

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

**by C.-S. Shon, D. Saylak, D.G. Zollinger,
and A.K. Mukhopadhyay**

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

2 Shon et al.

Chang-Seon Shon is a PhD candidate in the Zachry Department of Civil Engineering at Texas A&M University, College Station, Texas. His research interests include use of by-product materials in construction engineering and development of new technologies and material testing relating to concrete durability and high performance concrete.

Don Saylak is a professor in the Zachry Department of Civil Engineering at Texas A&M University, College Station. His research interests include utilization of coal combustion by-products, high-performance cement-based materials, nondestructive testing, and fracture mechanics of cement-based systems.

Dan G. Zollinger is an associate professor in the Zachry Department of Civil Engineering at Texas A&M University, College Station. He received his PhD in civil engineering from the University of Illinois at Urbana Champaign in 1989. He is a member of committees 325, Concrete Pavement Design. He specializes in pavement material, design, and construction. His research interests include highway and airfield pavement distress evaluation and performance of concrete.

Anal K. Mukhopadhyay is an Associate Research Scientist at the Materials and Pavements Division of Texas Transportation Institute, Texas A&M University. His research interests include alkali-silica reactivity, cement hydration, mineralogical modeling of coefficient of thermal expansion for aggregate and concrete, use of siliceous river gravel in concrete pavement, optimized aggregate gradation, use of fly ash in paving mixtures, fluidized bed ash, petrography and microstructural characterization of constructional materials.

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 barriers¹. 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 passengers². It is important to consider the energy

absorption capability of the barrier in order to minimize the incidence of injuries. 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 cells³. 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 hardened 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 (CaSO₄·2H₂O, gypsum), calcium sulfite (CaSO₃), 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 Marsh⁴ 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 $100 \pm 5^\circ\text{C}$ 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:

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

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

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.

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

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

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 obtained⁵. 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.

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

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 set⁶. 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-99⁷ 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. Ölmez and Erdem⁸ 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/m³. 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/m³, whereas mixture 0.5-50FGD-5 with FGD material showed the density of 978 kg/m³.

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 investigation⁹, 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 ages¹⁰.

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.

REFERENCES

1. Giavotto, V., and Perneti, M., "Comparison of Collisions of Rigid Trucks and Articulated Trucks Against Road Safety Barriers," *Transportation Research Record*, No.1779, 2000, pp. 141-149
2. Lvey, D.L., and Marek, M.L., "ADIEM: Development of a Low Cost High-Performance Terminal for CMBs and PCMs," *TTI Report* 990-1, August 1991.
3. Jones, M.R., and McCarthy, A., "Utilizing Unprocessed Low-Lime Coal Fly Ash in Foamed Concrete," *Fuel* 84, 2005, pp. 1398-1409.
4. Day, R.L., and Marsh, B.K., "Measurement of Porosity in Blended Cement Paste," *Cement Concrete Research*, Vol. 18, No. 1, 1988, pp.177-182.
5. Murata, J., and Suzuki, K., "New Method of Testing Flowability of Grout," *Magazine of Concrete Research*, Vol. 49, No. 181, 1997, pp. 269-276.
6. Kosmatka, S.H., Kerkhoff, B., and Panarese, W.C., "Design and Control of Concrete Mixtures," Portland Cement Association, 14th Edition, 2002.
7. The American Society for Testing and Materials, "Annual Book of ASTM Standards," Section 4, Vol. 04.02, Concrete and Mineral Aggregates, Philadelphia, Pennsylvania, 1992.
8. Ölmez, H., and Erdem, E., "The Effects of Phosphogypsum on the Setting and Mechanical Properties of Portland Cement and Trass Cement," *Cement and Concrete Research*, Vol. 19, No. 3, 1989, pp. 377-384.
9. Kearsley, E.P., and Wainwright, P.J., "The Effect of High Fly Ash Content on the Compressive Strength of Foamed Concrete," *Cement and Concrete Research*, Vol. 31, No. 1, 2001 a, pp.105-112.
10. Kearsley, E.P., and Wainwright, P.J., "The Effect of Porosity on the Strength of Foamed Concrete," *Cement and Concrete Research*, Vol. 32, No. 2, 2001 b, pp.233-239.

Table 1. Physical properties and chemical analyses of cementitious materials

Composition	Cement	Fly ash	FGD
SiO ₂	19.12	35.20	0.66
Al ₂ O ₃	5.07	21.60	0.15
Fe ₂ O ₃	3.40	5.40	0.09
(SiO ₂ +SiO ₂ +Fe ₂ O 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 ₂ O	-	-	20.06
Na ₂ O	-	-	0.36
P ₂ O ₅	-	-	0.78
F	-	-	0.76
SrO	-	-	0.03
Na ₂ O Equivalent ^a	0.65	-	-
Na ₂ O 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 Na₂O_e, as per ASTM C 150.

^b Available alkali, expressed as Na₂O_e, 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)

└─ Air content: 30, 50, and 70
└─ Cement Factor: 3, 5, and 7

└─ Water to cementitious material ratio: 0.4 and 0.5

Table 3. Testing factors and standards for the testing methods

Properties	Test procedure	Test method	Testing factors
Fresh concrete	Flowability	ASTM C 143/143M-05	Immediately after casting
	Bleeding	ASTM C 940-89	
	Expansion	ASTM C 940-89	
	Setting time	ASTM C 403-99	
	Wet density		
Hardened concrete	Compressive strength	ASTM C 39/39M-05	3, 14, 28, 51, and 91 days
	Dry density	ASTM C 642-97	At 28 days
	Absorption	Vacuum saturation method	
	Porosity	Vacuum saturation method	
	Energy absorption	Vertical drop method	

Table 4. Fresh and hardened cellular concrete properties

Mixtures	Theoretical density (kg/m ³)	Wet density (kg/m ³)	Dry density (kg/m ³)	Bleeding (%)	Relative flow area (Γ_m)	Subsidence (%)	Porosity (%)	Water Absorption (%)
0.4-50Plain-5	1139.42	1169.13	1100.22	0.49	0.30	0.99	31.25	14.20
0.4-30FGD-5	1543.27	1584.25	1520.15	0.51	0.29	1.10	23.74	6.99
0.4-50FGD-5	1072.12	1094.85	1014.73	0.55	0.31	1.21	33.65	17.25
0.4-70FGD-5	600.96	637.28	571.58	0.67	0.35	1.35	37.56	35.65
0.5-50Plain-5	1096.15	1113.42	1046.11	0.93	0.41	1.61	34.99	17.68
0.5-30FGD-5	1506.41	1528.55	1464.45	1.04	0.43	1.61	27.47	8.79
0.5-50FGD-5	1035.26	1045.78	978.47	1.17	0.46	1.73	32.91	15.43
0.5-70FGD-5	564.10	586.88	524.38	1.29	0.51	1.84	40.93	37.67
0.5-50FGD-3	1091.35	1118.73	1053.02	1.10	0.55	1.61	37.88	20.95
0.5-50FGD-7	977.56	1146.58	1085.68	1.00	0.47	1.37	25.87	13.43

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

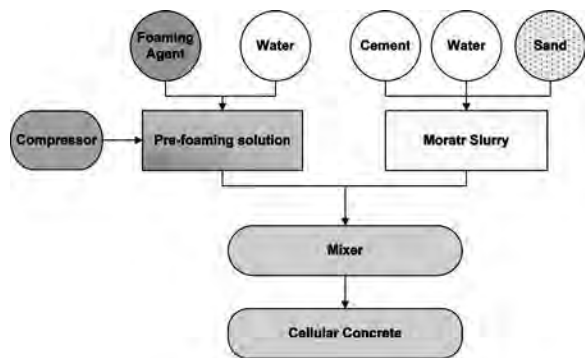


Fig. 1—Mixing procedure.

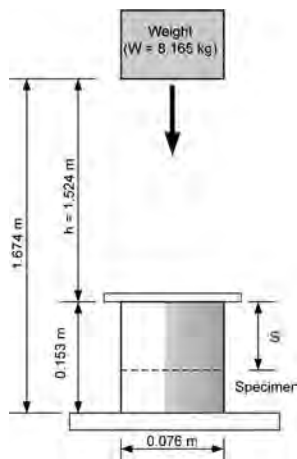


Fig. 2—Vertical drop test.

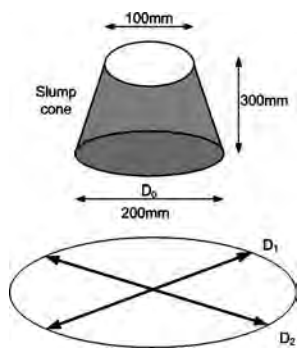


Fig. 3—Mixing procedure.

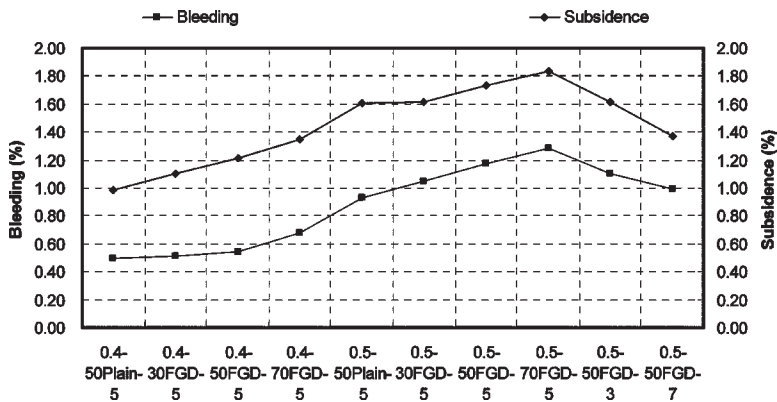


Fig. 4—Bleeding and subsidence.

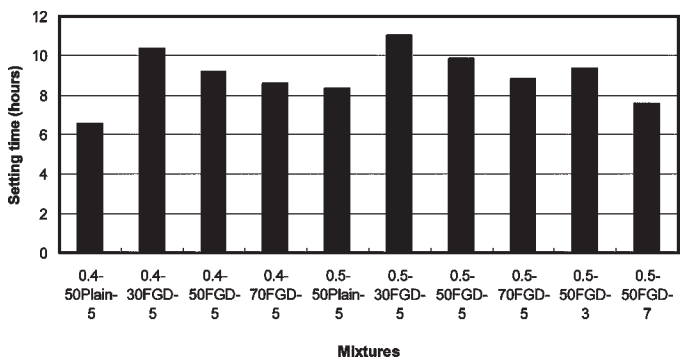


Fig. 5—Setting time.

◆ w/c=0.4, CF=5 ■ w/c=0.5, CF=5 ▲ w/c=0.5, CF=3 × w/c=0.5, CF=7

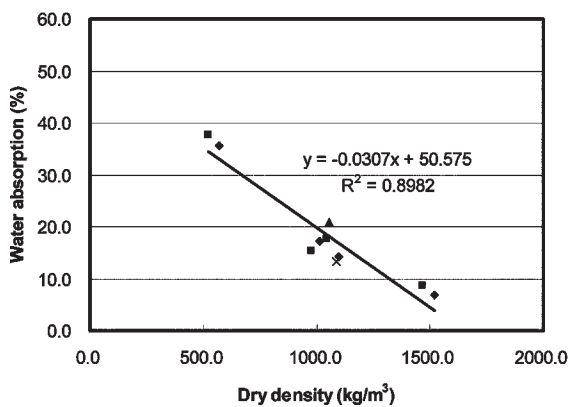


Fig. 6—Relationship between water absorption and dry density.

◆ w/c=0.4, CF=5 ■ w/c=0.5, CF=5 ▲ w/c=0.5, CF=3 × w/c=0.5, CF=7

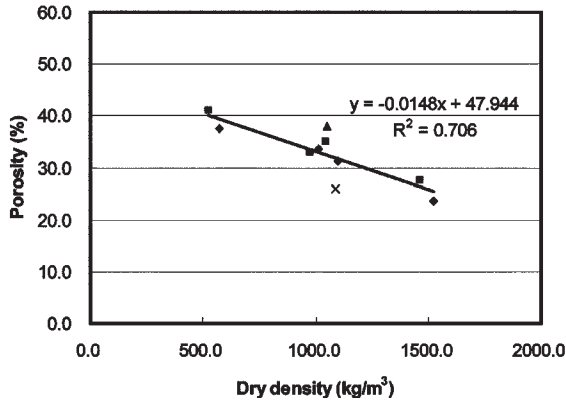


Fig. 7—Relationship between porosity and dry density.

◆ w/c=0.4, CF=5 ■ w/c=0.5, CF=5 ▲ w/c=0.5, CF=3 × w/c=0.5, CF=7

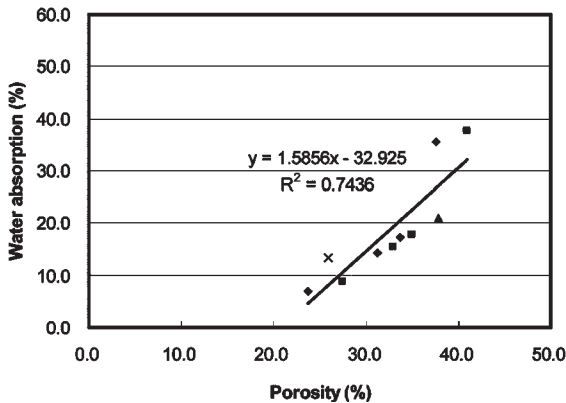


Fig. 8—Relationship between water absorption and porosity.

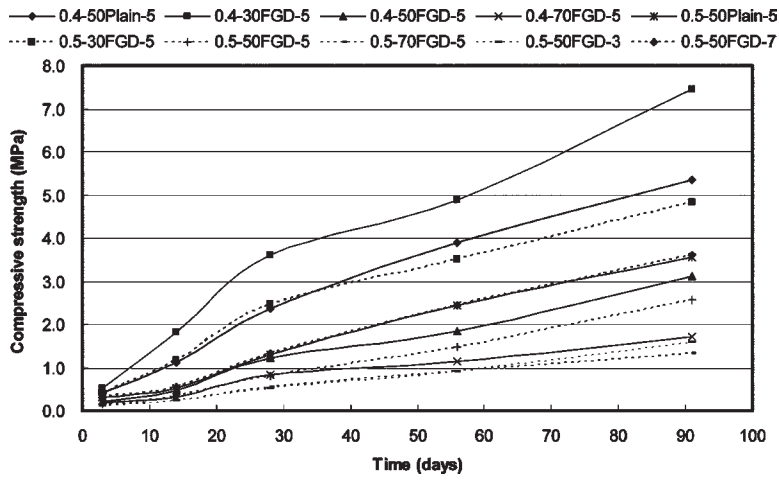


Fig. 9—Compressive strength development of different mixtures.

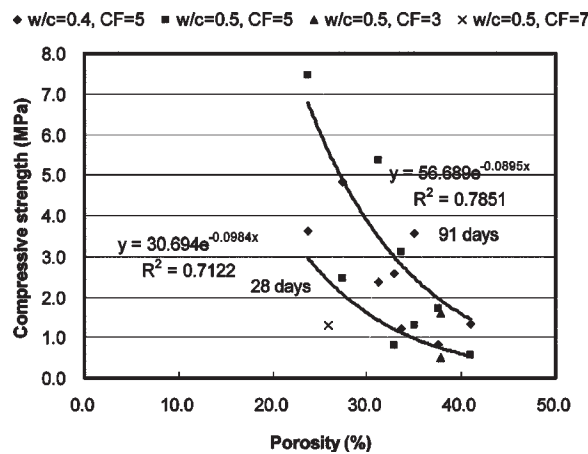


Fig. 10—Compressive strength at 28 days and 91 days as a function of porosity.

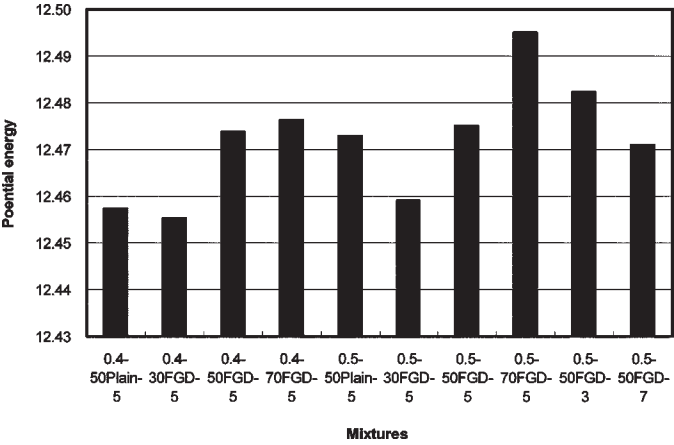


Fig. 11—Energy absorption.

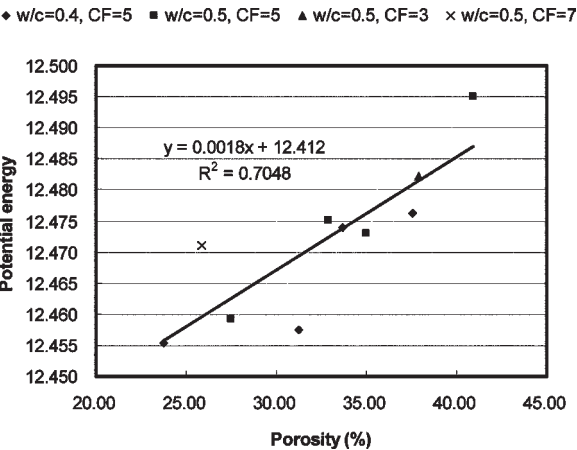


Fig. 12—Relationship between energy absorption and porosity.

Efflorescence of Concrete Products for Interlocking Block Pavements

by H. Nhar, T. Watanabe, C. Hashimoto, and S. Nagao

Synopsis: Today, a number of engineering structures and building are being constructed to match environment and urban landscape. From an aesthetics point of view, occurrences of efflorescence on colored concrete, unfinished concrete and concrete products of these structures are critical problems.

This research aimed to study and compare the efflorescence of concrete products that substituted cement with industrial by-products namely, fly ash, blast furnace slag and gypsum and normal concrete. Both concrete products and normal concrete were manufacture for paving application in form of interlocking blocks. In this paper, we use the term “non-cement” concrete to refer to the concrete not using industrial cement. A methodology is presented that enables a quantitative evaluation of the total, soluble and insoluble efflorescence and this methodology was used to analyze both non-cement concrete and normal concrete specimens. The results show that the insoluble efflorescence of non-cement concrete is less than that of normal concrete.

Keywords: blast-furnace slag; efflorescence; fly ash; interlocking block pavement

20 Nhar et al.

Heng Nhar received his Bachelor Degree in Civil Engineering from Hiroshima University in the year 2002. He received his M.Eng. Degree in Civil Engineering from Tokushima University in the year 2004, and now he is a Graduate Student of Doctoral course on Macro-systems Control Engineering at the Graduate School of Engineering at this University. His research interests are recycled aggregate concrete, utilization of fly ash as representative material instead of small aggregate in concrete.

Takeshi Watanabe received his M.Eng. and Dr.Eng. Degree in Civil Engineering from Kumamoto University in the year of 1998 and 2001, respectively. He has been working as a Research Associate at Tokushima University since 2000. His research interests are recycled aggregate concrete, nondestructive testing of concrete.

Chikanori Hashimoto received his M.Eng. and Dr. Eng. Degree in Civil Engineering from the University of Tokyo in the year of 1984 and 1989, respectively. He worked as a research assistant at Nagaoka University of Technology from 1985 to 1991. He then became an Associate Professor at Gunma University in 1992. Then he worked as a Associate Professor at Tokushima University in 1997, and has been a Professor at this University since 1998. His research interests are recycled aggregate concrete, utilization of fly ash as representative material instead of small aggregate in concrete, high performance of concrete machine using visualization technique and flow analysis of fresh concrete.

Satoshi Nagao received his B.Eng. and M.Eng. Degree in Civil Engineering from the University of Tokushima in the year of 2004 and 2006, respectively.

INTRODUCTION

Recently, landscape and environmental issues plays leading role in concrete structure. Efflorescence is a crystalline deposit on surfaces of masonry, stucco or concrete. It has been a problem to mar and detract with other beautiful and serviceable concrete products.

In Japan, the construction of coal-fired thermal power stations has been promoted because of the need to secure the supply of electric power ⁽¹⁾. Coal ash is a by-product of coal-fired thermal stations. In recent years, the protection of the environment gained global importance, advanced utilization or recycling of coal ash is an important research subject as the amount of coal ash gradually increases in Japan. Fly ash, blast furnace slag and gypsum were substituted for cement and sodium hydroxide (NaOH) was added to activate the slag hydration in order to have the same of flexural

strength as normal concrete products ⁽²⁾.

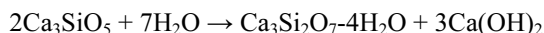
The aim of this study is to investigate efflorescence occurring on surface of the concrete products. Up to this point, the evaluation of efflorescence is performed by visual observation. In this study a test methodology is proposed by the authors to calculate the quantity of the efflorescence. This test method is then applied to investigate properties of non-cement concrete by comparing the quantity of occurring efflorescence with normal concrete products. Moreover, a scanning electron microscope was used to qualify at a molecular level the occurrence of efflorescence of these concrete products.

MECHANISMS OF EFFLORESCENCE

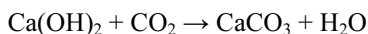
Efflorescence is a different thing to different people. To the manufacturers, it is an insoluble problem; to the contractor, it is something else the client can blame on them; to the homeowner it is a whitish discoloration that can appear to be like a powder or like the soapy scum seen on dirty bathwater, while to the chemist, it is most easily described as calcium carbonate with lesser quantities of other carbonate, sulfate, and chloride salts. The bulk of efflorescence seen from concrete paving is calcium carbonate, whereas for clay pavers, the main components are usually sodium chloride, table salt, along with sulfates and some carbonate. The remaining of this section focuses on calcium carbonate efflorescence observed on concrete products, which is the most common form.

In simple terms, calcium carbonate is a by-product resulting from an interaction between the cement used to manufacture the paving and the natural environment, which includes the ground, the weather, and the atmosphere. The result is a deposit or salt that appears on the surface of the paving.

Sparingly soluble calcium hydroxide, Ca(OH)_2 , comes from the cement hydration as exemplifier by the main mineral alite.



This soluble calcium hydroxide can migrate to the surface of the paving, where upon it has the opportunity to react with carbon dioxide (CO_2) in the atmosphere, to form calcium carbonate, which is not soluble, and with some water.



This carbonation of the calcium hydroxide results in the insoluble calcium carbonate being dumped on the surface of the paving while the water simply evaporates away. It is this calcium carbonate that forms the white deposit which is the most visible indicator of ongoing efflorescence of paving.

EXPERIMENT

Materials

Normal portland cement having density of 3.15 g/cm^3 and $334 \text{ m}^2/\text{kg}$ of specific surface was used as cement in this experiment.

The physical property of fly ash is shown in Table 1. It was produced from coal-fired thermal power station of Shikoku Electronic power cooperation in Japan. Blast furnace Slag with 2.86 g/cm^3 of density, $462 \text{ m}^2/\text{kg}$ of specific surface and gypsum with 2.29 g/cm^3 of density were also used. Both fly ash and gypsum are by-products of coal-fired thermal power station of Shikoku Electronic power cooperation, were used in this experiment.

River sand having specific gravity of 2.6 g/cm^3 , fineness modulus 3.21 and water absorption of 1.03% was used as fine aggregate. The coarse aggregate having 2.60 g/cm^3 specific gravity, water absorption 1.7% and fineness modulus 4.9 was used. This coarse aggregate was crushed into size of 2 mm to 7 mm, which it differs from aggregate size of normal concrete (over 5 mm) for paving blocks.

Sodium hydroxide solution (NaOH) with 1.26 g/cm^3 density and 24% concentration was used in this experiment.

Mixture Proportion of Concrete Products

The w/cm (water to cementitious material ratio) was fixed at 26%, which is usually selected on the basis of the required quality and performance for concrete products devoted to interlocking block pavements.

According to the research of HIRATSUKA ⁽²⁾, the weight ratios of fly ash, blast furnace slag, and gypsum are 1.0, 0.4 and 0.1 respectively at maximum flexural strength of non-cement concrete and mixing water is containing 3% NaOH by weight of water. The non-cement concrete mixture used in this study was the same mixture proportion of HIRATSUKA ⁽²⁾. This mixture proportion used of non-cement concrete products is shown in Table 2.

Mixture proportion of normal concrete products was replaced by the quantity of by-products to Normal Portland Cement and it is not added with NaOH solution (Table 3).

Mixture Method

The 50 liters forced mixing type of concrete mixer was used. The total mixing time is set to 6 minutes. First, by-product powder and aggregate are mixed together in 2 minutes, and then water is added to further mix in 4 minutes.

Compaction Method

Vibration compaction was used in order to obtain concrete products with the required quality. Oscillating time was set to 5 seconds, and vibration method was 50Hz frequency with the amplitude of 1.4mm.

Specimen Dimension

The dimension of specimens was a concrete block form of Length 200mm×Width 100mm×Height 60mm. For estimating efflorescence, thin slab

(100×60×15mm) specimens were cut from concrete block (200×100×60mm) by concrete cutter after curing as shown in Fig. 1. Ten pieces of thin slab form specimens were cut from one concrete block to investigate the occurrence of efflorescence.

Curing Method

These specimens of concrete products were cured sufficiently after casting in order to meet the required flexural strength set by Japan Interlocking Block Pavement Engineering Association (JIBPEA). Two different curing methods such as packing curing and water curing were performed. Concrete block specimens were packed by polyethylene bag after casting and were laid safely in factory until it reach the determined period of curing (Fig. 2). The curing periods were 7 days and 28 days for investigation on the different occurrence of efflorescence.

Flexural Strength Test

Flexural strength test was performed according to flexural strength structure pavement design of JIBPEA using the equation (1) below,

$$\sigma = \frac{240}{b \times d^2} \times P \quad \text{-----(1)}$$

Where, σ : Flexural strength (MPa), P: Maximum Load (N)

b: Width of concrete block (mm), d: Height of concrete block (mm)

Efflorescence Test

Concrete product in this study has low *w/cm* ratio with zero slump in a short compacting time and improper curing concrete, which has low strength. Since the strength of concrete is low, we assumed that the change of value of specimen relative to soaking days is the occurrence of efflorescence.

This test method was performed in accordance with the test determined by Japan testing center construction materials ⁽³⁾. Thin slab (100×60×15mm) specimens were cleaned and dried in the drying equipment for 24 hours in order to measure the mass of these dried specimens. And then, the halves of specimens were soaked into the water (20 °C, 60% humidity) in order to accelerate the occurrence of efflorescence (Fig. 3). The accelerated period was determined to take 7 days, 28 days and 91 days.

After finishing every accelerated day, the specimens were taken out from water and dried again 24 hours at 100 °C of drying equipment. Dried specimens were measured its weight including the mass of efflorescence and were calculated using equation (2) as the total occurrence of efflorescence (W_{To}).

$$W_{To} = \frac{w_2 - w_1}{w_1} \times 100 \quad \text{-----} \quad (2)$$

Where, W_{To} : Total ratio occurrence of efflorescence (%)

W_1 : Weight of dried specimen before occurring efflorescence (g)

W_2 : Total of dried specimen and the occurrence of efflorescence (g)

Efflorescence occurred on the surface of specimens were washed under the flow of water, and dried again in the drying equipment for 24 hours in order to measure the weight of insoluble efflorescence that might remained in the specimens. This quantity of efflorescence is called insoluble efflorescence (W_{In}), which is calculated by equation (3).

$$W_{In} = \frac{w_3 - w_1}{w_1} \times 100 \quad \text{-----} \quad (3)$$

Where, W_{In} : Ratio occurrence of insoluble efflorescence (%)

W_3 : Weight of specimen and efflorescence remained in the specimen (g)

Observation of scanning electron microscope

Scanning electronic microscope was used to observe the occurrence of efflorescence and analyzed it by taking their photos. Moreover, Fluorescent x-ray was used in order to analyze composition of efflorescence.

RESULTS AND DISCUSSION**Flexural Strength**

The result of flexural strength is presented in Fig. 4. Four types of specimens, non-cement concrete with water curing (R-water), non-cement concrete with packing curing (R- Packing), normal concrete with water curing (N-Water) and normal concrete with packing curing (N-Packing), were taken for study. All types of specimens showed high flexural strength more than 5MPa without relating to the different mixture proportion or curing method, which satisfies the required flexural strength of Japan Interlocking Block Pavement Engineering Association (JIBPEA).

The Total Occurrence of Efflorescence

Figures 5 and 6 show the total efflorescence in for concrete blocks cured for 7 and 28 days respectively. For the blocks cured for 7 days, after 91 days of soaking the total efflorescence ratio for non-cement concrete is 1.4% and the total efflorescence ratio for normal concrete is 1.9%. For blocks cured for 28 days after 91 days of soaking the total efflorescence ratio for non-cement concrete and normal concrete are 2.0% and 2.5% respectively. These results showed that the total occurrence of efflorescence of non-cement concrete is less than that of normal concrete.

By observation on 28 days of soaking of 7 days curing specimens showed the same value of efflorescence ratio without consideration to curing method or sort mixture proportion (Fig. 5). This result could also be seen on 28 days curing specimens, except packing curing method of non-cement concrete, which showed higher efflorescence ratio

than normal concrete (Fig. 6).

When the soaking period is at least 91 days, the efflorescence ratio of non-cement concrete is lower than that of normal concrete without involving the curing period or curing method (Fig. 5 and 6). It is considered that, the compounds occurred efflorescence of non-cement concrete is less than from the normal concrete; however it needs further study on this result. On the other hand, other curing method (packing curing and water curing) does not differ much on the occurrence efflorescence of the same mixture proportion concrete.

Insoluble efflorescence

Figures 7 and 8 show the relationship between insoluble efflorescence ration with respect to soaking days. For blocks cured for 7 days (Fig. 7) there is little differentiation between specimens the first 28 days after which the specimens diverge into 2 distinct profiles one for non-cement concrete and one for normal concrete. In comparison, for the blocks cured for 28 days (Fig. 8), each specimen has a distinct efflorescence ratio profile.

When the soaking period is at least 91 days, the efflorescence ratio of non-cement concrete is lower than that of normal concrete (Fig. 7 and 8). This result is independent from the curing period (7 or 28 days) and it agrees with the results of the total efflorescence ratios (Fig. 5 and 6). The test methodology proposed by the authors clearly shows that the total efflorescence and insoluble efflorescence can be measured and evaluated separately. Moreover, the soluble efflorescence can also be measured. Table 4 shows that for blocks cured for 28 days and soaked for 91 days the occurrence of soluble efflorescence of non-cement concrete was similar to normal concrete where as the insoluble efflorescence of non-cement concrete was less than that of normal concrete.

Observation of scanning electron microscope

The occurrence of efflorescence on the surface of 28 days packing curing

concrete specimens, which soaked into water for 91 days was observed by scanning electronic microscope as shown in Fig. 9 and 10. Figure 9 illustrates that the efflorescence occurring on the surface of non-cement concrete seems to be relatively round shape. On the contrary, efflorescence occurred on the surface of normal concrete is needle crystal and that crystal structure is quite different from its non-cement concrete (Fig. 10). According to our analysis on the element chemical efflorescence of non-cement concrete, much amount of existing sulfur and sodium were observed. It is considered that they are soluble alkaline salts. On the other hand, calcium element existed in the efflorescence of normal concrete products.

Even though, quantities of soluble and insoluble efflorescence were seen on the surface of both concrete products as shown in table 4, still 72% of efflorescence occurred on the surface of non-cement concrete is soluble, and 57 % of insoluble efflorescence is observable in normal concrete. It was considered that more quantities of soluble efflorescence increased on the surface of non-cement concrete because of high solubility of sodium sulfate existed. Sodium sulfate (Na_2SO_4) is formed according to the mixture proportion of non-cement products containing gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which added with sodium hydroxide (NaOH) solution. Conversely, the deposits of efflorescence on the surface of normal concrete are mostly calcium carbonate, which is not soluble. It is also considered that the calcium carbonate forms relative to cements having a high content of water-soluble alkalis, which is more compared to fly ash and blast-furnace slag. The alkalis are conducive to efflorescence because they greatly increase the solubility of carbon dioxide. It is likely that the relatively insoluble calcium carbonate is precipitated and more calcium hydroxide is leached ⁽⁴⁾.

CONCLUSIONS

Within the scope of this study, the following conclusion has been drawn.

The test method that was proposed in this paper was effective and was able to qualify the total, insoluble and soluble efflorescence of both non-cement concrete and normal cement concrete under accelerated soaking conditions.

The total and insoluble efflorescence of non-cement concrete is less than normal concrete.

REFERENCES

1. Kiyoshi Kohno, "Use of Fly Ash Having High Ignition loss for Concrete," Fourth CANMET/ACI International Conference on Recent Advances in Concrete Technology, 1998.5.
2. Kazuo Hiratuka, "Study on Dry-Concrete Substituted Cement with Industrial By-Products Containing Waste," Japan Concrete Institute Vol. 26, pp. 1485-1490, 2004.7.
3. Mano et al., "Efflorescence Testing Method of Cement Material," Japan Testing Center For Construction Materials, pp.14-19, 1982.7.
4. Adam Neville, "Efflorescence—Surface Blemish or Internal Problem?" *Concrete International*, Vol. 24, pp. 86-90, 2002.8.

Table 1-- Physical and Chemical Properties of Fly Ash

Type of Fly ash	Specific gravity g/cm ³	Specific surface area m ² /kg	Chemical composition (%)	
			SiO ₂	Ignition Loss
Fly ash	2.32	346	45.9	1.7
JIS 6201	Over 1.95	Over 250	Under 45	Under 5.0

Table 2--Mixture Proportion of Non-Cement Concrete

Type of Mixture	w/cm (%)	s/a (%)	Unit Content (kg/m ³)						
			Water	P*			Fineness Aggregate	Coarse Aggregate	NaOH **
				FA	BS	Gypsum			
Recycle	26	75	107	273	110	27	1198	400	3%

* P is the total of power content. FA is Fly ash, and BS is Ground granulated blast-furnace slag

** NaOH is Sodium hydroxide, and is used in 3% of water unit content.

Table 3-- Mixture Proportion of Normal Concrete product

Type of Mixture	w/c (%)	s/a (%)	Unit Content (kg/m ³)			
			Water	Cement	Fineness Aggregate	Coarse Aggregate
Normal	26	75	107	410	1198	400

Table 4--Comparison between Soluble Efflorescence Ratio and Insoluble Efflorescence Ratio of 91 Days Soaking

Sort of Mixture Proportion	Soluble Efflorescence ratio (%)		Insoluble Efflorescence ratio (%)	
	7 days curing	28 days curing	7 days curing	28 days curing
R-Packing	0.7	1.3	0.8	0.5
N-Packing	0.8	1.0	1.4	1.3
R-Water	0.6	1.1	0.8	0.9
N-Water	0.5	1.3	1.4	1.4

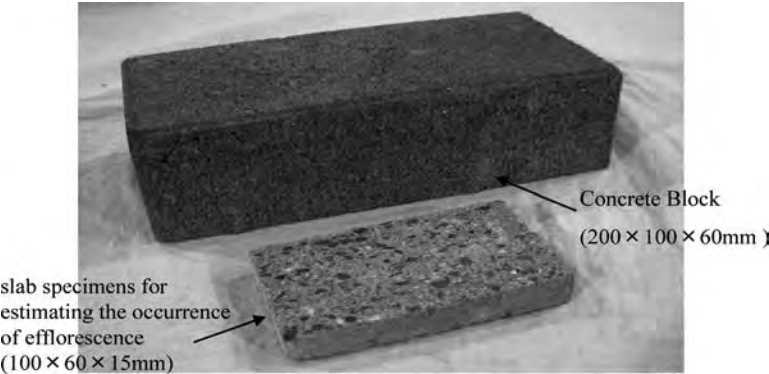


Fig. 1—Concrete block and thin slab specimen for estimating the occurrence of efflorescence.



Fig. 2—The situation of packing curing by polyethylene bag after casting.

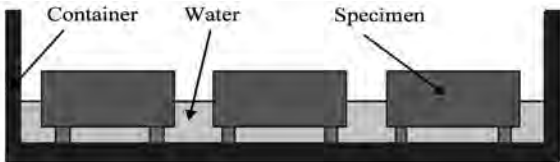


Fig. 3—Accelerating occurrence of efflorescence by soaking into water (20 °C, 60% humidity).

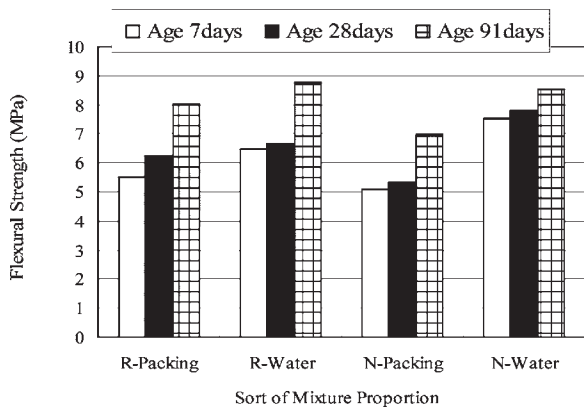


Fig. 4—Relation between flexural strength and curing days.

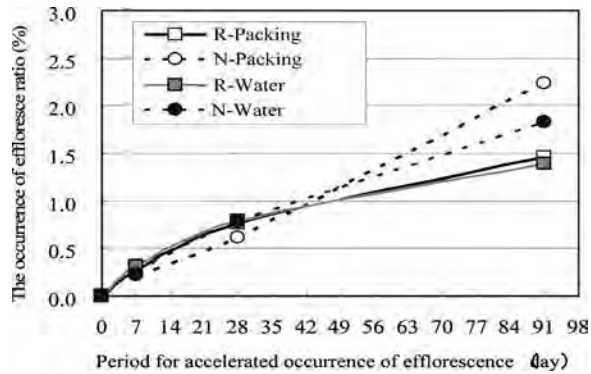


Fig. 5—Relation between total occurrence of efflorescence ratio of 7 days curing specimen and soaking days.

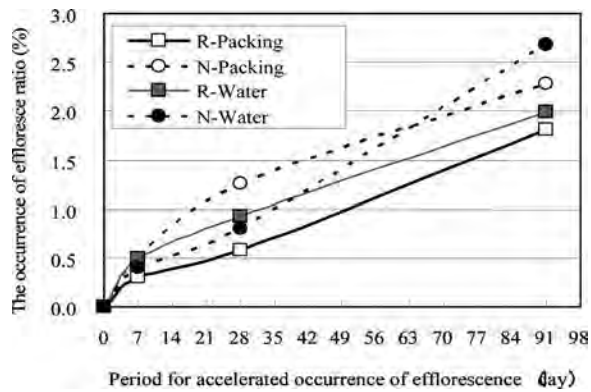


Fig. 6—Relation between total occurrence of efflorescence ratio of 28 days curing specimen and soaking days.

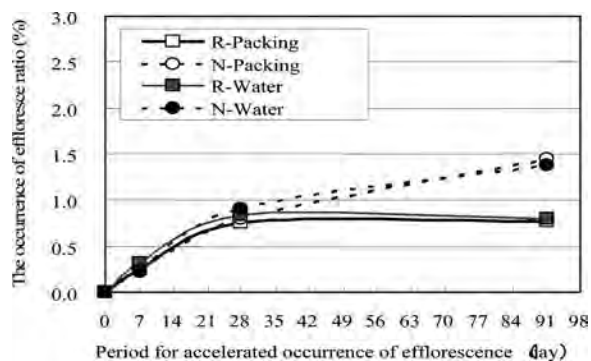


Fig. 7—Relation between insoluble efflorescence ratio of 7 days curing specimen and soaking days.

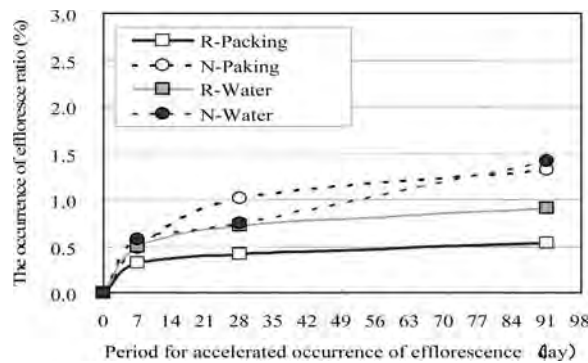


Fig. 8—Relation between insoluble efflorescence ratio of 28 days curing specimen and soaking days.

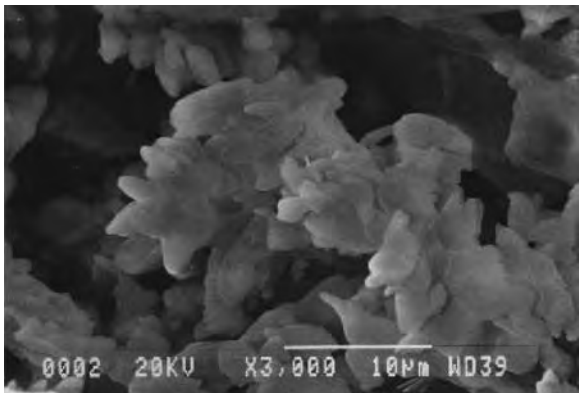


Fig. 9—Soluble efflorescence occurred on the surface of non-cement concrete product.

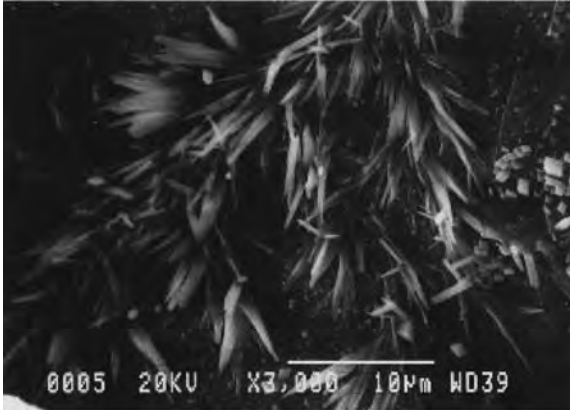


Fig. 10—Insoluble efflorescence occurred on the surface of normal cement concrete product.

The Effect of Metakaolin and Silica Fume on the Properties of Lightweight Self Consolidating Concrete

by M. Hubertova and R. Hela

Synopsis: The paper is concerned with the development of lightweight self-consolidating concrete, especially with the comparison of the effect of metakaolin and that of silica fume on the properties of this concrete. The use of metakaolin for improving the durability and for achieving better physico-mechanical properties of concrete is relatively new approach in concrete technology. The experimental works which are described in this paper used for the manufacture of lightweight self-consolidating concrete of different fractions of the expanded clay lightweight aggregate Liapor with different fractions of normalweight aggregate. The metakaolin used was of Czech production.

Keywords: lightweight aggregate; lightweight self-consolidating concrete; metakaolin; silica fume

36 Hubertova and Hela

Dipl.Ing. Michala Hubertova, Ph.D. is a research worker at the Brno University of Technology, Faculty of Civil Engineering, Institute of Technology of Building Materials and Components, Veveri 331/95, 662 00 Brno, Czech Republic, E-mail: hubertova.m@fce.vutbr.cz. She specialises in concrete technology, especially on lightweight concrete technology.

Assoc. Prof., Dipl.Ing. Rudolf Hela, Ph.D., is a lecturer and research worker at the Brno University of Technology, Faculty of Civil Engineering, Institute of Technology of Building Materials and Components, Veveri 331/95, 662 00 Brno, Czech Republic, E-mail: hela.r@fce.vutbr.cz. He is authorized engineer in the field of Diagnostics of construction structures and judicial expert in the field of civil engineering.

INTRODUCTION

Lightweight high-performance concretes including Lightweight Self-consolidating Concrete (LWSCC) and lightweight fiber-reinforced concrete are new types of concrete and therefore there is not much practical experience with their application. It is necessary to say that development of new types of concrete always faces problems caused by absence of directives for mixing and lack of practical experience.

The basic problems of proportioning, production and placing of LWSCC are high water-absorbing capacity, low density and low strength of lightweight aggregate. Hence properties of this type of concrete is affected chiefly by properties of lightweight aggregate. The fundamental task of development of LWSCC is to reach “high performance” standard using lightweight aggregate with strength below 10 MPa and bulk density up to 900 kg.m^{-3} (these are the properties of the industrially produced lightweight Liapor aggregate produced in the Czech Republic, Karlovy Vary). The principal objective of LWSCC development in this project was to reach as high strength as possible. For this reason, siliceous fly ash and reactive metakaolin were, also used as active admixtures.

METAKAOLIN

One of the first commercial applications of pure metakaolin as a concrete admixture was done by a division of CemFil Saint Gobain for production of durable glass-fiber reinforced concrete - GRC. Pure metakaolin has been used for more and more purposes in concrete technology since 1990. Metakaolin increases strength and reduces water absorption and also enhances durability in aggressive environments. It is also need for concretes in sea water, floor slabs and roads resistant to abrasion, prefabricated bridge beams and for maintenance and rehabilitation of bridges. Metakaolin can be combined with other pozzolans like fly ash, granulated micronized blast-furnace slag and silica fume.

Structure of metakaolin

Kaolin is contained mostly in clay minerals. Kaolin is created by changes in different kinds of cristal forms and amorphous glasses, e.g. spar and volcanic ash. The basic structural units of clay minerals are silicicous tetrahedrons and aluminum octahedrons. Kaolin is very chemically stable under normal conditions. Specific surface of pure kaolin (according to the method N_2 BET) is between $2000\text{--}20\,000 \text{ m}^2.\text{kg}^{-1}$. Heated to $700\text{--}900^\circ\text{C}$, kaolin loses up to 14 % of hydroxyl water and changes to metakaolin, with the

original lamellar structure becoming amorphous. Another important change of structure lies in change of structure of aluminium to tetrahedral coordination, which is most obvious in spectroscopy. Presence of typical tetrahedral AlO_4 proves existence of metakaolin. Tetrahedral aluminium is very important for pozzolan reactions of metakaolin. If the temperature rises above approximately 800°C , kaolin changes to relatively inert ceramic material like corundum, quartz and mullite. (Barnes et al. 2003)

Pozzolanic reaction of metakaolin

Metakaolin reacts with aqueous alkali forming different kinds of products depending on presence of other anions and cations, concentration of reacting ingredients and temperature. It is distinguished by three types of pozzolan reactions:

- With alkaline metal of hydroxyl group and soluble alkaline metallic silicates.
- With slaked lime.
- With portland cement, which forms alkalis, mainly Ca(OH)_2 and KOH , apart from other products of hydration. (Barnes et al. 2003)

Effect of metakaolin on basic properties of concrete with portland cement

Hardened cement paste is typically composed by volume of 20 % of CH phase, 30% of pores (filled with air or liquid) and 50% of hydrating phases of cement. Metakaolin reacts with all CH phase or with some part of it forming new hydrating phases; this changes the structure of pores (which is important where phases are in contact) and modifies composition and structure of gel phases. For these reasons, metakaolin as pozzolana can considerably change the structural and mechanical properties of cement pastes and concretes.

Metakaolin increases compressive strength by changing of the structure on the boundary of components and improving the strength of aggregate – cement paste bond. Metakaolin also slightly increases the flexural strength. It was found that Metakaolin decreases pH of water in pores in hardened cement paste reduces chloride diffusion and enhance water tightness. It was also increases the percentage of Cl/OH of ions dissolved in water in the pores. (Barnes et al. 2003)

Metakaolin used in experiments

The metakaolin used in experiments was made in the Czech republic in the factory Sedlecký kaolin a.s. It is produced in wet process from purified kaolin clay by firing at the temperature of $600 - 800^\circ\text{C}$. Chemical composition of this metakaolin is stated in table 1 and the differential thermal analysis is in Fig. 1.

An X-ray diffraction analysis was made for characteristic composition of metakaolin from the factory Sedlecký kaolin a.s. and was found to have the following composition:

- kaolinite $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$
- β -quartz SiO_2

Firing of kaolin (at 600°C) changes structure from being crystalline to being amorphous.

SILICEOUS ASHES (SILICA FUME)

Siliceous ashes (silica fume) enhances strength, impermeability and resistance to corrosion. It is used to improve these properties especially in high-performance concretes. Siliceous ash is available in two forms – in powder and in suspension with solid contents of about 50 %. To bind all CaO released during hydration of C_3S and C_2S it would be theoretically possible to add 25 - 30 % of Si ash. Such amounts of admixture is almost never used in Czech practice. As for strength, it is known that the strength of common and high-performance concretes increases considerably with 5 – 10 % addition of siliceous ash. Further addition of silica fume also contributes increase strength. (Brno University of Technology 2006)

LIGHTWEIGHT ARTIFICIAL AGGREGATE LIAPOR

Liapor (commercial name in the Czech republic) is very lightweight aggregate produced by expanding natural clay. It is a ceramic like material and is technically described as a lightweight artificial porous aggregate made from expanded clay. Particles are almost spherical with homogenous and porous inner structure enclosed in sintered surface. Basic properties are stated in table 2 and 3. (Lias Vintirov LSM k.s. 2006)

Grains of Liapor are nearly spherical, external surface is closed, inner part is porous. Figure 3 shows a section of LWSCC, where the difference between compactness of outer shell and porous inside of the Liapor lightweight aggregate is clearly visible.

METHODS OF DEVELOPMENT OF LIGHTWEIGHT SELF-CONSOLIDATING CONCRETE

The objective of the project was to create an optimal method of designing LWSCC and tests suitable for industrially produced lightweight aggregate based on expanded clays. It was necessary to deal with specific problems of high aggregate absorption capacity, which can have negative effect on the behavior of fresh concrete and on the final properties of hardened lightweight concrete. Proving the possibility of using SCC testing methods for LWSCC including determination of new criteria of testing or defining parameters of individual tests and defining properties of fresh LWSCC was another important stage. At the same time, possibility of using supplementary materials as active admixtures was tested with a view of partial substituting of cement to increase overall amount of fine parts with size up to 0,125 mm in order to enhance rheological properties of fresh LWSCC was investigated.

The method of solving the project was as follows:

- Solving of problems of proportioning of dry or wet aggregate.
- Suitability of proportioning by volume or by weight of lightweight aggregate.
- Proportioning of LWSCC solely with lightweight aggregate of different fractions and density.
- Proportioning of LWSCC with combination of lightweight and natural aggregate.
- Possibilities of proportioning with supplementary cementitious materials (in particular fly ash).
- Examining of adding ultra fine admixtures for reasons of increasing strength and improving flow characteristics

- Designing optimal algorithm for proportioning of components and times of mixing.
- Proving the possibility of using test methods used for self-consolidating concretes (SCC) for lightweight self-consolidating concretes (LWSCC).
- Testing ultra fine admixtures for the purpose of increasing strengths and enhancing other properties.

Brief summary of results of individual stages of LWSCC developments is stated in following chapter. Experiments conducted during testing of ultra fine admixtures including results are also stated below.

PROPERTIES OF LIGHTWEIGHT SELF-CONSOLIDATING CONCRETE WITH LIAPOR AGGREGATE WITHOUT ULTRA-FINE ADMIXTURES

As part of the project, more than 40 mixtures were designed with different strengths and densities. First, mixtures LWSCC solely with lightweight aggregate Liapor were designed, then combination of light-weight and natural aggregate were used. Finally ground limestone and supplementary cementitious materials, in particular fly ash were added to these mixtures.

Principles and suggestions for proportioning of LWSCC

All mixtures were designed with maximum size gradated aggregate. Lightweight aggregate Liapor is not produced in fractions bigger than 8 mm in sufficient quality. Size fractions of 0 - 1 mm, 0 - 2 mm, 0 - 4 mm, 1 - 4 mm and 4 - 8 mm were used. It is possible to use either dry or water prewet lightweight aggregate Liapor. When using dry lightweight aggregate, the mixing water consists of effective water and additional water. Certain amount of effective water is necessary for required workability; this water contributes to cementing compound and counts in W/C. Additional water is necessary for absorption of lightweight aggregate during mixing, but does not contribute the W/C ratio. The amount of additional water depends on absorbing capacity of lightweight porous aggregate which technically depends on absorbing capacity of lightweight porous aggregate, its type and size of fraction. After extensive comparing different mixtures using dry and water prewet aggregate, it was concluded, that it is much more useful to use prewet lightweight aggregate. There are two reasons: It is difficult to determine the real amount of additional water needed since individual fractions of lightweight aggregate have different rate and absorbing capacity and in practice also different initial degree of wetness, which has considerable effect on absorbing capacity. Using prewet aggregate also eliminates problems with consistency and workability. It has also been proven that using this approach will improve physico-mechanical properties in particular strength and durability of LWSCC. Values of strength of mixtures with dry aggregate were 5 MPa lower and the freezing and thawing resisting coefficient is up to 7 % lower compared to mixtures with prewet aggregate. Dry aggregate concrete mixtures showed higher loss of surface material after testing for resistance to freezing and thawing. The best way of prewetting Liapor aggregate for laboratory prepared LWSCC was to soak dry aggregate in water for 24 hours. In practice the easiest way is spray the deposit of aggregate for several days with a garden sprayer which raises the moisture content to about 20 %.

Examining suitability of proportioning by volume or by weight showed that individual mixtures can not be reproduced and meet the requirements of once verified properties including workability of individual mixtures if proportioning by weight is used. The reason is simple. Manufacturer of Liapor gives declared difference of values of volume weights of individual fractions of light-weight aggregate up to $\pm 15\%$. For example, if volume weight of aggregate is 1200 kg.m^{-3} and batch of this fraction is 100 kg.m^{-3} of concrete, in practice it can mean that by declared difference of $\pm 15\%$ the range of proportioning will be between 85 and 115 kg.m^{-3} . If it is not possible to check real volume weight in the course of production, it is necessary to use proportioning by volume instead of proportioning by weight. If it is impossible to use proportioning by volume for any reason, higher attention must be paid to determining real density of the aggregate.

To ensure sufficient amount of fine fractions, finely ground limestone was used in example mixtures, which affected positively the rheological properties and workability of LWSCC. The possibility of using supplementary cementitious materials were examined and tested. It was found that both types of fly ash were suitable for the technology of LWSCC. Mixtures with fly ash had higher values of strength and densities by as much as 15% . Still, mixtures with finely ground limestone showed better strength values.

Portland cement class 42,5 (CEM I 42,5) was used for designing and production of LWSCC. Superplasticizing admixtures based on polycarboxylates and stabilizers for light-weight pumpable concretes were used.

Using natural aggregate increases strength of LWSCC. It is dependent on observing certain rules, though. Taking into consideration the fact that the maximum size of Liapor aggregate used is only 8 mm, it is suitable to use natural sand of size fraction 0 - 4 mm. Adding normalweight aggregate of bigger size fraction causes problems. Larger particles rising and heavier grain of normalweight aggregate cause segregation with lightweight particles rising of fresh concrete.

Properties of fresh LWSCC

After examination of the suitability of test methods for fresh self-consolidating concretes for LWSCC we chose typically used methods: Slump flow, T500 Slump flow, Orimet, J – Ring and L – Box were selected. Recommended range of values for these test methods were taken from Directive (Ermeo 2005). All of them were tested immediately after mixing and after 60 and 90 minutes to ensure long-time workability, which is important in the transportation of ready mixed concretes. On the basis of the results we can say that methods used are in principle suitable for determining consistency of LWSCC but it is only necessary to adjust the criteria of tests in cases of longer time intervals of outflow discharge. This is because the density of LWSCC is lower and its kinetic energy is not as high as normalweight concretes. It is necessary to say that it does not affect final results of fresh LWSCC in terms the requirements of homogeneity and even compaction across the whole cross-section. This phenomenon is easy to understand on the basis of Slump flow test and T 500 Slump flow test of LWSCC. The concrete simply needs “more time”. As a result of measurements, adjustment of some of the criteria of methods is suggested some as - increasing the time interval of outflow discharge of fresh concrete. Increase time value of T 500 Slump flow from recommended 2 – 5 s to 5 - 10 s and increased time values of Orimet test from 1 - 5 s to 4 – 10 s is suggested.

Properties of hardened LWSCC

Combining lightweight Liapor aggregate with normalweight aggregate, above mentioned admixtures (finally ground lime stone, pozzolans) and portland cement CEM I 42,5 R in constant batch of 370 kg.m^{-3} resulted in maximal class of strength according to EN 206 LC 30/33 with dry volume weight of class D 1,6. LWSCC with natural aggregate Liapor has good freeze resistance (freeze resistance coefficient is after 100 cycles between 90 % and 98 %). Using lightweight Liapor aggregate results in good thermal characteristics (thermal conductivity coefficient up to $\lambda = 0.29 \text{ W.m}^{-1}.\text{K}^{-1}$). The thermal properties degrade when increasing proportion of normalweight aggregate are incorporated into the concrete mixture (from $\lambda = 0.33 \text{ W.m}^{-1}.\text{K}^{-1}$ for a density of 1150 kg.m^{-3} to $\lambda = 0.69 \text{ W.m}^{-1}.\text{K}^{-1}$ for a density of 1700 kg.m^{-3}). Lightweight concretes in general have low values of static elastic modulus. Values of LWSCC with lightweight Liapor aggregate only are around 1700 MPa.

EXPERIMENTAL PART

After previous research, in which maximal strength class LC 30/33 was reached by means of combining lightweight Liapor aggregate and normalweight aggregate, admixing powder and suspension silica fume and reactive metakaolin were tested for the purpose of increasing strength. These ultra fine admixtures were tested on several sets of mixtures. One of these sets is described below.

For reasons of comparison, the same amounts of cement (370 kg), admixtures (148 kg) and additives (poly-carboxylate based superplasticizer, stabilizer) were used in each of mixtures. Composition of aggregate were unchanged as well. The amount of water was between 160 and 170 l depending on admixture used so that individual mixtures were of the same consistency. The basic and reference mixture (Mixture 1) was proportioned with 40 % of weight of cement substituted by finally ground lime stone. This mixture was modified by 5 % of metakaolin (Mixture 2), 10 % of metakaolin (Mixture 3) and 10 % of suspension silica fume (Mixture 5) of weight of cement and effect of admixtures on rheological properties of fresh concrete and physico-mechanical properties of hardened concrete were tested. Table 4 states individual mixtures. Rheological properties of these mixtures are stated in Table 5 and their basic physico-mechanical properties are stated in table 6. Figure 4 shows the comparison of compressive strengths.

DISCUSSION OF RESULTS

To increase strength and durability of concrete, the following supplementary cementitious admixtures were tested: fly ash, silica fume and metakaolin. After 28 days, mixtures with 10 % of powder silica fume admixture had the highest values of strength, higher by 35 %. Micro silica and metakaolin increased also splitting tensile strength, by 20 %. All mixtures mentioned belong to volume weight class D 1,8 (according to EN 206). In view of the fact that compared concretes had different densities, the direct comparison is not appropriate. Therefore it is more suitable to compare coefficients of structural efficiency (strength/density ratio). Mixtures with silica fume reached the highest structural efficiency coefficient. Mixtures with admixture of 10 % powder silica fume had higher values of strength than mixtures with admixture of 10 % suspension silica fume. Batch of 10 % of metakaolin does not seem to be economical, because the value of strength is not noticeably higher compared to 5 % batch. The results show that admixtures of metakaolin and micro silica positively affect strength of LWSCC. However it is necessary to

consider using of silica fume and metakaolin primarily for reasons of higher cost. On the other hand, if price of 1 m^3 in relation to strength is considered, using these expensive admixtures does not necessarily mean loss. This is confirmed by mixtures with 5 % of metakaolin, where the price/strength ratio is the best.

Previous research suggests that self-consolidating concrete is not resistant to chemical anti-freezing agents (CHRL). It has been proved that metakaolin significantly increases this resistance. Batch of 10 % of metakaolin decreased loss from 2500 g.m^{-2} to 850 g.m^{-2} . Still, it has to be said that resistance of this kind of concrete to chemical anti-freezing agents is in general very low. All mixtures showed excellent resistance to freezing and thawing with values between 90 % and 100 %. Admixtures of silica fume and metakaolin increased this coefficient on average by 5 %.

It is more difficult to compare physico-mechanical properties of individual mixtures of lightweight concrete because variance of results is higher than variance of results of standard concretes with natural aggregate. The reason is variation of density of lightweight aggregate. Manufacturer of the Liapor aggregate states declared variance of volume weight as high as $\pm 15 \%$. Neither W/C is so weighty as it is usual with common high-density concrete. It is caused mainly by high absorbing capacity of Liapor aggregate. Literature (Aitcin 2005) says that with porous aggregate it is possible to produce lightweight concrete with strength up to 100 MPa but all authors agree that it is possible to reach such results only with particular porous aggregate. Absorption rate and capacity of porous aggregate is another important characteristic. Aggregate with high absorbing capacity that are not prewetted can cause problems in some cases. For example, absorbing capacity of different fractions of Liapor varied after one day of soaking from 10 % to 38 %. Other problems may be caused by different absorbing capacity of different batches and different fractions of porous aggregate, which makes production of concrete with guaranteed properties more difficult.

CONCLUSION

As for rheological properties, all mixtures fulfilled the requirements of self-consolidating concretes. Since lightweight concrete has lower kinetic energy, it flows more slowly than normalweight concrete. Admixtures of metakaolin and silica fume made rheological properties of LWSCC slightly worse. Considering the strengths reached, this special concrete can be used not only for reconstruction of old buildings and prefabrication technique but also for bearing monolithic structures.

Acknowledgment

The research work presented in this paper has been supported by the VVZ MSM 0021630511 "Progressive Building Materials with Utilization of Secondary Raw Materials and their Impact on Structures Durability." and through the project GA 103/05/2687 which is sponsored by Czech Science Foundation.

REFERENCES

Barnes, P., Bensted, J., and Jones, T.R., *Structure and Performance of Cements*. 2nd edition. Chapter 15, Metakaolin as pozzolanic addition to concrete, pg. 372-398. ISBN 0-419-23330-X. England, 2003.