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An experimental research on the fluidity and mechanical properties of high-strength lightweight self-compacting concrete

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Abstract

This paper evaluates the high-strength lightweight self-compacting concrete (HLSCC) manufactured by Nan-Su, of which the main factor PF of its design mixing method has been modified and improved.

The study analyzes HLSCC performance at its fresh condition as well as its mechanical properties at the hardened condition.

The evaluation of HLSCC fluidity has been conducted per the standard of second class rating of JSCE, by three categories of flowability, segregation resistance ability and filling ability of fresh concrete.

For the mechanical properties of HLSCC, the study has been conducted as follows: compressive strength with elapsed age, splitting tensile strength, elastic moduli and density, all at its cured after 28 days.

As a result, HLSCC at its fresh condition has been rated as less than LC 75% and LF 50% for the mix ratio of lightweight aggregate, thus satisfying the second class standard of JSCE.

The compressive strength of HLSCC at 28 days has come out to more than 40 MPa in all mix except the case with LC 100%, while the structural efficiency in relation to its density tended to increase proportionally as the mixing ratio of LF increases. The relationship between the splitting tensile and compressive strength has been calculated as $f_s=0.076f_{ck}+0.5582$. The range of elastic moduli has come out as 24–33 GPa, comparably lower than the control concrete.

Compressive strength and structural efficiency of HLSCC at 28 days from the multiple regression analysis resulted as $f_c=-0.07619LC_A+0.08648LF_B+46.714$ and $f_{se}=-0.00436LC_A+0.0627LF_B+20.257$, respectively.
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Keywords: High-strength lightweight self-compacting concrete (HLSCC); Fresh concrete; Compressive strength; Elastic moduli

1. Introduction

Lightweight concrete is known with its advantage of reducing the self-weight of the structures, reducing the areas of sectional members as well as making the construction convenient [1,2]. Thus, the construction cost can be saved when applied to structures such as long-span bridge and high rise buildings.

However, the lightweight concrete requires specific mix design method that is quite different from conventional concrete. Using conventional mix design method would give rise the material segregation as well as lower the strength by the reduced weight of the aggregate. To avoid such problems, it is recommended to apply the mix design method of high-performance self-compacting concrete for the lightweight concrete. Lightweight concrete designed by the mix method of high-performance self-compacting concrete increases viscosity in its fresh condition, avoids the material segregation and stabilizes its quality, thus is possible for a production of concrete with more than 35 MPa of compressive strength. Such aspects have brought

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Table 1
Chemical compositions of OPC and ALA (wt.%)

Components	OPC	ALA
SiO_2	21.60	74.20
Al_2O_3	6.00	13.20
Fe_2O_3	3.10	1.00
CaO	61.41	1.00
MgO	3.40	0.10
SO_3	2.50	–

numerous studies conducted and are still being held in recent days [3–6].

Excellent in segregation resistance ability and its flowability at its fresh condition, self-compacting concrete is generally known as the concrete capable of filling up the given structure only using its self-weight without an additional compaction. It was first developed in Japan during 1986, with further mix design method introduced by professor Okamura of Tokyo university in 1993 [7,8]. Mix method used for the self-compacting concrete is significantly different from the typical method as well as its rating standards and testing since the design of method needs to consider the two opposite properties of flowability and segregation resistance ability at the same time to assure the compacting capacity of the concrete.

The most popular mix design method used for the self-compacting concrete is introduced by professor Okamura. His method conducts the cement paste and mortar test before moving onto evaluating properties of the superplasticizer, cement, fine aggregate and pozzolanic material for saving the process from the redundancy of unnecessary testing, although its complicated procedure makes it difficult to apply to companies which manufacture the ready-mixed concrete. Overcoming such obstacle, Taiwan-based Nan-Su suggested a new mix design method that is more convenient. Apart from its simplicity, Nan-Su's new method has some problems with the fluctuating range of PF, which is the most important variable [9,10].

Therefore, this study introduces a production of HLSCC by utilizing PF-modified and improved version of Nan-Su's mix design method of self-compacting concrete [11,12].

Through a series of test mixes conducted during the study, the quality of the concrete at its fresh condition has been evaluated with the second class rating standards of self-compacting concrete published by JSCE, especially focused in its flowability, segregation resistance ability and filling ability [13].

The measurement of the mechanical properties of concrete, including compressive strength (f_c), splitting tensile strength (f_t) at 28 days, elastic moduli and density, as well as its structural efficiency (f_{se}) were carried out [14].

Modified and simplified mix design method was applied to find out whether it could be suitable for the HLSCC, appropriate for the site application, as well as its use for the lightweight aggregate.

Furthermore, multiple regression analysis was carried out to determine and review the compressive strength and structural efficiency per mixed ratio of lightweight aggregate and to project the estimated equation for a suggestion.

2. Experimental outline

2.1. Materials

Cement used in the study was the ordinary portland cement (OPC) typically produced in Korea, with density of 3.15 g/cm^3 and blaine fineness of 3539 cm^2/g, while the artificial lightweight aggregate (ALA) was used with its major ingredients of rhyolite powder. Chemical ingredients of OPC and ALA are shown in Table 1.

Natural coarse (NC) aggregate of crushed stone with 20 mm of G_{max} and the same size of lightweight coarse (LC) aggregate were used. Natural fine (NF) aggregate used was river sand. Physical properties of the aggregates are measured according to Korean industry standard (KS), as shown in Table 2.

Furthermore, crushing ratio of aggregate was measured by BS 812. For manufacturing of high-strength lightweight self-compacting concrete (HLSCC), high-range water reducing of polycarbonate acid (HRWR) and air entraining agent (AEA) were used. Specific gravity of HRWR and AEA are 1.10±0.02 and 1.04±0.01, the amount of HRWR and AEA are about 0.5–2.0% and 0.005% of cement weight, respectively.

2.2. Mixture proportion of concrete

Concrete mix design in this study has been modified and improved from Nan-Su's method. In other words, PF value was obtained through the pretest to solve the obscurity in assumption of PF value that is a main factor within Nan-Su's method. PF revised through this study is the percentage of unit weight at the compacted stage from the loosely filled aggregate according to Korean industry

Table 2
Physical properties of aggregate

Components	NF	NC	LF	LC
Density (g/cm^3)	2.55	2.72	1.86 (1.61)[a]	1.58 (1.23)[a]
Bulk density (kg/m^3)	1677	1695	1127	793
Absorption (%)	2.43	0.80	13.71	28.09
Percentage of solids (%)	62.6	62.3	60.3	50.2
Fineness moduous	2.81	6.72	2.64	6.40
Crusing value (%)	–	15	–	24

[a] Density under oven-dry condition.

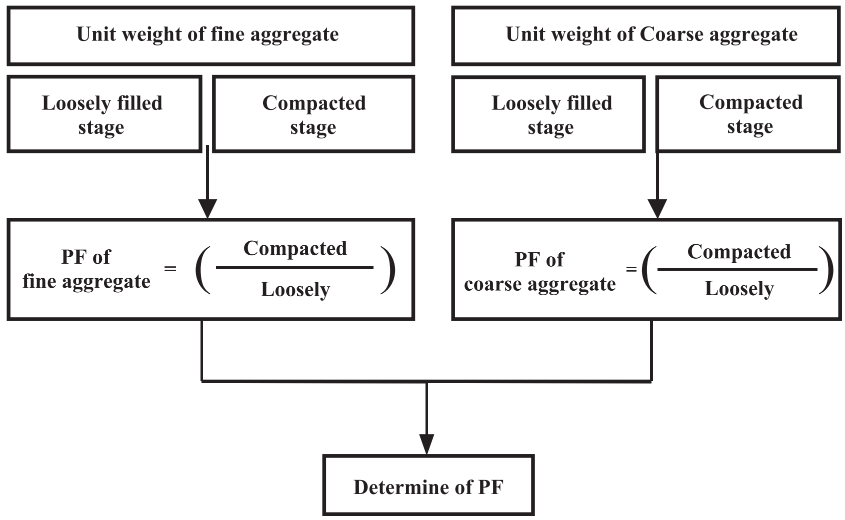

Fig. 1. Step of determining the PF value.

standard, thereby indicating the value obtained by applying the added weight per fine aggregate to be added into the mixed concrete.

Determination of appropriate PF value has saved significant amount of redundancy in time and efforts during the pretesting phase, which was designed to obtain the proper concrete mix.

Fig. 1 shows the steps of determining the PF value through measuring the unit weight of fine and coarse aggregate as Fig. 2 illustrates application of the determined PF value to design mix of SCC.

After obtaining the PF value through such mix design process followed by mixing the concrete with decision of fine aggregate ratio and amount of SP to review its fluidity. If in case the fluidity appear inappropriate, more proper PF values from the testing will be taken for the better mix. The unit weight measured from the compacted stage compared to the loosely filled stage of the aggregate according to KS have resulted as 1461 kg/m^3 at the loose condition and 1668 kg/m^3 at the compacted stage for the coarse aggregate as compared to 1376 kg/m^3 at the loose stage and 1666 kg/m^3 at the compacted stage for the fine aggregate. Fine aggregate ratio of 53% was applied to calculate its PF value, which came out to be approximately 1.18 as illustrated in Eq. (1).

$$\mathrm{PF} = \frac{\text{Unit weight of coarse aggregate (compacted stage)}}{\text{Unit weight of coarse aggregate (loosely filled stage)}} \times \left(1 - \frac{\mathrm{S}}{\mathrm{a}}\right) + \frac{\text{Unit weight of fine aggregate (compacted stage)}}{\text{Unit weight of fine aggregate (loosely filled stage)}} \times \frac{\mathrm{S}}{\mathrm{a}} \qquad (1)$$

S/a—volume ratio of fine aggregates to total aggregates.

Table 3 shows the mixture proportion of concrete as its categories of group A, B, C, D are divided per use of lightweight fine (LF) and coarse (LC) aggregate.

2.3. Test methods

As for the evaluation of fluidity of HLSCC, the testing for slump flow (mm), time required to reach 500 mm of slump flow (s), time required to flow through V-

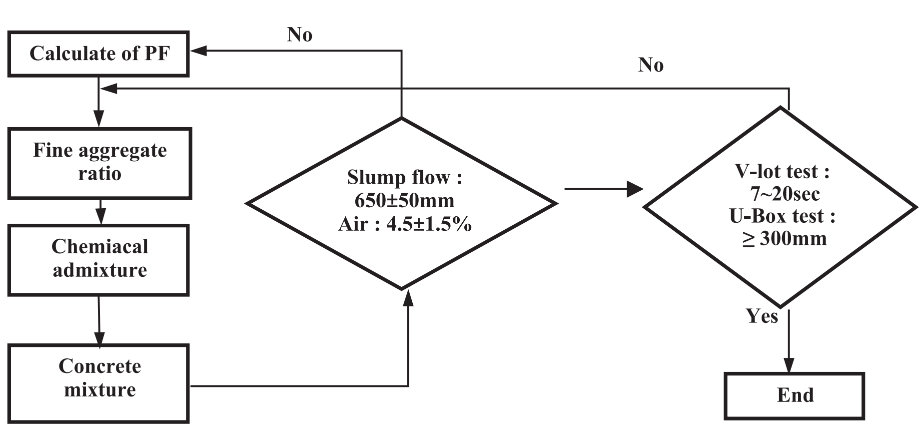

Fig. 2. Flowchart of the SCC mix design method.

Table 3
Mixture proportions of concrete

Group No.	Mix No.	PF	S/a (%)	W/C (%)	LC/(LC+NC) (%)	LF/(LF+NF) (%)	Unit weight (kg/m^3)					
							W	C	NC	LC	NF	LF
A	1	1.18	53	38	0	0	175	460	810	0	861	0
B	2	1.18	53	38	25	0	175	460	608	117	861	0
	3	1.18	53	38	50	0	175	460	405	234	861	0
	4	1.18	53	38	75	0	175	460	203	352	861	0
	5	1.18	53	38	100	0	175	460	0	469	861	0
C	6	1.18	53	38	0	25	175	460	810	0	645	158
	7	1.18	53	38	0	50	175	460	810	0	430	316
	8	1.18	53	38	0	75	175	460	810	0	215	473
	9	1.18	53	38	0	100	175	460	810	0	0	631
D	10	1.18	53	38	75	50	175	460	201	353	433	315
	11	1.18	53	38	75	75	175	460	201	353	217	473

funnel (s) and filling height of U-box test (mm) has been conducted immediately after the mixing of the concrete, while its method borrowed from testing methods for the self-compact concrete published by JSCE, and its standards are shown in Table 4.

Specimen for concrete testing has been manufactured as 100×200 mm (ø) without the compacting. Its mold was taken out after 24 h followed by standard curing until the next test. Compressive strength of the concrete was tested at 3rd, 7th and 28th days, while splitting tensile strength, elastic moduli and density were measured after 28th days of curing.

In addition, multiple regression analysis has been carried out by using SPSS, the statistics program used to determine the characteristics per mix of the lightweight aggregates ratio for the hardened concrete. For the analysis, mix ratios of LC (group B) and LF (group C) were designated as the independent variable, while the mechanical properties of the hardened concrete, the compressive strength at the 28th day and structural efficiency were assumed to be the dependent variable. Proposed formula obtained from this analysis was then compared and reviewed along with the combination of LC and LF (group D).

Table 4
Specification of SCC proposed by JSCE

Rank	1	2	3
Construction condition			
Minimum gap between reinforcement (mm)	30–60	60–200	≥200
Amount of reinforcement (kg/m^3)	≥350	100–350	≤100
Filling height of U–box test (mm)	≥300	≥300	≥300
Absolute volume of coarse aggregates per unit volume of SCC (m^3/m^3)	0.28–0.30	0.30–0.33	0.30–0.36
Flowability slump flow (mm)	650–750	600–700	500–650
Segregation resistance ability			
Time required to flow through V-funnel (s)	10–20	7–20	7–20
Time required to reach 500 mm of slump flow (s)	5–25	3–15	3–15

3. Results and discussion

3.1. Properties of fresh concrete

Figs. 3, 4 and 5 illustrate the flowability, segregation resistance ability and filling ability of HLSCC. As shown in Fig. 3, the result of slump flow test to rate the fluidity came out as 600–700 mm at all mixes, which satisfied the range of standard capacity of self-compacting concrete per the second class rating of JSCE. Such result seemed to be caused by reduced self-weight of the concrete when mixing the lightweight aggregate, allowing satisfactory level of flowability, and the increase of water content by prewetting [15,16].

Fig. 4 illustrates the relationship between the time required to reach 500 mm of slump flow (s) and the time required to flow through V-funnel (s) to determine the

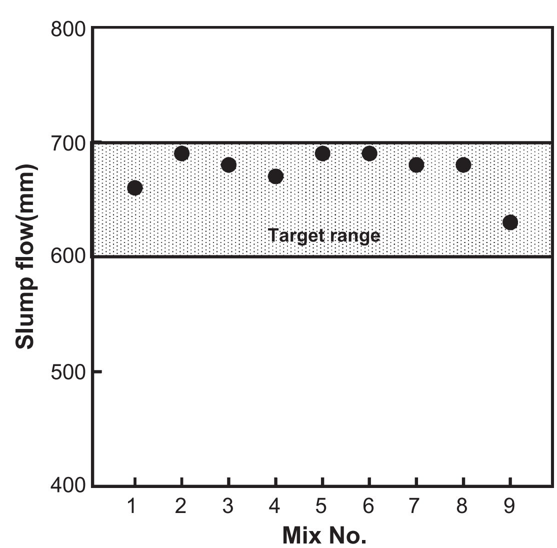

Fig. 3. Slump flow.

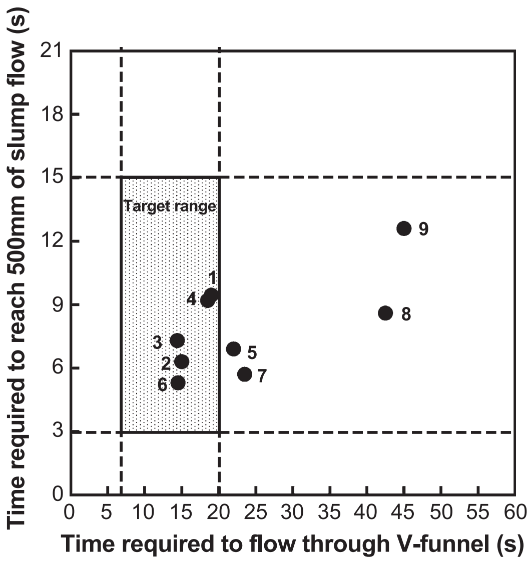

Fig. 4. Relationship of time required to flow through V-funnel and to reach 500 mm of slump flow.

material segregation resistance ability of HLSCC at its fresh condition.

The time required to reach 500 mm of slump flow (s) shown in Fig. 4 satisfied the expected capacity range at all mixes. However, time required to flow through V-funnel (s) satisfied only with standard mix (Mix No. 1), mix with LC (Mix No. 2–4) and the mix with LF (Mix No. 6). On the contrary, the mix with more than 50% of LF (Mix No. 7–9) did not satisfy the expected level of result.

Particularly for mixing with LF, both time required to reach 500 mm of slump flow (s) and time required to flow through V-funnel (s) has increased as the percentage of LF increased (Mix No. 6–9) as opposed to the slump flow that comparatively decreased. Such tendency is assumed to be caused by the higher viscosity per proportional increase in powder from LF mix ratios.

Fig. 5 illustrates the result of filling height of U-box test (mm) for the filling ability of HLSCC. As shown in this figure, all mixes, including the standard (Mix No. 1) and mixes with LC (Mix No. 2–5) satisfied the expected level of result. For the mixes with LF, however, only the mix with 25% of LF (Mix No. 6) satisfied the standard caused by relative decrease in fluidity and increase in viscosity due to the proportional increase in the similar to Figs. 3 and 4 [16].

3.2. Mechanical properties

Fig. 6 represents the result of testing HLSCC for the compressive strength with elapsed age. As shown in the figure, contrasting results occurred depending upon the mix ratio of the lightweight aggregate, where the compressive strength of the LC mix ratio up to 75% (Mix No. 2–4) seem to show merely 6% decrease (average) compared to the control concrete (Mix No.1), yet the LC mix ratio of 100% (Mix No. 5) decreased almost 31%. However, for the LF-mixed concrete, more than 50% ratio (Mix No. 8–9) showed 8–20% increase in the strength compared to the mix up to 50% (Mix No. 6–7) that had similar 6% decrease in relation to the control concrete (Mix No. 1). Such result seems to be caused by some physical properties of the lightweight aggregate, more specifically as follows: (1) lower compressive strength as the LC mix ratio increased caused by the crushing ratio of LC that is approximate 63% higher than NC, making the strength of the aggregate less and (2) absorption ratio of LC of 28.09% is significantly higher than the absorption rate of NC, thus causing the increase in overall volume of the mix per prewetting [17]. However, (3) the reason why the compressive strength increases as the LF mix ratio increases is because the more microparticles are produced

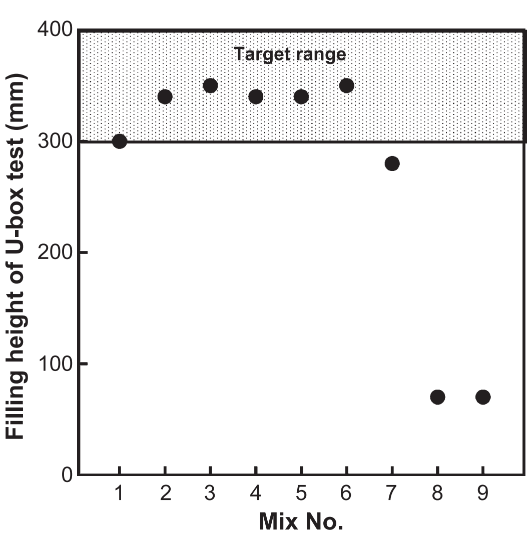

Fig. 5. Filling height of U-box test.

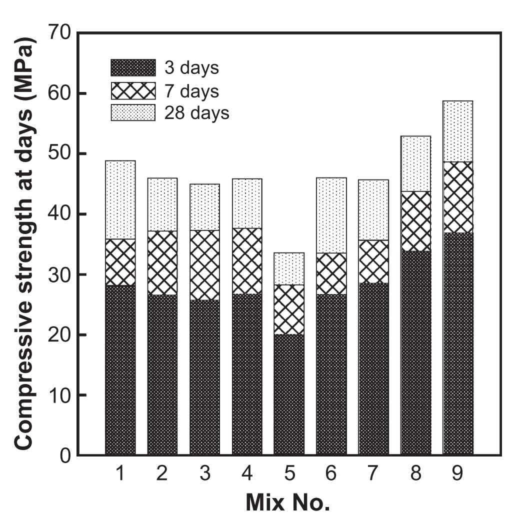

Fig. 6. Compressive strength at days.

Table 5
Calculation of structural efficiency

Group No.	Mix No.	Density (kg/m^3)	Compressive strength (MPa)	Structural efficiency ($\times 10^{-3}$ MPa m^3/kg)
A	1	2306	49	21.2
B	2	2221	46	20.7
	3	2135	45	21.1
	4	2051	46	22.8
	5	1965	34	17.0
C	6	2248	45	20.0
	7	2191	46	21.0
	8	2133	53	24.8
	9	2076	59	28.3

as LF mix ratio increases and roles as a filler to fill up the voids.

For typical concrete mix with the lightweight aggregate, compressive strength is decreased as the density decreases, and such tendency is evaluated upon the structural efficiency that is a ratio of the strength and density of the concrete. Hence, the results converted into the structural efficiency are listed in Table 5 and illustrated in Fig. 7.

As shown in Fig. 7, the structural efficiency of HLSCC appears different upon the mix ratio of the lightweight aggregate.

Mix with only LC at its ratio of 75% (Mix No.4) showed 7% increase in structural efficiency compared to the control concrete (Mix No. 1), while the mix with 100% (Mix No. 5) showed 20% decrease in its structural efficiency. Such result for the 100% LC mix seemed to be affected by the 31% decrease in its compressive strength compared to the control concrete (Mix No. 1). On the other hand, concrete mixes with LF showed increase in structural efficiency proportional to the mix ratio as the mix with LF 75% (Mix No.8) and 100% (Mix No.9) showed the structural efficiency to be increased by 17% and 33%, respectively. This seemed to be caused by the development of compressive strength.

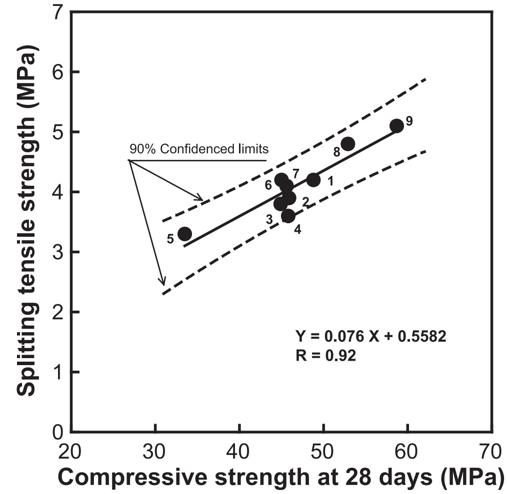

Fig. 8. Relationship of compressive strength and splitting tensile strength.

Fig. 8 represents the relationship between the compressive and splitting tensile strength of HLSCC at 28 days through the regression analysis with 90% reliability.

As shown in this figure, correlation coefficient came out as 92%. In addition, for the concrete with only LC or LF, the ratio of splitting tensile and compressive strength (f_c/f_t) came out to be 10.5–12.8 depending upon the mix ratio.

The relationship between the compressive strength and the elastic moduli of the concrete at 28 days per mix ratio is shown in Fig. 9. Upper and lower curve of this figure indicates the standard of 318/318R from ACI per each unit weight. As shown in the figure, the relationship between the compressive strength and the elastic moduli for both HLSCC mix with LC and LF satisfies the range curve of ACI standard. In general, elastic moduli of the lightweight

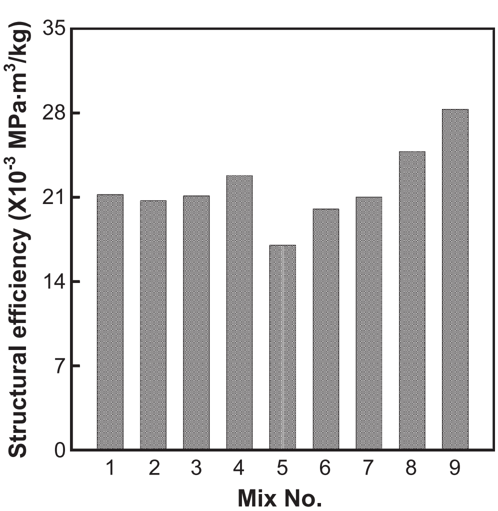

Fig. 7. Structural efficiency.

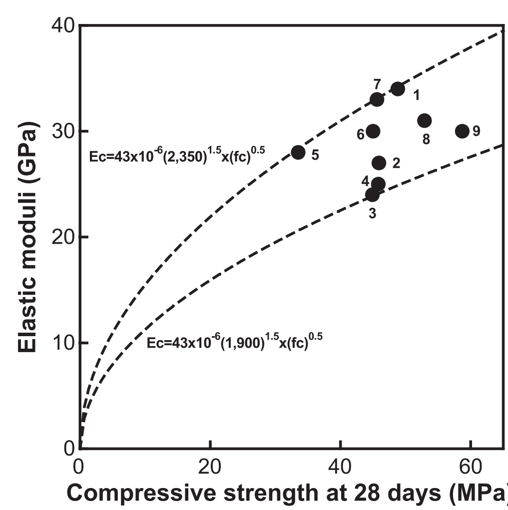

Fig. 9. Relationship of compressive strength and elastic moduli.

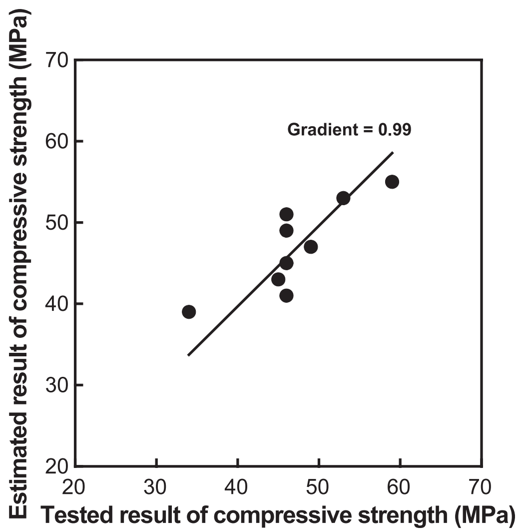

Fig. 10. Relationship of compressive strength between tested and estimated values.

concrete are affected by the types and properties of the aggregate, as well as the compressive strength and unit weight of the concrete, marking around 40–70% compared with normal concrete. This is because the elastic moduli of the aggregate itself are comparably small.

The range of the elastic moduli shown in Fig. 9, approximately 71–82% for LC mix and 88–97% for LF mix, were recorded in comparison to the control concrete (Mix No. 1) [16].

3.3. Statistics analysis by multiple regression

Eqs. (2) and (3) were obtained from the multiple regression analysis by taking each of LC mix ratio (group B) and LF mix ratio (group C) as an independent variable. Eq. (2) represents the compressive strength at 28 days (f_c), Eq. (3) incorporates the structural efficiency (f_{se}) both of equations used as a dependent variable.

$$f_c = -0.0762\ LC_A + 0.0865\ LF_B + 46.714 \quad R = 0.83 \tag{2}$$

$$f_{se} = -0.0044\ LC_A + 0.0627\ LF_B + 20.275 \quad R = 0.80 \tag{3}$$

$LC_A LF_B$—A, B is replacement ratio of each lightweight aggregate (LC and LF).

Figs. 10 and 11 show the summarized result of Table 6. Fig. 10 shows the comparison of testing and the estimated values regarding as compressive strength of the concrete, showing that the slope of 0.99 represents the testing value slightly lower than that of estimated value. Fig. 11 is the comparison of value calculated using the formula for the structural efficiency, of which its slope 0.99 indicates the testing value little less than the calculated value from the analysis.

Eqs. (2) and (3) are obtained from the multiple regression analysis of HLSCC that is manufactured each with LC and LF, while the level of similarity between the testing and estimated value for the mix of both LC and LF (group D) is evaluated in Table 7.

As Table 7 indicates, the difference between the testing and estimated value of both compressive strength and structural efficiency ranged within 10%, showing a fairly good result.

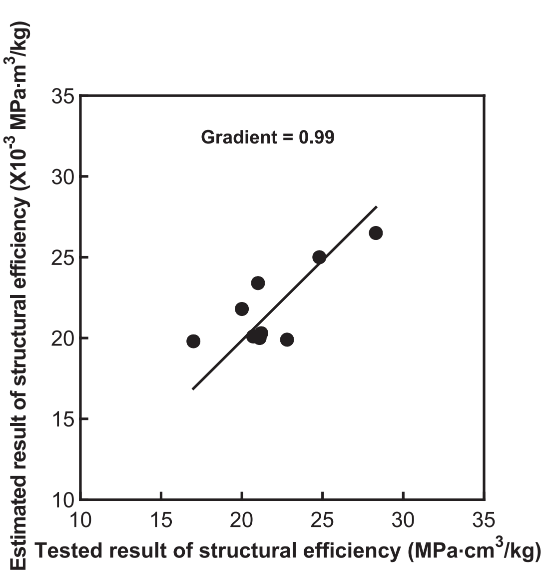

Fig. 11. Relationship of structural efficiency between tested and estimated values.

Table 6
Relation of between tested and estimated result

Group No.	Mix No.	Compressive strength (MPa)		Structural efficiency ($\times10^{-3}$ MPa m^3/kg)	
		Tested	Estimated	Tested	Estimated
A	1	49	47	21.2	20.3
B	2	46	45	20.7	20.1
	3	45	43	21.1	20.0
	4	46	41	22.8	19.9
	5	34	39	17.0	19.8
C	6	45	49	20.0	21.8
	7	46	51	21.0	23.4
	8	53	53	24.8	25.0
	9	59	55	28.3	26.5

Table 7
Relation of between tested and estimated result

Items	Mix No. 8		Mix No. 9	
	Tested	Estimated	Tested	Estimated
Compressive Strength (MPa)	44	45	43	47
Structural efficiency ($\times10^{-3}$ MPa m^3/kg)	23.8	23.1	24.0	24.6

4. Conclusions

(1) Although the tests of slump flow (for measuring of flowability) and time required to reach 500 mm of slump flow (s) (for measuring of segregation resistance ability) of HLSCC satisfied the expected capacity level in all mixes, time required to flow through V-funnel (s) (for measuring of segregation resistance ability) only satisfied the level in most of the LC mixed concrete (Mix No. 2–4) and one of LF mixed concrete (Mix No. 6).

(2) From the result of filling height of U-box test (mm) to determine the filling ability of HLSCC, all mixes with LC (Mix No. 2–5) satisfied the second class rating of JSCE as pursued by this thesis, while only the mix with LF 25% (Mix No. 6) satisfied the expected level.

(3) As a result of compressive strength test, LC mixes up to 75% showed an average decrease of 6% compared to the control concrete, in contrast to LC 100% which caused a substantial 31% decrease. For LF mixes, ratio up to 50% tends to decrease approximately 6% compared to the control concrete, while higher percentage of mix resulted 8% to 20% increase in compressive strength development.

(4) The structural efficiency of HLSCC tended to increase 7% for the LC mix with 75%, while 100% mix caused 20% decrease. For LF mixes, the structural efficiency increased proportionally as the mix ratio increased as LF 75% and LF 100% indicated 17% and 33% increase, respectively.

(5) The relationship between the compressive and splitting tensile strength at 28 days of HLSCC was evaluated by the linear regression analysis per mix ratio of the lightweight aggregate. In result, correlation coefficient is 92%, indicating a close relationship between the two strengths. The relationship between the compressive strength and elastic moduli per mix ratio of the lightweight aggregate was tested by the ACI 318/318R standard, and its result was satisfied within the upper and lower curve range of ACI standard unit weight.

(6) As for the compressive strength and estimated value of structural efficiency from the multiple regression analysis, with LC and LF as independent variables, the testing value appeared to be smaller than the estimated value. For the comparison of the testing and estimated value for the HLSCC mix with LC and LF together, the values were within 10% differences for both compressive and structural efficiency.

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