An Experimental Study on the Engineering Properties of Lightweight Aggregate Concrete

경량골재 콘크리트의 공학적 성질에 관한 실험적 연구

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요 약

건설기술과 산업의 발전에 따라 구조물은 대형화되어 가고, 건설공사의 급격한 팽창으로 골재 수요량이 급증함에 따라 천연골재자원은 점차 부족현상을 면치 못할 처지에 있다. 또한, 무리한 천연골재의 채취는 자연환경을 훼손시킬 뿐만 아니라 자연보호 측면에서도 심각한 공해문제로 대두되고 있어 공급량 부족현상은 날로 심화되고 있다. 이에 세계 몇몇 나라에서는 산업부산물을 이용한 골재 생산으로 공해예방과 폐기물 활용방법을 연구하고 있다. 산업부산물중 플라이 애쉬 생산량은 전 세계적으로 매년 약 2억여톤에 달하고 있으나 이중 일부만 활용되고 있는 실정이다. 이와같은 부산물을 활용하기 위한 일환으로 산업부산물인 PFA(Pulverized Fuel Ash)로 만든 인공경량골재의 년생산량이 영국은 600,000m^3, 미국은 300,000m^3이며, 매년 증가추세에 있다.

고성능 경량골재 콘크리트는 단위중량의 증가없이 내구성과 강도를 향상시켜 실용화 측면에서 경제적인 효과가 있으며, 플라이 애쉬로 만든 경량골재는 시멘트와의 친화력이나 접착면에서 우수한 것으로 알려져 있다.

본 시험에 사용한 골재는 플라이 애쉬로 만든 인공경량 조골재와 강모래이고, 결합제로서 포틀랜드 시멘트를 사용하였다. 부수적인 결합재로서는 플라이 애쉬, 슬래그, 실리카 흄을 사용하였으며, 고성능 경량골재 콘크리트를 개발코자 재령 28일과 180일의 압축강도가 각각 50MPa와 60MPa가 되도록 배합설계를 하였다.

본 연구에서는 플라이 애쉬, 슬래그, 실리카 흄과 같은 산업부산물을 혼입했을때 경량골재 콘크리트의 압축강도, 휨강도, 동탄성계수, 공극체적, 공극률, 단위중량, 공극 크기별 분포등의 변화를 실험적으로 구명하여 제반 구조용 콘크리트에 활용하기 위한 기초자료를 마련코저 한다.

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I. Introduction

Lightweight aggregate concrete, incorporating fly ash(FA) as partial replacement of cement and utilizing coarse aggregate made from FA, occupy a unique position in the aspect of the large quantities of fly ash available in many parts of the world. Another uniqueness of FA lightweight aggregate concrete is the excellent aggregate matrix bond that develops between the fly ash aggregate and portland cement or portland cement fly ash matrix[3]. Tests show that there is a close chemical affinity among the constituents of this type of concrete and also there is evidence that this contributes to the enhanced strength and durability of the concrete. Extensive test data on mix design and physical properties of FA aggregte concrete are now available[4]. Tests on reinforced concrete beams made with such aggregates show that structural members have adequate ductility and factors of safety at failure, and strains of 2,500 to 5,000 microstrains can be developed prior to failure[6].

Equations are also developed to predict the shear strength of beams made with FA aggregates[5]. Short fibres can also be incorporated in lightweight aggregate concretes to enhance their toughness and ductility, and these properties can be utilized to further improve the structural behaviour of beams and slabs[8].

Because of the economical, practical and technical benefits of lightweight aggregate concrete, a high performance concrete will have special attractions for applications in offshore and marine structures, high buildings and long span bridges. A decreasing density without reducing strength or increasing strength without increasing density combined with high durability can lead to cost effective engineering solutions. Supplementary cementing materials such as fly ash, slag, silica fume, etc. are known to be able to contribute to the improvements of strength and durability. For example, silica fume has been extensively used in the development of high strength lightweight aggregate concrete[1,2,9].

The overall objective of this project is to develop a high performance concrete using fly ash and slag, together with a highly reactive pozzolan like silica fume.

II. Experimental Program

Four concrete mixtures as shown in Table-1 were used in the study. All the mixes were equal in the aspects of total cementing content and free water/binder(W/B) ratio. The mixes were so designed to have the same amounts of fine and coarse aggregates. And a superplasticizer(SP) was added, the amount of which was adjusted to give workable consistencing with a slump of 100 to 150mm. The main variable in the mixes was the composition of the cementing content : as shown

Table-1. Mix design of lightweight aggregate concrete

Mixes No.	Cement (kg/m³)	SF (kg/m³)	Slag (kg/m³)	FA (kg/m³)	Sand (kg/m³)	Lytag (kg/m³)	Free (W/B)
N	350	–	–	–	635	715	0.4
F	300	20	–	30	635	715	0.4
S	300	20	30	–	635	715	0.4
SF	250	10	45	45	635	715	0.4

in Table-1 silica fume was used in all the mixes, and fly ash ground granulated blast furnace slag(GG/BFS) or both were used as additional supplementary cementing materials. This study was carried out was to identify the composition of a cement matrix that will guarantee high durability and strength for lightweight concrete.

1. Materials

All the cementing materials used in the mixes are conformed with their respective BS Codes. The portland cement, ASTM Type 1, had a specific surface of 365m^2/kg and a total equivalent sodium oxide alkali content of 0.83%. The slag had a fineness of 417m^2/kg whilst the fineness of the fly ash expressed as the mass proportion of the ash retained on a 45μm mesh was 7.6%. The silica fume was used in liquid form with 50% solid contents.

Natural sand, with a fineness modulus of 2.04, was used as fine aggregate. The coarse aggregate was the lightweight aggregate (LW) made from sintered pulverized fuel ash (trade name "Lytag") with a maximum size of 14mm. Two parameters associated with lightweight aggregates generally influence on mix design such as moisture content and water absorption. The Lytag aggregates were initially dried to a constant moisture content of 0.6%. The water absorption of the Lytag aggregates after 30 seconds, 30 minutes and 24 hours were 9.0%, 9.7% and 13.5 % respectively and an average value of 12% was adopted for mix design purposes[4].

2. Manufacture and Curing of Specimens

A special mixing procedure was adopted to reduce bleeding as well as the early loss of slump. The fine and coarse aggregates were initially mixed for 2 minutes with half of the total amount of water containing the liquid SF; cement and other cement replacement materials were then added together with the rest of the water and mixed for another 2 minutes. Half of the total amount of SP was then added, and mixed for 1 minute, and then the remaining SP was added and mixed for 1 minute. A cohesive composite concrete mix with good flowability properties was thus obtained.

All the specimens were cast in steel moulds and internally vibrated. After demoulding in 24 hours, two different curing regimes were used : continuous water curing and 7 days water curing followed by exposure to ambient air conditions.

3. Methodology

Various engineering properties of the concrete mixtures were obtained : flexural strength was measured on 100×100×500mm prisms ; modified compressive strength was obtained from the broken halves of the prisms ; dynamic modulus of elasticity and ultrasonic pulse velocity were also obtained. Two microstructural properties were investigated ; pore structure of the mortar in the concretes through mercury porosimetry. The pore structure tests were carried out at 180 days. The spcimens were cut into 5mm thick slices using a diamond saw, and small pieces of mortar were selected by removing all aggregates from the slices. The samples were oven dried at 105℃ for 24 hours and then cooled in a desiccator. In the tests, the contact angle between mercury and the surface of the sample was fixed at 130° and the surface energy was assumed as 485dyn/cm.

Ⅲ. Results and Discussion

1. Strength

The compressive strength of the concretes tested are shown in Table-2. These data reveal that the hydration process of FA and slag with portland cement is a two stage process. Early strength of concretes with supplementary cementing materials are dependent on the amount and type of portland cement. But the long term strength are dependent on the type and amount of mineral admixture[7].

The addition of a highly reactive pozzolan like silica fume can compensate for the loss of early age strength as shown in Table-2. The degree of compensation is dependent on the type of pozzolan and the mix design technique. According to the data shown in Table-2, mixes F and S showed lower compressive strengths at 1 day, however, at more than 3 days both of these mixes had similar compressive strength for the control mix N. At 28 days and 180 days all mixes showed similar compressive strengths. These results demonstrate that FA and slag had almost similar effects on the strength of lightweight aggregate concrete.

Mix SF with a relatively lower portland cement content (replacement materials 28.6% of total binder compared to 14.3% in mixes F and S) showed a lower strength at 1 day, about 60% of that of the control mix N, but showed nearly the same strength with those of the mixes N, F and S at both 28 days and 180 days. These results demonstrate the effects of pozzolanic action of mineral admixtures such as FA and slag, and the importance of mix design techniques of tapping and mobilizing their ability to contribute to the strength.

The flexural strengths in Table-3 show that at low replacement levels(14.3% of total binder), the flexural strength is little affected at more than 3 days. Mix SF with 28.6% of total binder replacement showed lower strength than that of the other mixes, but even then, by 28 days and thereafter, even this mix had flexural strength(5.43 MPa)

Table-2. Compressive strength depending on curing age(MPa)

Mixes	Curing age(days)						
No.	1	3	7	28**	28*	180**	180*
N	31.3	36.6	48.0	53.8	59.0	61.1	61.7
F	27.3	34.3	42.8	48.0	53.8	59.9	62.1
S	25.0	39.1	41.7	50.4	55.6	63.2	65.6
SF	17.4	31.3	36.5	46.1	49.2	59.4	56.6

** wet curing   * 7days wet/air curing

Table-3. Flexural strength depending on curing age(MPa)

Mixes	Curing age(days)						
No.	1	3	7	28**	28*	180**	180*
N	4.35	5.01	5.52	5.73	2.97	5.48	5.55
F	3.78	4.96	5.33	5.75	2.60	5.77	5.80
S	4.44	5.11	5.27	5.95	2.91	4.93	5.25
SF	3.49	4.62	4.85	5.43	3.39	5.13	5.36

** wet curing   * 7days wet/air curing

comparable to mixes N, F and S(5.7 to 6.0 MPa).

The fly ash mix F showed the highest flexural strength at 180 days among the all other mixes. This might be attributed to the better bond between the fly ash LW aggregate and fly ash cement matrix, as has been reported earlier[3].

2. Dynamic Modulus of Elasticity

The development of the dynamic modulus of elasticity for all of the four different mixes is shown in Fig. 1. All concretes containing supplementary cementing materials have higher dynamic modulus than the portland cement concrete by about 10 to 15%. FA and slag concrete mixes have almost the same dynamic modulus at all ages, whereas mix SF with a lower portland cement content shows slightly lower value than those of mixes F and S.

3. Effects of Air Curing

Concrete structures are not continuously exposed to a humid environment. Very often, they are exposed to a dry environment, sometimes from an early age. Air drying, particularly at early ages, can cause bad effects on

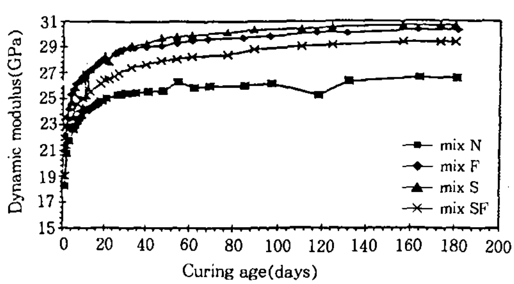

Fig. 1. Variation of dynamic modulus with age(wet curing only)

concrete properties. These effects have been investigated by adopting a curing regime of 7 days water curing followed by exposure to ambient conditions. The results are shown in Table-2 and Table-3, and Fig. 2 and Fig. 3.

Table-2 also shows the effect of curing on compressive strength. Concretes cured continuously in water has a slightly lower strength at 28 days than those exposed to air drying after 7 days. But at 180 days both curing regimes show similar compressive strength. There is no substantial and consistent difference owing to the curing methods, unlike the well known tendency of apparent strength increasing when exposed to dry environment before loading. The prolonged air curing has shown no adverse effect at 180 days. Probably this may be due to the moisture released by the porous aggregates. Moisture is effective on further hydration of the binder materials. The effect of air curing is most apparent in the flexural strength as shown in Table-3 at 28 days of age. The specimens cured in air are still in the process of drying, and the surface microcracking due to the moisture causes a major reduction in strength. All of the concretes together with portland cement concrete exhibit this phenomenon. But it is interesting that supplementary cementing materials show no significant disadvantage compared with portland cement concrete in this respect. However, once moisture equilibrium is secured, the loss of strength is fully recovered. All of the concretes with mineral admixtures compare well with the portland cement concrete, as far as flexural strength is concerned.

From of Table-2 and Table-3, it is found that flexural strength is much more sensitive than compressive strength in the aspects of moisture loss and air drying. This property can be critical when moisture loss happens before moisture equilibrium is secured. Table-3 shows that this period may extend up to about five months. Thus this may be a critical factor if structural elements are subjected to external loading during this period. The strength recovery is partly due to the healing of cracks as moisture equilibrium is secured. But such healing does not take place so easily in the presence of external loads. Structures exposed to aggressive environments may thus suffer a lose long term durability.

The effects of drying on dynamic modulus of elasticity for the four concrete mixes are shown in Fig. 2. Once drying starts, dynamic modulus does not increase any move: Actually there is a progressive reduction in the elastic modulus and, at six months, all the mixes had about the same value of dynamic modulus of about 24 to 25 GPa, which could be compared to the values of 29 to 31 GPa at the same age for the concretes with mineral admixtures cured in water.

Two important implications are stood out here. The contribution to both long term strength and stiffness of mineral admixtures depends very much on the continuous hydration process. But in a dry environment, this phenomenon is no longer found.

This loss in stiffness with the lapse of time is consistent with the pulse velocity shown in Fig. 3 for all concrete mixes exposed to air drying after the initial 7 days of water curing. The pulse velocity reflects the internal

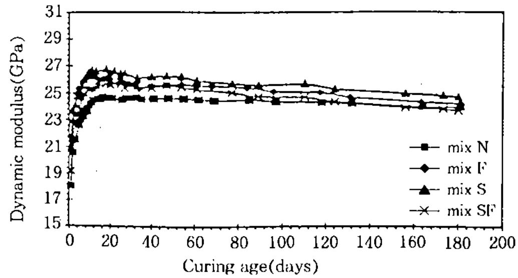

Fig. 2. Effect of dynamic modulus with age (initial 7days wet curing and air curing)

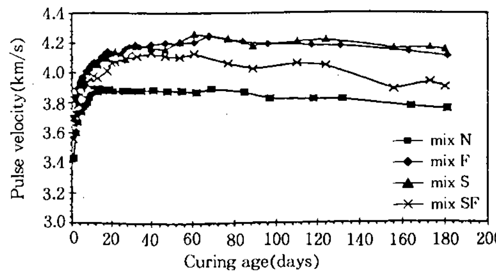

Fig. 3. Variation of pulse velocity with age (initial 7days wet curing and air curing)

structure of the concrete. Fig. 3 shows that even though exposed to a dry environment, concretes with mineral admixtures can have more sound and dense internal structure. Table-2 and Table-3, and Fig. 1 to Fig. 3 show the benefits to be derived from the concrete with mineral admixtures incorporated when new structures are to be exposed to drying conditions soon after demoulding, the use of a membrane can help concretes with mineral admixtures attain their full strength and stiffness.

4. Porosity

The mercury intrusion porosimetry tests were carried out at 180 days for the specimens of two different curing conditions. The results are shown in Table-4. As shown in Table-4, the mortar containing slag and SF

Table-4. Variation of pore volume, porosity and density

Specimen No.	Intrusion Volume (mℓ/g)	Porosity (%)	Density (g/mℓ)
N-10**	0.0550	11.79	2.1434
F-10**	0.0495	10.38	2.0976
S-10**	0.0395	8.35	2.1134
SF-10**	0.0507	10.70	2.1089
N-7*	0.0569	12.19	2.1427
F-7*	0.0593	12.23	2.0624
S-7*	0.0439	9.24	2.1073
SF-7*	0.0557	11.14	1.9985

**wet curing *7days wet/air curing

has exhibited the least total intrusion volume under both curing conditions. All samples with mineral admixtures except the FA have shown better pore structure than that of the portland cement mortar. FA mortar showed slightly higher pore volume and porosity than that of the portland cement mortar under the wet/air dry conditions.

Tabel-4 also shows the effects of continued air drying on the porosity of concrete samples. All the samples have shown higher pore volume and porosity than those under continued water curing. But, all specimens with mineral admixtures show better performance than the controlled portland cement mix. The fly ash mix, however, showed worse performance than the one controlled.

5. Pore Size Distribution

Fig. 4 and Fig. 5 show the effect of cement replaced materials on the pore size distribution in mortar under wet curing and 7days wet/air curing condition, respectively. Of all the mixes tested, the slag mortar mix showed the best performance in the aspect of pore refinement. The mix SF exhibited a better pore refinement than the fly ash mix. This is probably due to the higher volume of pozzolanic materials. It is also indicated that the fly ash mix is more sensitive to air drying. However, even with a marginally high total pore volume, the fly ash mix does show better pore refinement than that of the control mix(Fig. 4 and Fig. 5). Fig. 4 and Fig. 5 thus show that supplemental cementing materials decrease the volume of coarse pore and increase the volume of fine pore in mortar.

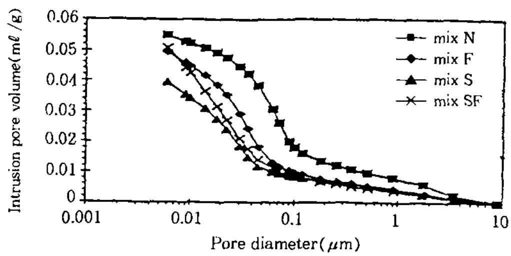

Fig. 4. Pore size distribution(wet curing only)

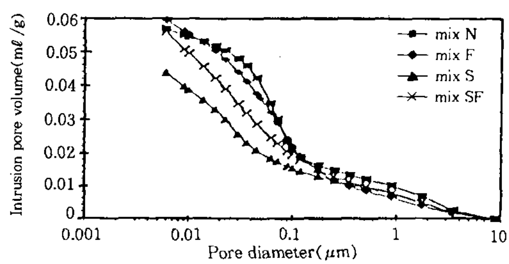

Fig. 5. Pore size distribution(initial 7days wet curing and air curing)

IV. Conclusion

The major results of this study are summarized as follows;

Using fly ash lighweight aggregates and a total cementitious content of 350kg/m^3 incorporating fly ash and/or slag together with a small amount of a highly reactive pozzolan such as silica fume, compressive strengths of about 50 MPa at 28 days and 60 MPa at 180 days have been developed. These concretes had flexural strengths in excess of 5 MPa and elastic modulus of 25～30GPa. Exposure of these concretes to a dry environment, however, decreased flexural strength until moisture equilibrium was restored, and elastic modulus, as in normal concrete, and this should be cosidered in design, However, even then pulse velocity showed that concretes with mineral admixtures can have more sound and dense internal structure.

Concrete with mineral admixtures showed a much better pore structure and pore refinement than concrete without them, and this quality was maintained even when the samples were exposed to air drying. Overall, mixtures with slag showed the best properties in terms of pore structure. Surprisingly, concrete with 250kg/m^3 portland cement and 100kg/m^3 of mineral admixtures was nearly as good as concrete with 300kg/m^3 cement and 50kg/m^3 of mineral admixtures.

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