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Mechanical Behavior of Steel Fiber Reinforced Lightweight Polymer Concrete

강섬유보강 경량 폴리머 콘크리트의 역학적 거동

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Abstract

In this study, the physical and mechanical properties of steel fiber reinforced lightweight polymer concrete were investigated experimentally with various steel fiber contents. All tests were performed at room temperature, and stress-strain curve and load-deflection curve were plotted up to failure.

The unit weight of steel fiber reinforced lightweight polymer concrete was in the range of 1,020~1,160 kg/m^3, which was approximately 50% of that of the ordinary polymer concrete. The compressive strength, splitting tensile strength, flexural toughness and flexural load-deflection curves after maximum load were shown with increase of steel fiber content. The stress-strain curves of steel fiber reinforced lightweight polymer concrete were bilinear in nature with a small transition zone.

Based on these results, steel fiber reinforced lightweight polymer concrete can be widely applied to the polymer composite products.

Keywords : Lightweight polymer concrete, Steel fiber, Strength, Stress-strain curve, Flexural toughness, Load-deflection curves

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I. Introduction

Polymer concrete (PC) and mortars (PM) have gained an increasing research interest due to their wide range of possible applications in civil construction.[3),9),11)] In this class of materials, a thermoset resin is used as binder of natural or artificial aggregates, replacing the paste of Portland cement/water of conventional hydraulic concretes. The most commonly used resins have been unsaturated polyesters, acrylics and epoxies, but vinyl ester, furan and urethane, have also been applied. The initial applications of PC, in the late 1950's, were the production of building cladding and cultured marble. But, its excellent properties rapidly widespread its application fields. Its rapid curing, excellent bond to concrete and steel reinforcement, high strength and durability made it a very attractive repair material. As a mortar it can be placed with thickness less than 10 mm. Overlays in PC, for bridge surfaces and floors, have also become widely used because of the ability to use thin layers, fast curing time, very low permeability, and high resistance to chemical and frost attack. Precast components are another excellent use of the material. The high strength to weight ratio, good damping properties, moldability and ability to form complex shapes make PC and PM's particularly attractive for these applications.[3]

The main limitation of concrete polymer materials is their cost. The cost per unit volume of polymer concretes is still significantly higher than Portland cement concrete. The higher cost of polymer concretes makes its use almost forbidden for high volume applications. One way to minimize this limitation is the development of a lightweight polymer concrete.

Artificial lightweight aggregates have been produced since the beginning of the 20th century in the US, and since the 1960's, the examples of concrete structures made with lightweight aggregates have multiplied throughout the world.[4] But, only in the 1970's, a broad research effort in lightweight aggregate concrete was achieved.[1] Since then, several investigations on Portland cement concrete and mortars with lightweight aggregates have been reported and there are worldwide environmental, economic and technical impetuses to encourage the structural use of these materials.[11]

The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Flexural strength, fatigue strength, tensile strength and the ability to resist cracking and spalling are also enhanced. To design and analyze structures using steel fiber reinforced concrete for compression, the stress-strain behavior of the material in compression is needed. While the compressive strength is used for the strength calculation of the structural components, the stress-strain curve is needed to evaluate the toughness of the material for consideration of ductility.

In this paper, the physical and mechanical properties of steel fiber reinforced lightweight polymer concrete under load are investigated experimentally with various steel fiber contents (vol.%).

Ⅱ. Materials

1. Unsaturated polyester resin

Unsaturated polyester resins are chosen as binders. Their superior chemical and mechanical properties, combined with their lower cost when compared with epoxy materials, as well as their wide commercial availability, make polyester resins the most widely used polymer in PC compositions.[8] Its general properties are shown in Table 1.

Table 1 General properties of unsaturated polyester resin

Type	Specific gravity	Viscosity (25℃, Poise)	Styrene content (%)	Acid value
Ortho	1.12	3.5	37.2	26.5

2. Initiator

Mineral turpentine solution with 8% of cobalt octanoic (CoOc) solution is generally used as an accelerator, and the DMP solution with 55% of Methyl Ethyl Ketone Peroxide (MEKPO) is used as initiator. Since UP resin has already been added by hardening accelerator when it was produced in a factory, it begins to harden immediately after being added with the initiator. The properties of initiator are shown in Table 2.

Table 2 General properties of initiator

Component	Specific gravity (25℃)	Active oxygen (%)
MEKPO 55% DMP 45%	1.13	10.0

3. Shrinkage Reducing Agent

In order to reduce the shrinkage, shrinkage reducing agent(SRA) is made by dissolving the thermal hardening plastic polystyrene in styrene monomer. Its general properties are shown in Table 3.

Table 3 General properties of shrinkage reducing agent

Type	Specific gravity (25℃)	Viscosity (25℃, Poise)	Styrene content (%)
SR-A	0.96	12.6	69.0

4. Filler

The fillers including powder of fly ash, heavy calcium carbonate, alumina, blast furnace slag powder, silica, cement, stone dust and so are commonly used.[12] Among these, the heavy calcium carbonate is used in this study since it is relatively cheap and easy to buy. The filler is dried at 100±5℃ for one day before use.[7] The physical properties of filler are shown in Table 4.

Table 4 Physical properties of filler

Bulk density (kg/m³)	Specific gravity (20℃)	Specific surface (Blain) (cm²/gr)
620	2.91	3,150

5. Aggregates

Coarse aggregate used is artificial lightweight aggregate and fine aggregate used is perlite. The artificial lightweight aggregate is manufactured from expanded clay. The perlite is a glassy volcanic rock, when heated rapidly to the point of incipient fusion (900 to 1100℃), expands due

Table 5 Physical properties of aggregates

Aggregate	Size (mm)	Specific gravity (20℃)	Absorption (%)	F.M	Unit weight (kg/m³)
Coarse	4.76 - 10	1.12	21	5.60	864
Fine	1.2 - 0.15	0.40	20 <	2.00	60

to the evolution of steam and forms a cellular. In this study, the perlite is used artificial expanded perlite. These aggregates are dried at the temperature of 100±5 ℃ for one day. The physical properties of aggregates are shown in Table 5.

6. Steel Fiber

Fiber used is hooked-type steel fiber. The general properties of steel fiber are shown in Table 6.

Table 6 General properties of steel fiber

Length (mm)	Diameter (mm)	Aspect ratio	Specific gravity (20℃)
35	0.55	65	7.85

7. Mix Proportions

For the purpose of evaluating the effect of steel fiber content for the lightweight polymer concrete, the mix proportions as shown in Table 7 are designed. The volume percentages of steel fiber to lightweight polymer concrete are 0%, 0.5%, 1.0%, and 1.5%.

8. Manufacture and Curing of Specimens

Specimens are prepared according to the Korean Standard Testing Methods, KS F 2419 (Specimen preparation methods for strength measure of polyester resin concrete).

Mixing was done using a conventional concrete mixer for a period of about three minutes. Specimens were then cast in moulds, vibrated, and allowed to cure at room temperature. All the specimens are demolded after being cured for three hours, and cured again to the curing age 7 days. Curing took place because the styrene combined with the reactive double bonds of the polyester chains, thus linking them together and forming a strong three-dimensional polymer network.

Ⅲ. Methodology

1. Unit weight

Unit weight of a steel fiber reinforced lightweight polymer concrete was evaluated from the following equation.

Table 7 Mix proportions of steel fiber reinforced lightweight polymer concrete

(Unit: wt. %)

Mix type	Binder		Filler	Coarse aggregate	Fine aggregate	Steel fiber
	U.P	S.R.A				
SRLP-N	29.75	5.25	23.0	29.38	12.62	-
SRLP-A				26.63	12.17	3.20
SRLP-B				23.97	11.79	6.24
SRLP-C				21.47	11.41	9.12

*SRLP: steel fiber reinforced lightweight polymer concrete
*Steel fiber content for total volume of polymer concrete: N: 0.0%, A: 0.5%, B: 1.0%, C: 1.5%

$$UW = \frac{W_c}{V_c}\ (kg/m^3) \quad \cdots\cdots (1)$$

where, W_c is weight of lightweight polymer concrete, and V_c is volume of lightweight polymer concrete.

2. Strengths and stress-strain curve

Compressive and splitting tensile strength tests were carried out according to the KS F 2481 (Compressive strength test method for polyester resin concrete) and KS F 2480 (Splitting tensile strength test method for polyester resin concrete), respectively. The size of the cylindrical specimens was ø75×150 mm. The strains were measured by means of electrical strain gauges that were longitudinally and laterally bonded to the specimens at mid-height and connected to a data acquisition system. Compressive strength test set-up is shown in Photo 1.

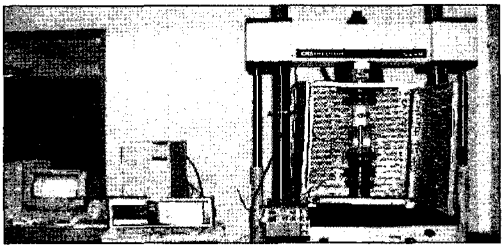

Photo 1 Compressive strength test set-up

3. Flexural toughness

The load was exerted by an Instron 1205 testing machine with displacement control. The central deflection was measured by LVDT and recorded using a digital recorder. To evaluate the toughness of the beam specimens, toughness indices calculated in accordance with ASTM C1018-89 were used. For the work presented here, the three well established toughness indices were calculated i.e. I5, I10 and I30. In essence, the indices are expressed as the areas under the load-deflection curve at set multiples of the first crack deflection, divided by the area to the first crack deflection.[5)]

Fig. 1 illustrates the method by which the toughness indices were calculated. Area A represents the energy required to cause the concrete matrix to crack and the behaviour changes from an elastic one to a non-linear behaviour. On the other hand, areas B, (B+C) and (B+C+D) represents the energy absorbed to cause the specimen to deflect to reach deflections of $3\delta_c$, $5.5\delta_c$ and $15.5\delta_c$ respectively (where δ_c = deflection at first crack). In this study, δ_c, was determined from the load-deflection curves. Thereafter, the calculation of the relevant toughness indices was straightforward.

By referring to Fig. 1, the toughness indices are calculated as follows:

$$I5 = \frac{A+B}{A} \quad \cdots\cdots (2)$$

$$I10 = \frac{A+B+C}{A} \quad \cdots\cdots (3)$$

$$I30 = \frac{A+B+C+D}{A} \quad \cdots\cdots (4)$$

The toughness indices I5, I10, and I30 have a minimum value of 1.0 for elastic-brittle behavior and values of 5, 10, and 30 for elastic plastic behavior. The size of the beam specimens was 50×100×500 mm.

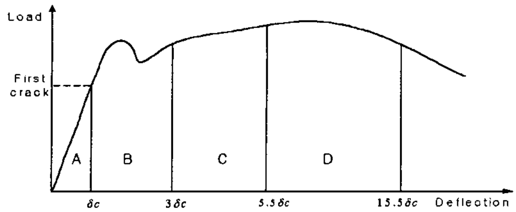

Fig. 1 Areas under the load-deflection curve used to determine toughness indices

Table 8 Mechanical properties of steel fiber reinforced lightweight polymer concrete

Mix type	Unit weight (kg/m^3)	Strength (MPa)		Toughness index		
		Com-pressive	Splitting tensile	I5	I10	I30
SRLP-N	1,020	26.38	3.33	-	-	-
SRLP-A	1,070	28.83	4.22	2.3	3.5	4.6
SRLP-B	1,110	32.85	5.39	3.8	5.6	7.7
SRLP-C	1,160	34.52	6.08	5.0	7.0	9.2

Ⅳ. Results and Discussion

1. Unit weight

Table 8 shows the results of unit weight tests on steel fiber reinforced lightweight polymer concrete. Unit weight of reinforced lightweight polymer concrete ranged from 1,020 to 1,160 kg/m^3 and it is largely dependent upon the mixture proportions. The unit weight of steel fiber reinforced lightweight polymer concrete was mainly affected by fiber content.

2. Strengths

Table 8 shows the compressive and splitting tensile strengths of steel fiber reinforced light-weight polymer concrete.

At failure, the lightweight polymer concrete shattered violently and the remaining core of the cylinders had either a cone shape or a near vertical failure surface. Photo 2 shows the failure mode of cylindrical specimens in lightweight polymer concrete with and with out fibers.

Compressive strength was increased as steel fiber content was increased. For steel fiber reinforced lightweight polymer concrete, the ultimate strength of polymer concrete is mainly controlled by the strength of the lightweight coarse aggregate. Under uniaxial compressive strength, longitudinal strain and lateral strain occurred in concrete, and the concrete defor-mation continuously increased with increasing in load. When lateral strain extended to the ultimate tensile strain of coarse aggregates, cracks occurred in coarse aggregates in concrete. The incorporation of steel fiber into the matrix serves to increase the ultimate compressive strength by the resultant arrested growth of cracks based on the bond of steel fiber and polymer paste.

Generally speaking, the improvement of splitting strength with similar content and type of fiber is more effective for lightweight concrete than that of the normal weight concrete. Therefore, in order to achieve similar increase in tensile strength for fiber reinforced normal weight concrete, a higher content ratio of fiber

Photo 2 Failure modes of lightweight polymer concrete

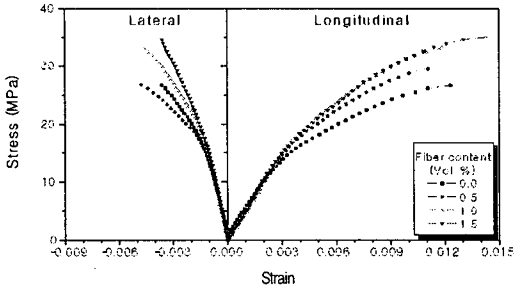

Fig. 2 Stress-strain curves of steel fiber reinforced lightweight polymer concrete

or fibers with improved fiber/concrete bond, e.g. hooked fiber, is needed.[1),6),10)] When the fiber content increased from 0 to 1.5%, the splitting tensile strength increased from 3.33 to 6.08 MPa. The rate of increase of splitting tensile strength is 26.7 to 82.6%, depending upon the fiber content.

3. Stress-strain properties in compression

Fig. 2 shows the axial stress plotted as a function of axial strain, drawn on the right side, and the axial stress expressed as a function of lateral strain drawn on the left side. The figure shows that the stress-strain curves of steel fiber reinforced lightweight polymer concrete are bilinear in nature with a small transition zone. The axial behavior of steel fiber reinforced lightweight polymer concrete under concentric loading can be divided into three regions. In the first region, the behavior of confined concrete is similar to that of lightweight polymer concrete without steel fiber, this is due to the fact that the influence of steel fiber is still not activated by the lateral expansion of the lightweight polymer concrete. In the second region, the lightweight polymer concrete reaches a state of unstable volumetric growth caused by excessive cracking. At this point, the steel fiber is activated and starts to gradually restrain the rapid growth of the lateral strains. This region of response is characterized by a transitional curve in the vicinity of the unconfined strength. In finally the third region, the specimens tended to reach a maximum load, then decrease capacity very slightly and hold that load while increasing the axial strain until failure. These specimens failed in a brittle manner. This behavior may be attributed to the effects of the matrix hardening and formation of micro-cracks parallel to fibers and at the fiber-matrix interface.

4. Flexural load-deflection curves

Fig. 3 shows typical flexural load-deflection curves of steel fiber reinforced lightweight polymer concrete. The addition of fibers increased the deflection corresponding to the peak stress. The deflection capacity of the lightweight polymer concrete was increased considerably with the inclusion of steel fibers. Increase in peak strain, is maximum for fibers having higher volume fraction. Both ascending and descending portion of the load-deflection curves were affected by the addition of steel fibers. However, the significant effect is noticed in the descending portion of the load-deflection curve. As is shown in Fig. 3, the load increases linearly until the peak point where the maximum loading occurs. After the maximum loading, there was a sudden decrease until the starting point of region I because of complete matrix cracking. In region I, the decrement of the loading take places slowly due to the debonding and fiber breakage. Then,

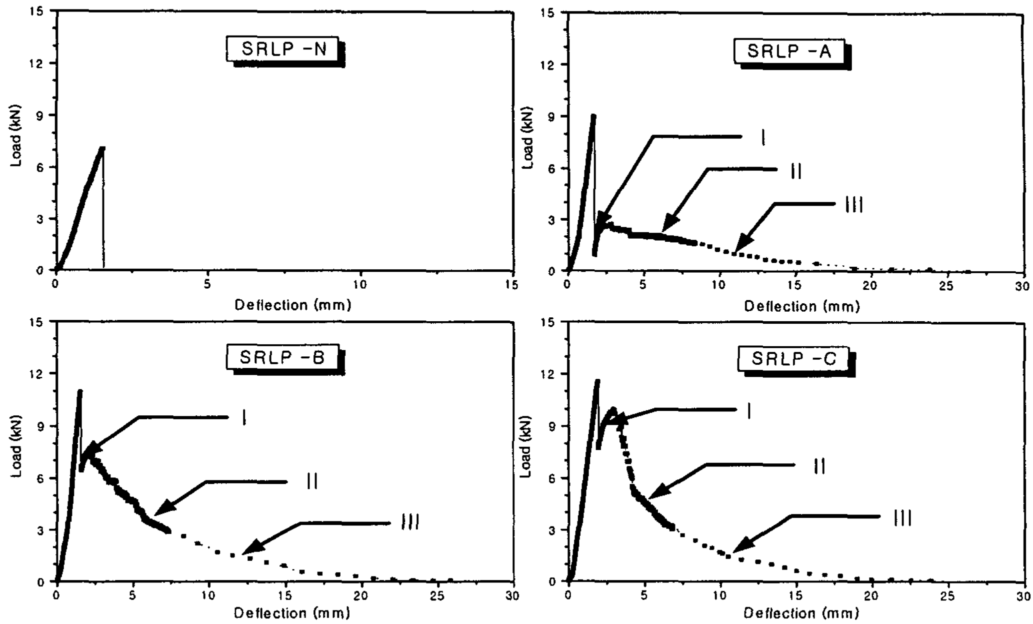

Fig. 3 Typical flexural load-deflection curves of steel fiber reinforced polymer concrete

the broken fibers were pulled out from the matrix easily. Regions II and III of the loading versus deflection graph show repeats of similar fracture characteristics.

5. Flexural toughness

Total area under the load−deflection curve indicates the energy absorbed by the flexural specimens. In this paper, the toughness indices suggested in ASTM C1018−89 were used because of its wide acceptance and use for design and construction although some limitations exist in this method.[5] The indices I5, I10 and I30 are calculated as ratios of the area under the load−deflection curve up to 3, 5.5 and 15.5 times of the first crack deflection, divided by the area up to the first crack deflection, respectively. For an elastic brittle material, all indices should be 1. But, for an elastic−ideal plastic material, I5, I10 and I30 should equal to 5, 10 and 30, respectively. Table 8 and Fig. 4 show the toughness indices in three−point bending tests. It is observed that toughness was increased as steel fiber content was increased. The increase in the value of the flexural fracture toughness is because of fiber pull−out and fiber debonding in the fracture process.

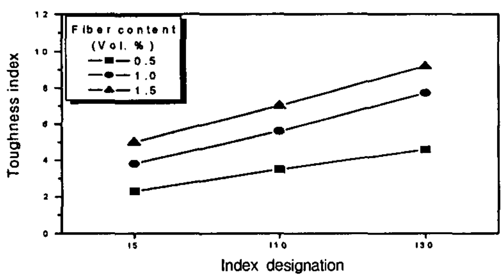

Fig. 4 Toughness indices of steel fiber reinforced lightweight polymer concrete in bending

V. Conclusions

This study was performed to evaluate the mechanical behavior of steel fiber reinforced lightweight polymer concrete. An unsaturated polyester resin, synthetic lightweight aggregates, heavy calcium carbonate and steel fiber were used. The following conclusions were drawn ;

1) Unit weight was ranged between 1,020 and 1,160 kg/m^3 and was largely dependent upon the fiber content. It was increaced with the increase of the strengths.

2) Compressive and splitting tensile strengths was ranged between 26.38 and 34.52 MPa and 3.33 and 6.08 MPa, respectively. It was increased compressive strength by 9.3 to 30.9% and splitting tensile strength by 26.7 to 82.6% compared to that of the lightweight polymer concrete without steel fiber, respectively.

3) Stress-strain curves of steel fiber reinforced lightweight polymer concrete were bilinear in nature with a small transition zone. The axial behavior of steel fiber reinforced lightweight polymer concrete under concentric loading can be divided into three regions.

4) Load-deflection curve observed that the flexural load and deflection were increased with the increase of fiber content. This may be attributed to the influence of the crack-arresting effect of the fibers.

5) Toughness was increased with an increase in fiber content. The increase in the value of the flexural fracture toughness was due to fiber pull-out and fiber debonding in the fracture process.

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