improve the sulphate attack resistance of mixture. However, it is necessary to investigate the potential of internal sulphate attack of portland cement-based mixture using FGD material before casting the roadside barrier.

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Table 1. Physical properties and chemical analyses of cementitious materials

Composition	Cement	Fly ash	FGD
SiO_2	19.12	35.20	0.66
Al_2O_3	5.07	21.60	0.15
Fe_2O_3	3.40	5.40	0.09
$(SiO_2+SiO_2+Fe_2O_3)$	27.59	62.20	2.04
CaO	64.73	25.90	32.81
MgO	0.64	4.80	0.09
SO_3	3.13	1.40	44.53
H_2O	-	-	20.06
Na_2O	-	-	0.36
P_2O_5	-	-	0.78
F	-	-	0.76
SrO	-	-	0.03
Na_2O Equivalent [a]	0.65	-	-
Na_2O Equivalent [b]	-	1.20	-
Loss on Ignition	2.26	0.09	21.55
Fineness [c]	95.30	15.33	-
Specific Gravity	3.11	2.65	2.32
Initial Set, min	150	-	-
Final Set, min	270	-	-

[a] Available alkali, expressed as Na2Oe, as per ASTM C 150.
[b] Available alkali, expressed as Na2Oe, as per ASTM C 311.
[c] Amount retained on 325 sieve %.

Table 2. Mixture proportions

Mixture	W/CM	Unit Weight (lb/yd^3)				
		Water	Cement	Class F fly ash	FGD	Sand
0.4-50Plain-5	0.4	188	329	141	-	1244
0.4-30FGD-5		188	329	141	1914	-
0.4-50FGD-5		188	329	141	1132	-
0.4-70FGD-5		188	329	141	1124	-
0.5-50Plain-5	0.5	235	329	141	-	1124
0.5-30FGD-5		235	329	141	1805	-
0.5-50FGD-5		235	329	141	1023	-
0.5-70FGD-5		235	329	141	241	-
0.5-50FGD-3	0.5	141	197	85	1395	-
0.5-50FGD-7		329	461	197	650	-

0.4(0.5)-30(50, 70)Plain (FGD)-5 (3, 7)
Cement Factor: 3, 5, and 7
Air content:30, 50, and 70
Water to cementitious material ratio: 0.4 and 0.5