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Introducing a New Quantitative Evaluation Method for Segregation of Normal Concrete

In-Deok Han¹ and Dongyeop Han^{2*}

Abstract

The aim of this research is to provide a quantitative method for evaluating concrete segregation. Because of various conditions of concrete materials, mix proportions, and delivery, concrete can be segregated. The acquisition inspection executed in construction field for supplied ready-mixed concrete is an important quality control process for concrete. Among the inspections conducted at the project site, segregation of concrete mixture should be evaluated before placing the concrete mixture, currently a qualitative inspection on concrete segregation was conducted. For a normal concrete mixture with slumping behavior, shear slump or collapse slump often occur as an indication of segregation. The suggested evaluation index of segregation for normal concrete (EISN) was induced from the shape of the concrete slumping: relation between the maximum distance of flow and the minimum distance of flow. To evaluate the feasibility of EISN, two different concrete mixture conditions were tested. The recommended EISN parameter of segregation is 1.09 using the three grades of concrete quality. This new quantitative method of evaluating segregation of the concrete mixture is expected to contribute to a more efficient quality control in concrete construction.

Keywords: Concrete segregation, Slump, Slump flow, Segregation evaluation, Quantitative method

1 Introduction

Because of changing conditions of concrete materials, such as aggregate quality or other supplementary cementitious materials, determining the appropriate concrete mix proportion needed to assure a good mixture consistency is difficult. The purpose of a concrete mix design is to secure the desirable performance at fresh state and hardened state concrete such as workability, strength, durability, and uniform appearance with acceptable economic advantage. Since concrete is a heterogeneous material with a wide range of particle sizes and weight, sustaining uniformity is important to secure a desirable performance during fresh state. Hence, the meaning of 'workability' should not only contain fluidity with good mobility, but also uniformity with segregation resistance (Tattersall & Banfill, 1983). A well-designed mixture

should have a segregation resistance during the working processes of delivering and placing; thus, unit water content and sand-to-aggregate ratio (S/a) are the representative factors dominating segregation (or uniformity) of the concrete mixture. Unit water content is the amount of water for unit volume (one cubic meter) of concrete mixture. For mixture proportioning, unit water content is determined by the target slump (ACI Committee 211, 2002; de Larrard, 1999). Hence, the unit water content can be considered as a determining factor for workability of the concrete mixture. On the other hand, with a consideration that concrete mixture is a suspension of aggregates within the cement paste (Erdem et al., 2010; Toutou et al., 2007), if the water-to-cement ratio remains the same, the unit water content is a portion of the cement paste. Therefore, an increase or decrease of the unit water content means an increase or decrease of cement paste to carry the aggregates. S/a is the ratio of a fine aggregate (sand) volume to the entire aggregate volume within the unit volume (one cubic meter) of the concrete mixture (Aïssoun et al., 2016; Bassuoni & Nehdi, 2009; Khayat

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et al., 1996; Popovics, 1973). To determine the appropriate S/a , the S/a should be as high as possible unless segregation has not occurred. Namely, the S/a is directly related to the segregation of the concrete, i.e., it is related through cohesion of the concrete mixture because the sand particles (fine aggregate) are relatively fine particles in the concrete mixture (Mindess et al. 2002).

Most construction sites use ready-mixed concrete manufactured in certified plants. Nevertheless, there is a possibility of segregation of concrete mixture due not only to the concrete mix proportion and materials, but also due to other factors such as a long transfer time; thus, the supplied concrete should be inspected at the project site. According to the construction specifications or guides from many countries (ACI Committee 311, 2004; Japan, 2009; Korea Standards Association, 2011); however, generally, the segregation of the concrete mixture is inspected by observing the conditions of the concrete mixture after the slump test, and this evaluation can be debatable because it is a qualitative method. Therefore, in this research, regarding a normal concrete mixture with a relatively low slump range (generally less than 150 mm) with slumping behavior, a quantitative method of evaluating segregation of concrete is introduced using the data obtained from the slump test result. The results of this research are expected to contribute on providing a new quantitative approach to segregation evaluation for normal concrete mixtures using simple slump test results.

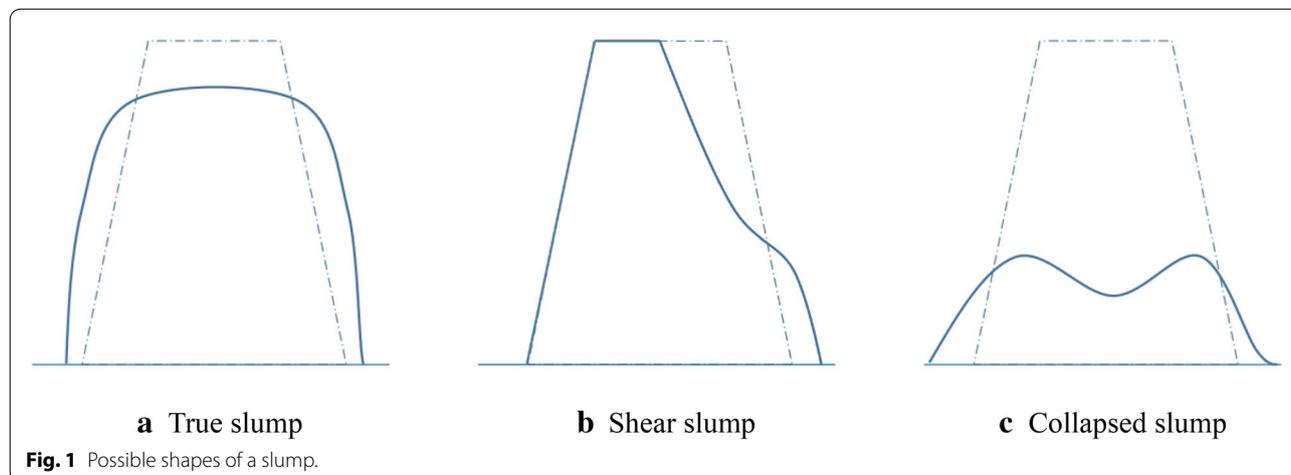
2 Quantitative Evaluation Method for Concrete Segregation

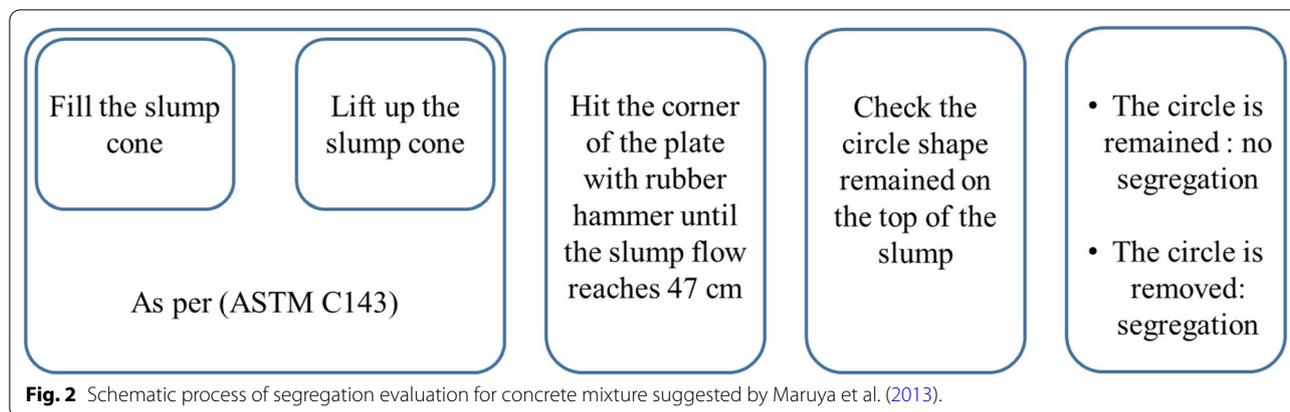
2.1 Current Methods

For normal concrete mixtures, slump test is a well-known test method for their ability to assess fresh state mixture conditions, that is, workability and uniformity (Mindess

et al., 2002; Neville, 2012). Hence, on the project site, the segregation or cohesiveness of the concrete mixture is evaluated during the slump test. According to Neville (Neville, 2012), shear and collapse slump can be a harsh mixture with insufficient cohesiveness (see Fig. 1). Additionally, from Maruya et al.’s technical report (Maruya et al., 2013), a new method of investigating concrete segregation was suggested. The method is observing the remaining circle shape on top of the slumped concrete after hitting the slump plate with a rubber hammer and causing the concrete to fly up to 47 cm (see Fig. 2). Although this suggested that the method can evaluate the segregation or segregation resistance of concrete mixture, this method is still a qualitative method and it cannot be clear for “remaining circle”.

As a quantitative evaluation method for segregation of concrete, several test methods were suggested such as column test (ASTM International, 2014), and sieve segregation test (British Standard Institution, 2010). Nevertheless, these test methods are suitable for not a normal concrete mixture but a high workability concrete mixtures or self-consolidating concrete. From the rheological aspect, concrete flow behavior can be analyzed using a Bingham model where the fluidity is measured based on yield stress and plastic viscosity (Papanastasiou, 1987). The cohesiveness of the mixture is related to the plastic viscosity of the mixture, and the segregation of the concrete mixture is induced by the insufficient plastic viscosity of the mortar mixture and cement paste for segregation of coarse aggregates (honeycomb) and water (bleeding), respectively (Han, 2014; Tregger et al., 2012). Therefore, measuring rheological properties of a concrete mixture can be a good method of evaluating the segregation resistance of a concrete mixture quantitatively. However, for normal concrete mixtures within the slump test range, it is hard to measure the rheological properties





with currently available rheometers (Koehler & Fowler, 2004) because of excessively high torque on the motor of the rheometer. Therefore, even a fluidity evaluation using rheometer and rheology can be applied for high fluidity concrete mixture. Moreover, rheometers are expensive, and their raw data are not only difficult to use, but also the rheological test is hard to apply at all construction project sites.

2.2 Suggested Method

Considering the shape of the normal concrete after the slump test, the segregation of concrete can be determined based on the shear slump due to insufficient cohesion (see Fig. 3). As shown in Fig. 3, measuring slump flow is not a valid. However, the concrete mixture with shear slump will collapse on one side of the concrete, and the spread distance will differ depending on the condition of the sides. Thus, the segregation possibility of a relatively low slump can be evaluated by calculating the ratio of the maximum distance of slump flow to the minimum distance of slump flow, which can be expressed as:

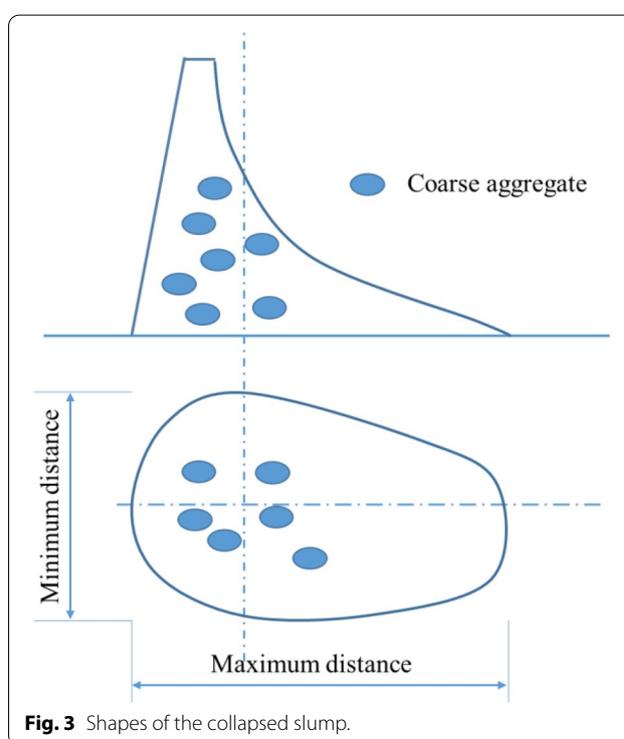
$$EISN = \frac{\text{The maximum distance of slump flow (mm)}}{\text{The minimum distance of slump flow (mm)}} \tag{1}$$

where EISN means evaluation index for segregation of normal concrete.

3 Experiment

3.1 Experimental Plan

In this research, to evaluate the applicability of EISN for normal concrete mixtures, two different concrete mixture types were prepared: normal concrete mixture with relatively high water-to-cement ratio and high-strength concrete mixture with normal slump range. Although EISN is designed for normal concrete mixture with slumping behaviors (generally less than 150 mm), it can be also used to evaluate the concrete mixture of slumping range



but designed as a high-strength concrete. As shown in Table 1, the water-to-cement ratios of each case was fixed to 0.50 and 0.30 for normal concrete mixture and high-strength concrete with normal slump range, respectively. Specifically, for high-strength concrete mixture, to control the fluidity to a similar range of the normal concrete mixture, superplasticizer was added 0.25% of the cement mass. Regarding two different concrete mixtures, S/a and unit water content were changed to induce segregation from 0.35 to 0.55, and from 165 to 205 kg/m³. To evaluate the workability and segregation of the mixtures, slump test was conducted, and slump and slump flow values were measured. The segregation of concrete mixtures

Table 1 Experimental plan.

Mixture conditions	w/c*	0.50 (for normal concrete mixture) 0.30 (for high-strength concrete mixture)
	Target air content (%)	4.5 ± 1.5
	S/a**	0.35, 0.40, 0.45, 0.50, 0.55
	W (kg/m ³)***	165, 175, 185, 195, 205
Tests	Fresh state	Slump, slump flow, air content, unit volume weight
	Hardened state	Compressive strength (@ 3, 7, and 28 days)

*w/c water-to-cement ratio.

**S/a sand-to-aggregate ratio.

***W unit water content.

Table 2 Mix proportions of normal concrete mixtures.

w/c*	Proportion**		Unit volume weight (kg/m ³)***			SP/AE**** (kg/m ³)
	S/a	W	OPC	Fine aggregate	Coarse aggregate	
0.50	0.35	165	330	624	1163	0.99/0.03
		175	350	609	1135	1.05/0.04
		185	370	594	1079	1.11/0.04
		195	390	579	1052	1.17/0.04
		205	410	564	1107	1.23/0.04
	0.40	165	330	713	1073	0.99/0.03
		175	350	696	1047	1.05/0.04
		185	370	679	1022	1.11/0.04
		195	390	662	996	1.17/0.04
		205	410	645	971	1.23/0.04
	0.45	165	330	802	984	0.99/0.03
		175	350	783	960	1.05/0.04
		185	370	763	937	1.11/0.04
		195	390	744	913	1.17/0.04
		205	410	725	890	1.23/0.04
	0.50	165	330	891	894	0.99/0.03
		175	350	870	873	1.05/0.04
		185	370	848	852	1.11/0.04
		195	390	827	830	1.17/0.04
		205	410	806	809	1.23/0.04
0.50	165	330	980	805	0.99/0.03	
	175	350	957	786	1.05/0.04	
	185	370	933	766	1.11/0.04	
	195	390	910	747	1.17/0.04	
	205	410	886	728	1.23/0.04	

*w/c water-to-cement ratio.

**S/a sand-to-aggregate ratio, W unit water content.

***OPC ordinary Portland cement.

****SP superplasticizer, AE air entrainer.

was determined based on observation, and the observation results were compared with EISN from slump and slump flow data. Additionally, air content and unit volume weight were checked, and compressive strength was also tested at 3, 7, and 28 days.

3.2 Materials and Test Methods

Ordinary Portland cement from South Korea was the cement used for this research. The properties of this cement are similar to the Type I ordinary Portland cement from ASTM C150 (ASTM International, 2012a).

Table 3 Mix proportions of high-strength concrete mixtures.

w/c*	Proportion**		Unit volume weight (kg/m ³)***			SP/AE**** (kg/m ³)
	S/a	W	OPC	Fine aggregate	Coarse aggregate	
0.30	0.35	165	550	547	1056	1.38/0.06
		175	583	529	1021	1.46/0.06
		185	617	511	986	1.54/0.06
		195	650	492	950	1.63/0.07
		205	683	474	915	1.71/0.07
	0.40	165	550	625	974	1.38/0.06
		175	583	604	742	1.46/0.06
		185	617	583	909	1.54/0.06
		195	650	563	877	1.63/0.07
		205	683	541	844	1.71/0.07
	0.45	165	550	703	893	1.38/0.06
		175	583	680	864	1.46/0.06
		185	617	656	834	1.54/0.06
		195	650	633	804	1.63/0.07
		205	683	609	774	1.71/0.07
	0.50	165	550	781	812	1.38/0.06
		175	583	755	785	1.46/0.06
		185	617	729	758	1.54/0.06
		195	650	703	731	1.63/0.07
		205	683	677	704	1.71/0.07
0.50	165	550	860	731	1.38/0.06	
	175	583	831	707	1.46/0.06	
	185	617	802	682	1.54/0.06	
	195	650	773	658	1.63/0.07	
	205	683	745	633	1.71/0.07	

*w/c water-to-cement ratio.

**S/a sand-to-aggregate ratio, W unit water content.

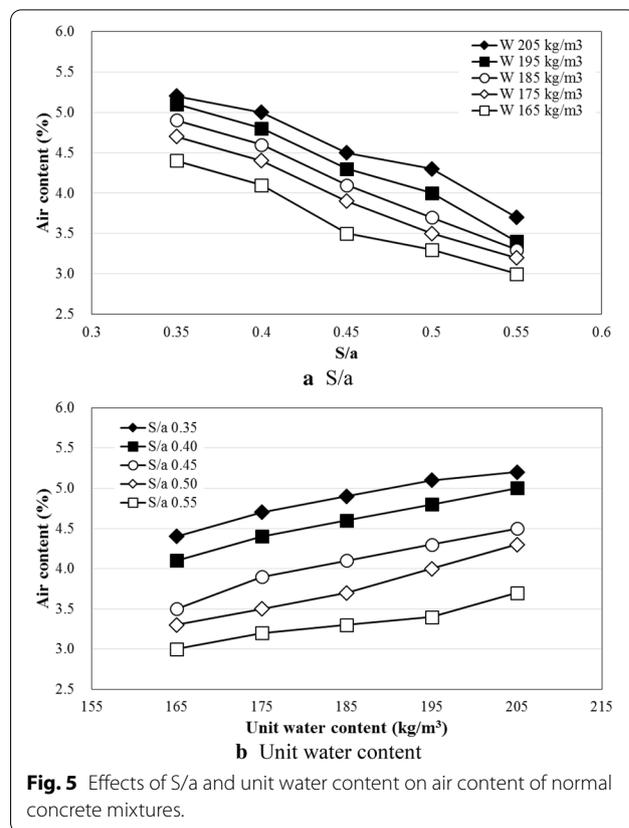
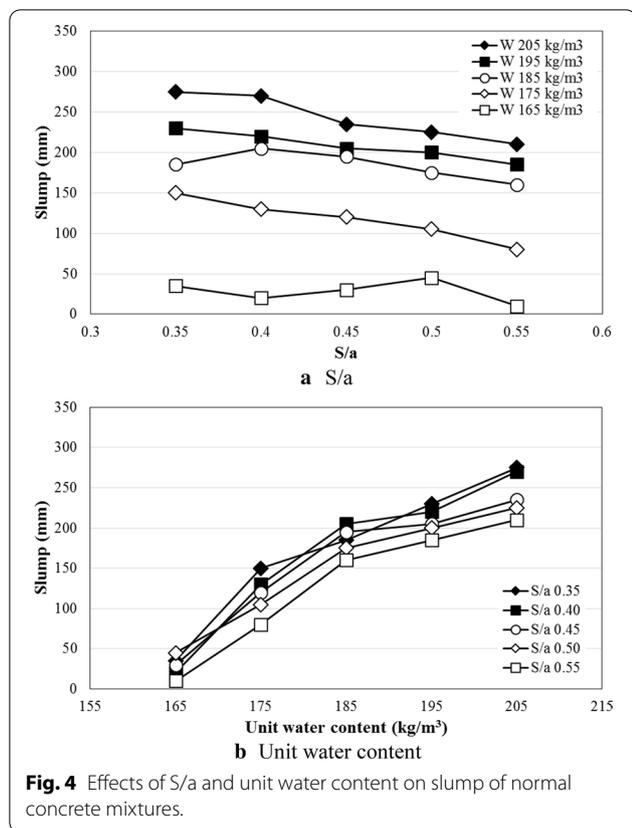
***OPC ordinary Portland cement.

****SP superplasticizer, AE air entrainer.

According to the manufacturer, the specific gravity is 3.15 and fineness is 3,390 cm²/g. For mixing water, tap water was used. Fine aggregate was natural river sand (specific gravity: 2.59, fineness modulus 2.21, and 0.08 mm sieve pass rate: 2.87) was used while coarse aggregate was crushed rock. To satisfy gradation of coarse aggregate, the nominal maximum size of 25 and 10 mm aggregates were mixed with ratio of 8 to 2. For coarse aggregate, specific gravity was 2.67, and fineness modulus was 6.59. As a chemical admixture, air entrainer and a superplasticizer (from Dongnam corp.) was used. The air entrainer was used for both normal and high-strength concrete mixtures, while the superplasticizer was used only for high-strength concrete mixture. All chemical admixtures used were general products from a South Korean vendor and the superplasticizer used was a naphthalene-based high-range water reducer.

Concrete mix proportions were designed based on the testing factors of unit water content and S/a as shown in Tables 2 and 3 for normal concrete and high-strength concrete, and an air entrainer was added as 0.01% of the cement mass to satisfy the target air content for the control mixture of S/a at 0.45 and the unit water content at 185 kg/m³. Concrete mixing was conducted with a pan-type mixer with a 60-L capacity. The mixing protocol followed ASTM C192 (ASTM International, 2013a). All fresh state tests were executed immediately after the mixing, and a concrete cylindrical mold was cured as per ASTM C192 with diameter 100 mm and height 200 mm and was used until the designated ages were determined for the compressive strength test.

To evaluate air content and unit volume weight, ASTM C231 (ASTM International, 2010a), and C138 (ASTM International, 2013b) methods were executed. The slump test was conducted as per ASTM C143 (ASTM



International, 2012b) and the EISN was calculated as shown in Eq. (1). Concrete flow distance was measured at both maximum and minimum distances as per ASTM C1611 (ASTM International, 2010b) without the inverted cone. The compressive strength was measured as per ASTM C39 (ASTM International, 2012c) at designated ages.

4 Results and Discussion

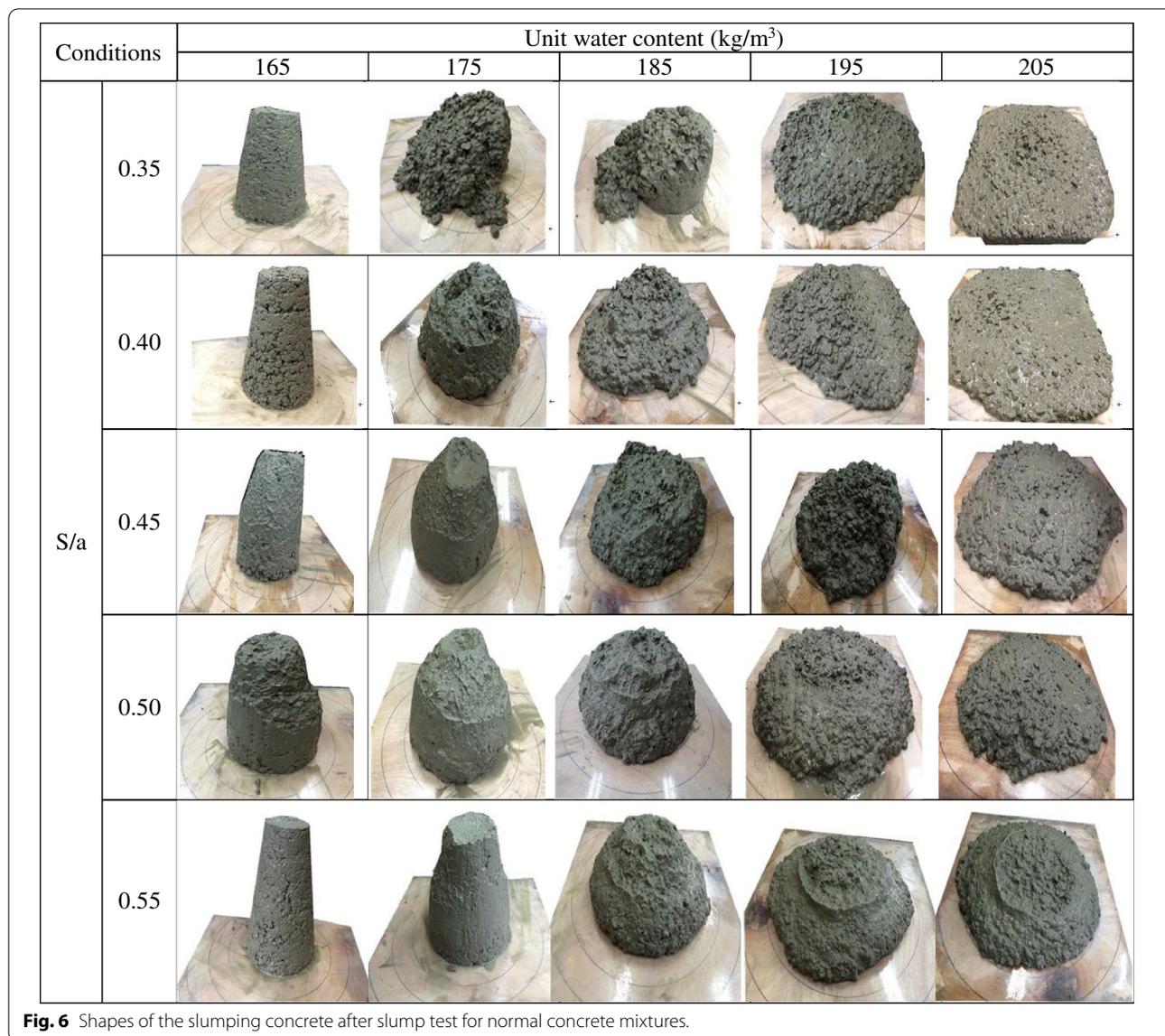
4.1 Normal Concrete Mixture

4.1.1 Basic Fresh State Properties

The basic properties of fresh state concrete were measured. These include slump, air content, and unit volume weight. Regarding slump test results, Fig. 4a, b shows the effects of S/a and unit water content on slump. Generally, slump varies from zero to 275 mm depending on test factors. For S/a, although S/a is known as controlling the cohesion of the mixture, increasing S/a decreased the slump of the mixtures. However, comparing the influence of S/a and unit water content on slump, unit water content showed higher influence on slump than S/a as widely known. Specifically, when unit water content was 165 kg/m³ (the lowest level under

this research's scope), slump was not influenced by S/a. Regarding the influence of unit water content on the slump of the mixture as shown in Fig. 4b, based on 185 kg/m³ of the unit water content, as the unit water content increased, the slope of the increasing slump became relatively gentle as the changing slope threshold of the slump started at approximately 175 mm (between 150 and 200 mm) of slump. It can be considered that the mixture intends to flow rather than slump over the 185 kg/m³ of unit water content. In other words, measuring slump cannot be measured efficiently after it reaches the slump threshold of approximately 175 mm.

Regarding the air content and unit volume weight of the concrete, as shown in Fig. 5a, b, although all cases satisfied the target air content range, air content decreased with increased S/a, and increased with increased unit water content. Naturally, the unit volume weight of concrete showed an inverse proportional relationship. The unit volume weight's influence on S/a affects air content, which means that increasing fine aggregate increased the removal of the air void. On the other hand, increasing the unit water content increased the portion of the cement paste to the aggregate. The increasing portion of cement paste means increasing



a portion of the volume where the air void is located; thus, the amount of air entrainer increases with the weight of the cement even though the dosage is fixed.

4.1.2 Segregation Evaluation (EISN)

To evaluate the segregation of concrete mixtures after the slump tests, the shape of the concrete slump is shown in Fig. 6. The segregation of concrete mixtures was evaluated by observation, and maximum and minimum distances were measured to calculate the EISN. The results of observation for segregation and EISN are summarized in Table 4 where the S/a decreases, and the unit water content increases causing segregation to occur. From EISN values calculated from maximum and

minimum distances of slump flow, all values were distributed between 1.00 and 1.16. Specifically, based on similar results occurring for segregation, the EISN values were decreased with increased S/a and increased with increased unit water content as shown in Fig. 7a, b, respectively. Namely, with an increasing EISN value (low S/a, and high unit water content), a possible segregation of the concrete mixtures exists. As shown in Eq. (1), 1.00 of EISN means same distance between the maximum and the minimum distance of slump flow, and thus it is highly possible that the true slump will appear without segregation or collapse slump. Therefore, Fig. 8 shows 1.09 of EISN as the maximum border when evaluating a non-segregating concrete mixture. Additionally, based on the

Table 4 Slump and slump flow test results and EISN calculation data of normal concrete mixtures.

Mixture*		Slump (mm)	Slump flow (mm)			Segregation	
S/a	W		Average	Max. (a)	Min. (b)	EISN (a/b)	Evaluation**
0.35	165	35	208	210	205	1.02	O
	175	150	293	310	275	1.13	X
	185	185	335	360	310	1.16	X
	195	230	435	460	410	1.12	X
	205	275	550	580	520	1.12	X
0.40	165	20	205	205	205	1.00	O
	175	130	253	260	245	1.06	O
	185	205	373	390	355	1.10	X
	195	220	445	470	420	1.12	X
	205	270	540	570	510	1.12	X
0.45	165	30	208	210	205	1.02	O
	175	120	235	240	230	1.04	O
	185	195	333	345	320	1.08	O
	195	205	350	370	330	1.12	X
	205	235	433	455	410	1.11	X
0.50	165	45	213	215	210	1.02	O
	175	105	218	220	215	1.02	O
	185	175	323	330	315	1.05	O
	195	200	423	435	410	1.06	X
	205	225	430	450	410	1.10	X
0.55	165	10	203	205	200	1.03	O
	175	80	210	210	210	1.00	O
	185	160	308	315	300	1.05	O
	195	185	400	410	390	1.06	O
	205	210	415	425	405	1.05	O

*S/a sand-to-aggregate ratio, W unit water content.

**Segregation of the concrete mixtures was evaluated by observation (O: non-segregation, X: segregation).

EISN and concrete segregation resistance, the concrete mixtures could be categorized into three quality grades. Quantitatively, it can be suggested to categorize EISN for grade I is between 1.00 and 1.03; grade II is between 1.03 and 1.06, and grade III is between 1.06 and 1.09.

4.1.3 Compressive Strength

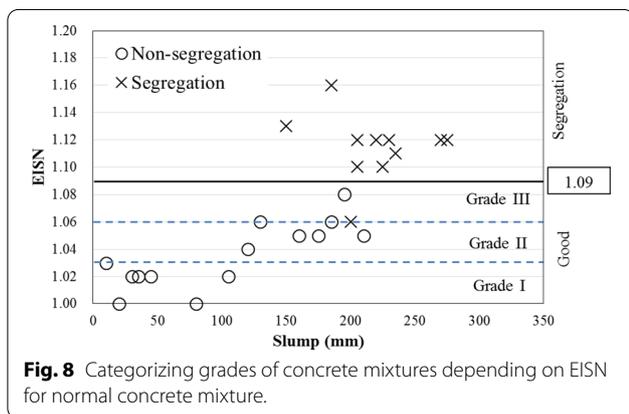
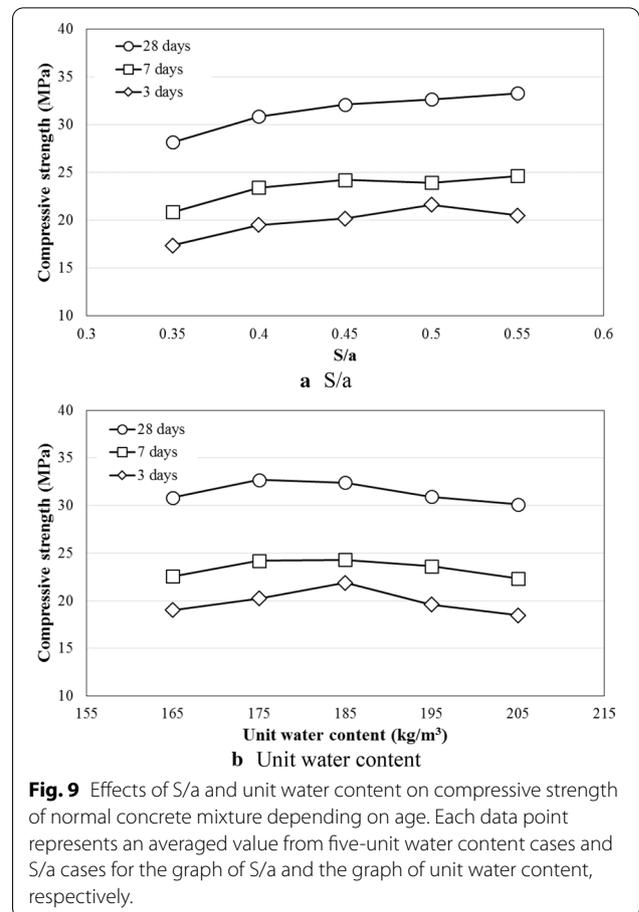
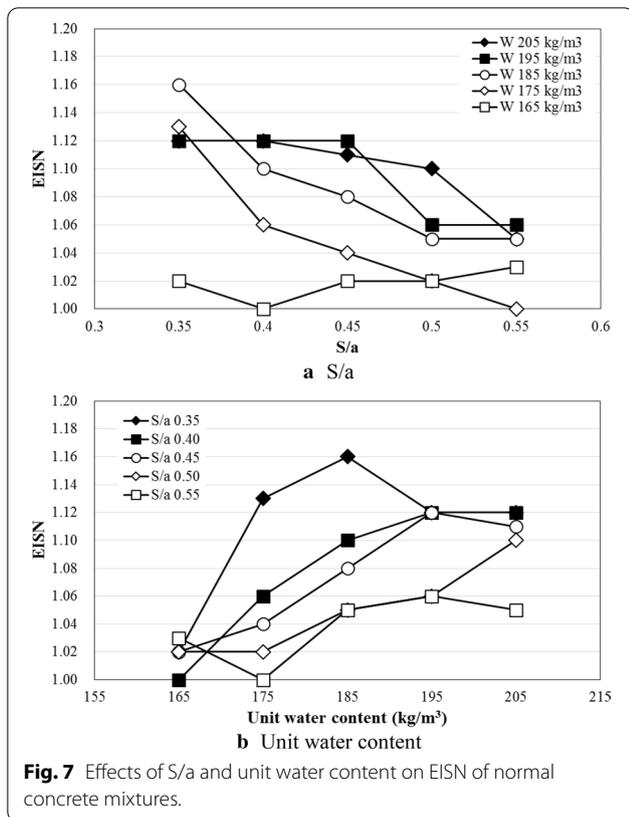
Compressive strength of the concrete mixture was evaluated based on S/a, and unit water content. Theoretically, changing S/a or unit water content should not affect the compressive strength of the concrete mixture since the water-to-cement ratio is same. However, Fig. 9a, b shows data with a scattered trend toward error for averaged compressive strength values from five different unit water contents with S/a. Compressive strength gradually increased with increased S/a as shown in Fig. 10a. Similar values usually appeared regardless of unit water content change (Fig. 10b). Compressive strength gradually increased with an increase in S/a. This was a result of improved packing

with small particles of fine aggregate. Based on this result, it can be considered that segregation or poor quality of fresh state properties of concrete mixture can affect the compressive strength of hardened state concrete.

4.2 High-Strength Concrete Mixture

4.2.1 Basic Fresh State Properties

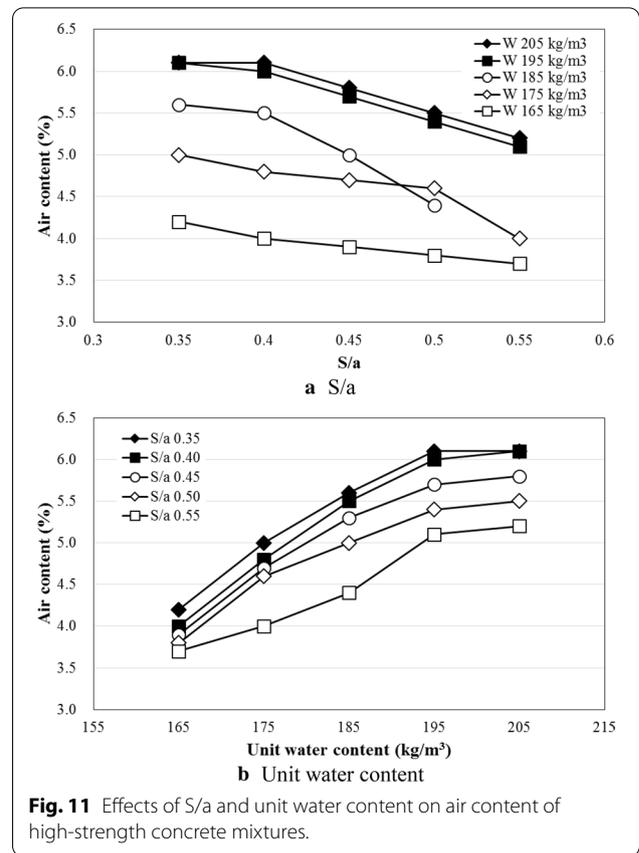
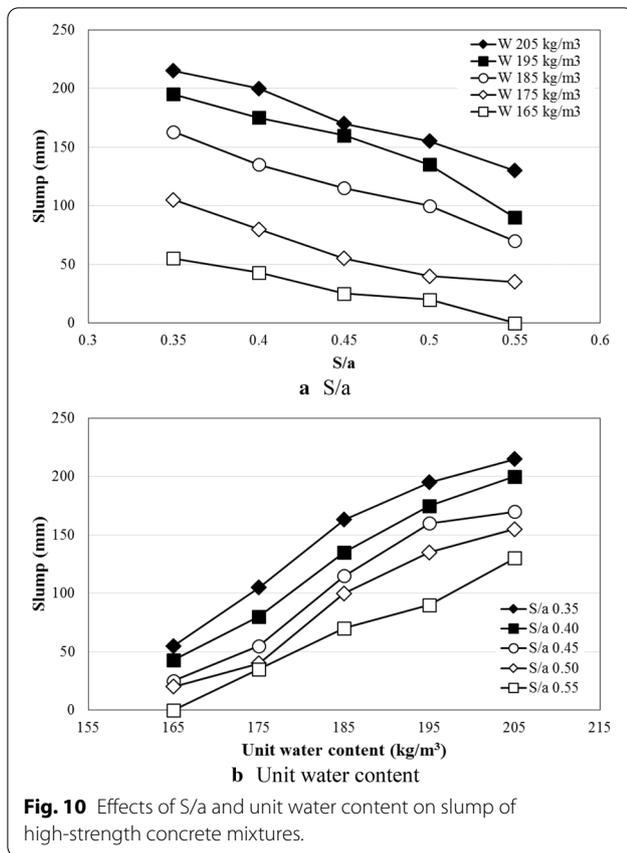
Unlike the normal concrete mixtures, although high-strength concrete mixtures were designed to have a similar range of slump values, high-strength concrete mixtures contain high volume of cement which can cause high viscosity and superplasticizer with dispersing action. For the slump, as designed, all mixture slump values were no higher than 215 mm. Depending on the S/a, as shown in Fig. 10a, the slump decreased with increased S/a. The effect of unit water content is shown in Fig. 10b, where slump increased with increased unit water content. Although both S/a and unit water content affected the slump of the concrete



mixtures, unit water content had a greater effect than S/a on the slump of the concrete mixtures as well as the normal concrete mixtures. Regarding air content and unit volume weight, air content decreased as the S/a increased as shown in Fig. 11a and increased as the unit water content was increased as shown in Fig. 11b. The unit volume weight had an inverse proportional relationship with air content. Comparing S/a and unit water content, unit water content had more of an effect on air content than S/a.

4.2.2 Segregation Evaluation (EISN)

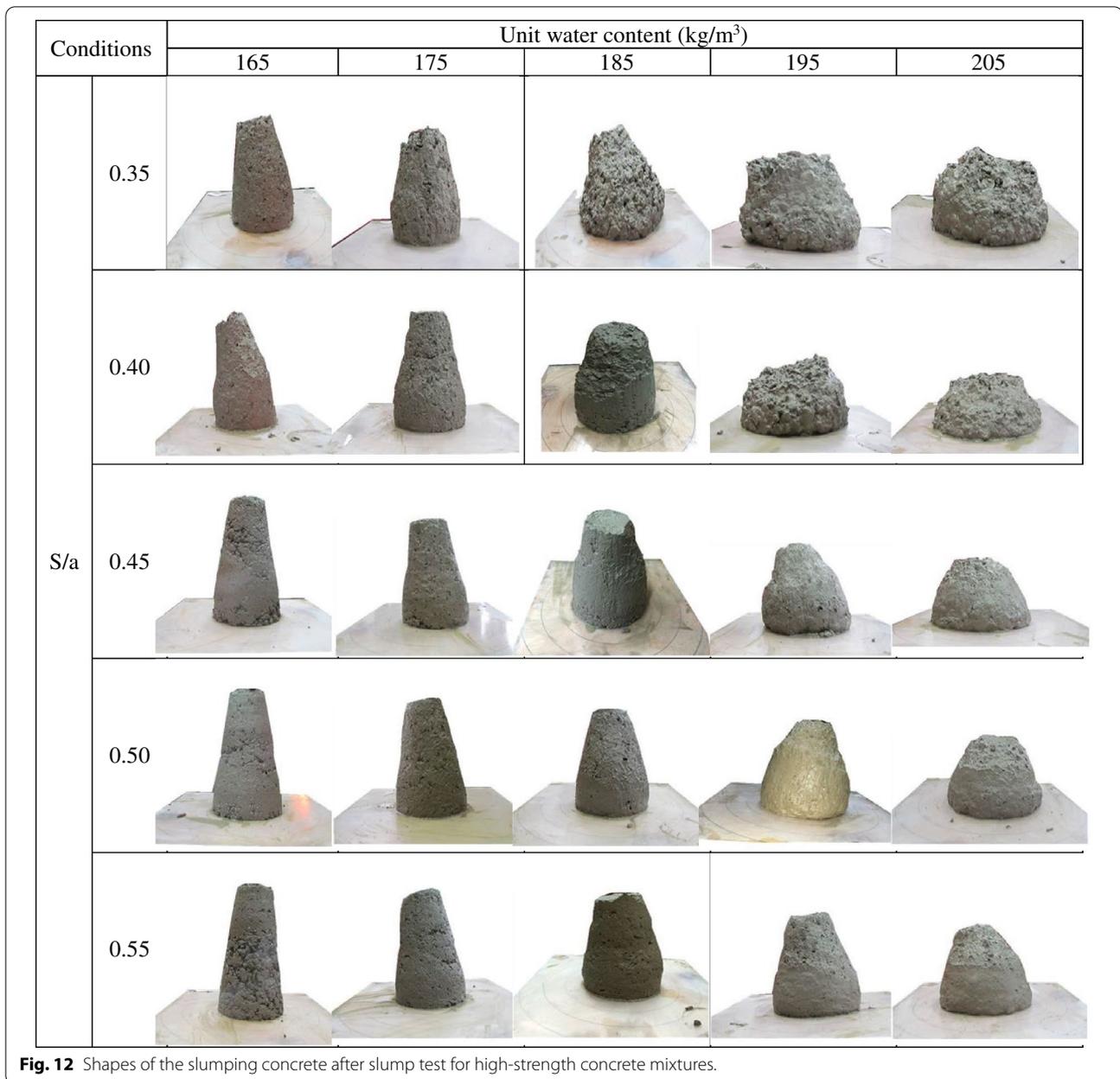
Figure 12 shows the segregation evaluation measures of the concrete mixtures based on the shapes of the concrete after the slump test. Because of the relatively high cohesiveness of the mixtures due to the low water-to-cement ratio, these mixtures were hard to evaluate as a segregation or collapsed slump for high-strength concrete mixtures. This also relates to the relatively low slump values of high-strength concrete mixtures compared to the slump value of normal concrete mixtures (comparing Fig. 5 with Fig. 13). Additionally, to compare to the other evaluation methods, the remaining circle method by Maruya et al. (Maruya et al. 2013) was used (see Fig. 13). As shown in the figure, the Maruya et al.'s method determined the mixtures with less than 0.40 of S/a as a segregation although the mixtures were not segregated. To calculate EISN, the maximum and minimum distances were measured (see Table 5). As shown in Fig. 14a, b, there was no clear relationship between EISN and S/a and unit water content. The relation between slump and EISN is expressed in Fig. 15 in which all cases show less than 1.09 of EISN



values without any segregation, while the Maruya et al.'s method evaluated as a segregation in some cases. Namely, in the case of high-strength concrete mixtures with a high solid volume fraction of 0.30 water-to-cement ratio due to high cohesiveness or plastic viscosity, shear slump or collapse slump did not occur, and based on the EISN method, there was no evaluation as a segregation. On the other hand, according to Maruya et al.'s evaluation method, because there was no remaining ring at S/a 0.35 and 0.40, the concrete mixtures were evaluated as segregated mixtures, although low unit water content mixtures did not show the segregation (see Fig. 15). Therefore, it can be stated that Maruya et al.'s method is not completely suitable for a high viscous concrete mixture such as high-strength concrete mixtures with low water-to-cement ratio (high solid volume fraction). Furthermore, additional study on the feasibility of the EISN method is needed for slumping concrete mixtures with high viscosity.

4.2.3 Compressive Strength

For compressive strength of the concrete mixture, all values were within 49.4–57.4 MPa. As shown in Fig. 16a, b, the influence of S/a and unit water content was not significant for compressive strength. Specifically, in the case of S/a, the compressive strength was increased by increasing S/a until S/a 0.45, and the compressive strength either remained constant or decreased after reaching S/a 0.45. Notably, when increasing a portion of fine aggregate, it can fill the void of the concrete mixture while excessively high portions of fine aggregate does not help to increase compressive strength. For unit water content, compressive strength generally decreases when unit water content increases within a small or limited range. This study examined the compressive strength results pertaining to S/a and unit water content used during the mix proportioning process. Study results indicate that even though the factor dominating compressive strength is not the S/a and unit water content, an inappropriate range of S/a and unit water content can be harmful to the compressive strength of concrete mixtures.



4.3 Valid Range for Slump or Slump Flow

In this research, for the normal concrete mixture with slumping behavior, slump test was conducted and slump, and slump flow were measured to calculate the EISN. An EISN formula was determined to obtain segregation of the concrete mixture with slumping for both normal and high-strength concrete mixtures. A valid range of EISN was determined by measuring the slump and slump flow of concrete mixtures; thus, “the slumping concrete

mixture” was defined. Generally, a slump test is conducted for the concrete mixture with slumping and normal workability, while slump flow tests are conducted for the concrete mixture with flowing and high workability. In a typical slump flow test, the flowing concrete mixture has no meaningful height for slump. In rheological aspect, the flowing concrete mixture has very low or no yield stress. Based on the definition of yield stress pertaining to the minimum stress that must be overcome

Conditions			Unit water content (kg/m ³)				
			165	175	185	195	205
S/a	0.35	Shape					
		Evaluation	X	X	X	X	X
	0.40	Shape					
		Evaluation	X	X	X	X	O
	0.45	Shape					
		Evaluation	O	O	O	O	O
	0.50	Shape					
		Evaluation	O	O	O	O	O
	0.55	Shape					
		Evaluation	O	O	O	O	O

Fig. 13 Evaluation of segregation of high-strength concrete mixtures by Maruya et al. method. The segregation evaluation was also conducted by the same method, and the circles on the concrete show the consistently appearing circle shape.

for starting the mixture flow, the flowing concrete mixture begins to flow after lifting the slump cone. Because of the low or no yield stress of the concrete mixture, the concrete mixture can flow and spread widely whether the mixture suffers segregation or not; thus, no stacking occurs in the mixture to be measured as a slump. Furthermore, if there is a stacking of the mixture for a flowing concrete mixture, it is a stack of coarse aggregates due to the separation of the mortar or cement paste (segregation). Figure 17 shows the relation between slump flow and slump in normal concrete mixture, the figure shows the changing slope relationship. From the trend

line, the slump value for changing the slope of the trend line (the point of the tangent line slope is one) can be calculated as 115.50 mm. Therefore, based on this result, a valid range of slump test and slump flow test results can be determined as an approximately 120 mm of slump. However, with the slump result of the normal concrete mixture in Fig. 4, it is applicable for practical conditions that 150 mm of slump as a boarder of the valid range of slump. Additionally, for EISN, it can be state that the concrete mixture with less than 120 mm slump is valid for EISN.

Table 5 Slump and slump flow test results and EISN calculation data of high-strength concrete mixtures.

Mixture*		Slump (mm)	Slump flow (mm)			Segregation	
S/a	W		Average	Max. (a)	Min. (b)	EISN (a/b)	Evaluation**
0.35	165	55	203	205	200	1.03	X
	175	105	210	215	205	1.05	X
	185	163	275	280	270	1.04	X
	195	195	283	285	280	1.02	X
	205	215	233	335	330	1.02	X
0.40	165	43	203	205	200	1.03	X
	175	80	205	210	200	1.05	X
	185	135	245	250	240	1.04	X
	195	175	268	270	265	1.02	X
	205	200	295	295	295	1.00	O
0.45	165	25	200	200	200	1.00	O
	175	55	205	205	205	1.00	O
	185	115	240	245	234	1.05	O
	195	160	253	260	245	1.06	O
	205	170	273	275	270	1.02	O
0.50	165	20	200	200	200	1.00	O
	175	40	203	205	200	1.03	O
	185	100	233	235	230	1.02	O
	195	135	243	245	240	1.02	O
	205	155	265	275	255	1.08	O
0.55	165	0	200	200	200	1.00	O
	175	35	203	205	200	1.03	O
	185	70	205	205	205	1.00	O
	195	90	215	220	210	1.05	O
	205	130	257	260	255	1.02	O

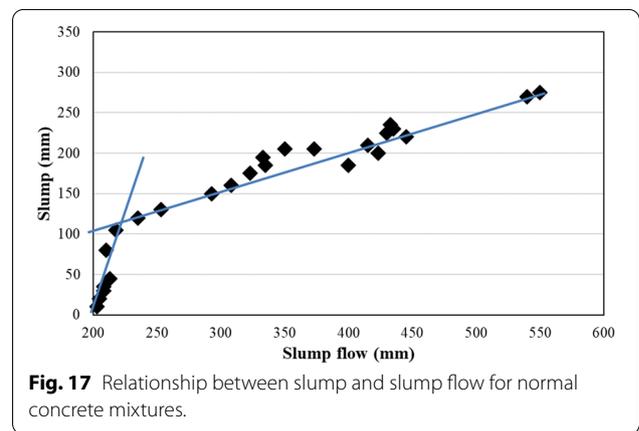
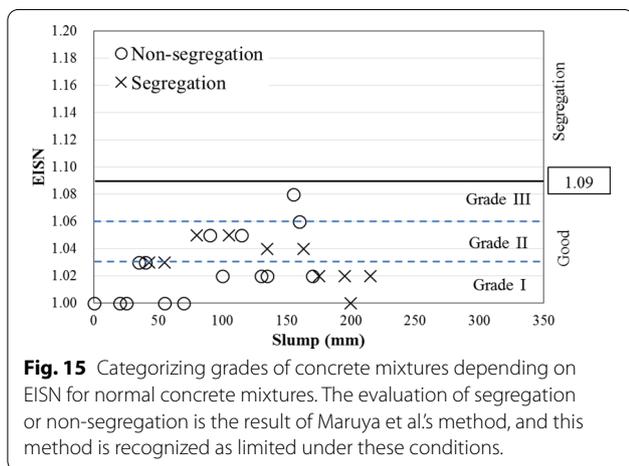
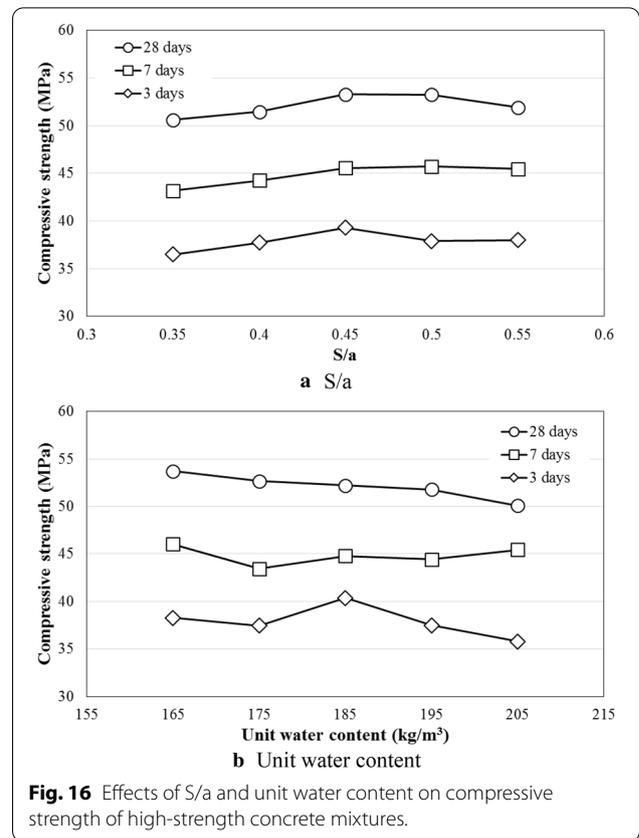
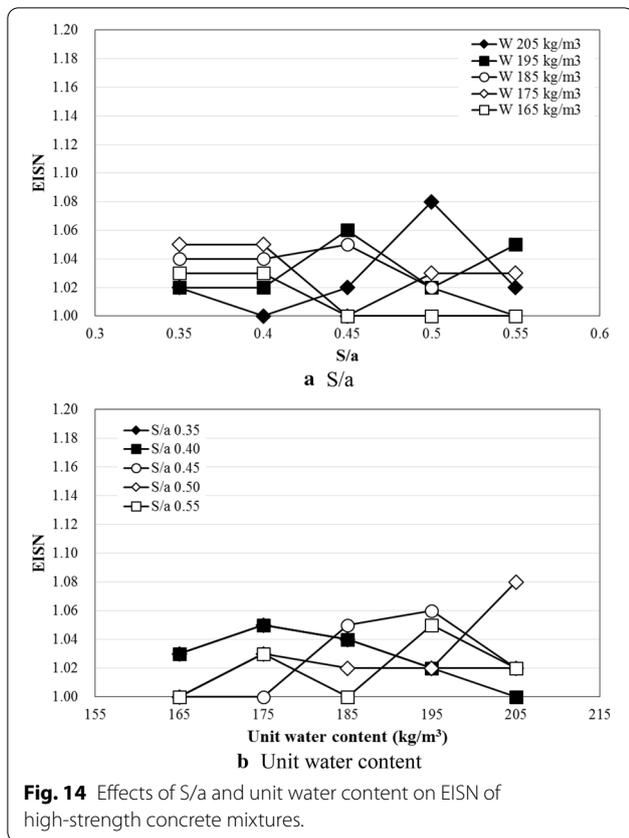
*S/a sand-to-aggregate ratio, W unit water content.

**Segregation of the concrete mixtures was evaluated by Maruya et al. suggested method (O: non-segregation; X: segregation).

5 Conclusions

In this research, a quantitative evaluation method for segregation of normal concrete is introduced, which uses observation after the slump test, currently. Based on the collapsed slump or shear slump shape, the shape of the segregated concrete mixture was defined after the slump test, and the quantitative evaluation method was defined. By measuring both maximum and minimum flow distances of the concrete mixture after the slump test, the EISN value can be calculated and based on 1.09 of EISN value, thereby allowing the segregation of concrete mixture to be assessed. This method is also applicable for high-strength concrete mixtures

including high volume of powders and superplasticizers as long as the concrete mixture is slumping. Additionally, according to the relation between slump and slump flow, a valid range of slump test and slump flow test was determined, and a valid range of EISN was also defined. Currently, determining segregation of concrete relies on the observation of engineers, and the evaluation method is qualitatively conducted. By using the method introduced in this paper, quality control of ready-mixed concrete can be improved in the normal strength concrete range.



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I-DH: test execution and research planning. DH: manuscript writing and test execution supervision. Both authors read and approved the final manuscript.

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Availability of data and materials

All measured data were obtained by lab tests. The lab test results are provided in Excel format.

Declarations

Ethics approval and consent to participate

Done.

Consent for publication

Done.

Competing interests

None.

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