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Experimental investigation for ECC improving shrinkage crack resistance and workability

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ABSTRACT: This study focused establishing ECC mix proportion which enables us to control shrinkage cracking due to high unit water amount and to secure reasonable workability by overcoming relatively high fiber volume fraction. The former task was successfully achieved by involving anti-shrinkage admixture, and effects of those admixtures were investigated via drying shrinkage tests and restrained cracking tests. The latter task was secured by involving natural water soluble polysaccharide ride type viscous agents replacing well known cellulose type viscous agent. Fresh compacting tests were adopted to demonstrate semi self compacting fresh property of ECC with polysaccharide ride type viscous agents. As a result, proposed mix proportion demonstrated sufficient ability to be applied to actual construction project via full scale mixing tests.

1 INTRODUCTION

ECC is a pseudo strain hardening cement composite, which is expected to apply to structural elements to improve both mechanical performance and durability. Some applications have been accomplished, e.g., in coupling beam connecting structural walls in high rise reinforced concrete structures (Kanda et. al 2005).

However, ECC involves two problems to be overcome, i.e., shrinkage restraint cracking and workability. The former is caused by large amount of unit water content, which leads to severe drying shrinkage. This problem should be resolved with large unit water content condition. The latter problem arises because ECC should have strong viscosity to secure fiber dispersion in fresh status. Workability tends to be deteriorated due to this strong viscosity. Appropriate workability should be realized by maintaining strong viscosity.

This study investigates the above two issues for ECC with PVA fiber. First, shrinkage cracking experiment is performed to restrain drying shrinkage of ECC and to improve anti-cracking resistance. Second, workability experiment is conducted to improve workability by investigating the effects of constitutive materials. As a result of the two experiments, ECC is demonstrated to be sufficient performance to be applied to actual structures.

2 EXPERIMENT

2.1 *Plan of shrinkage cracking experiment*

Scope of the shrinkage cracking experiment is to find mix proportion showing shrinkage cracking resistance comparable to normal concrete by investigating effects of unit water content and additives to restrict drying shrinkage. Experimental parameters and those levels are listed in Table 1. Three parameters, unit water content, Shrinkage reducing admixture (SRA, hereafter), and curing condition were adopted as show in Table 1. Unit water content is broadly known strongly influence drying shrinkage, and three levels from 400 to 360 kg/m^3 were adopted as practical range to maintain practical fresh and mechanical properties via trial mix tests. SRA is expected to substantially reduce drying shrinkage, and two types were selected in commercial products. Curing condition is added to parameters. This is because pre-cast production is expected major in appli cation of ECC, where steam curing is usually conducted. Effects of steam curing (max temperature 35°C, 8hr duration) should be clarified in addition to normal 20°C curing.

Table 2 shows the combinations of parameters, and resulting five mixes were tested. As a reference normal concrete mix is added in the experiments.

Table 3 shows mix proportions of specimens. Water-to-binder ratio (w/b hereafter) is set around 46% in all mixes. Binder was combination of cement and fly ash, whose weight ratio was 7:3. Fly ash was selected from products satisfying type II requirement in Japanese Industrial Standard A 6201. Due to very high unit water content over 350 kg/m^3, solely SRA

Table 1. Outline of shrinkage cracking experiment.

Exp. Parameter	Level
Unit water cont.	400, 385, 369 kg/m^3
SRA type	ASR1, ASR2
Curing conditeion	20^{o}C, Steam curing

addition appears insufficient and combination with expansive agent was considered mandatory to achieve targeted shrinkage cracking resistance. The content of expansive agent was fixed 60 kg/m^3 in all ECC mixes. SRA content was determined via trial mix tests. Air content was initially targeted 6%. However, the unit water content reduction led to significantly increasing viscosity, which was aimed to be restricted by increasing air content to 10% using air-entraining agent. Adopted fiber was 12mm long PVA with 0.04mm diameter. The fiber's tensile strength and elastic modulus are 1690 MPa and 40.6GPa respectively. The reference normal concrete is typically designed for building construction with water-to-cement ratio 57% and unit water content 185 kg/m^3.

Testing items are summarized in Table 2, where three testing items, restrained shrinkage test, free shrinkage test, and restrained cracking test, were listed. The former two tests were conducted by following JIS A 6202 and JIS A 1129. Standard free shrinkage test in JIS 1129 adopts an original point for length change variation at 7 day age, at the end of water curing. However, in this study, the original point is set at de-molding, 1 day age. The restrained shrinkage test in JIS A 6202 was designed to clarify semi-free shrinkage of concrete with expansive agent. In this test, restraint rebar is arranged at the center of specimen (section 100x100mm), where reinforcing ratio is 0.95%. The restrained cracking test is outlined in Figure 1 and specified as testing method for restraint autogenous shrinkage stress in JCI report (JCI 2002). The adopted restraint cracking test modified drying condition after 7 days age from sealing condition in the JCI test. In the three kinds of tests, three specimens were prepared for each identical test condition. Curing condition in shrinkage cracking experiment is summarized in Table 4. For all ECC mixes to confirm mechanical property, tensile test (Kanda & Li 1999) and compressive test were to be conducted. For normal concrete, compressive test was also conducted.

Table 2. Combination of parameters and tests.

				Test		
Speci men	Unit wa ter cont. (kg/m^3)	SR A t ype	Curin g con d	Restra int sh rinka ge tes t	Free shrin kage test	Restra int cr ackin g test
W400	400	AS R1	20^{o}C	done	done	-
W385	385	AS R1	20^{o}C	done	done	done
W360	360	AS R1	20^{o}C	done	done	-
W360 Ad	360	AS R2	20^{o}C	done	-	-
W385 s	385	AS R1	Steam	done	-	-
NC	185	-	20^{o}C	-		done

Table 3. Mix proportion.

Mix	Water to binder ratio	Unit waterc ont.(kg /m^3)	Sand to bin der ratio	SRA cont ent (kg/ m^3)	Fiber vol. (%)	Air cont. (%)
W400	46	400	0.6	20	2	6
W385	46	385	0.8	20	2	6
W360	47	360	0.9	20	2	10
W360 Ad	45	360	0.8	10	2	10

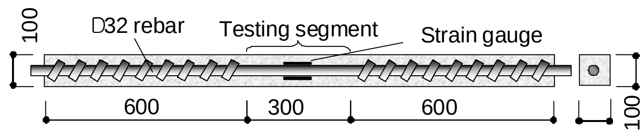

Figure 1. Specimen of restraint cracking test (unit: mm).

2.2 *Plan of workability experiment*

ECC generally has difficulty in maintaining both appropriate viscosity and good workability. For example, ECC in this study involves 2% volume of fiber with high aspect ratio, and its dispersion appears secured by viscosity in fresh status. However, viscosity

Table 4. Curing condition in shrinkage cracking experiment.

Specimen	Curing cond.	Curing cond. bef ore de-molding	de-moldinga ge (days)	Curing cond. a fter de-molding	Drying initiatio n age (days)	Drying cond.
Restraint s hrinkage t est	20^{o}C	20^{o}C 80%RH	1	20^{o}C in water	7	20^{o}C 60%RH
	Stem	Max 35 oC Steam curing	1	20^{o}C sealed	7	20^{o}C 60%RH
Free shrin kage test	20^{o}C	20oC 80%RH	1	20^{o}C in water	7	20^{o}C 60%RH
Restraint Cracking t est	20^{o}C	20^{o}C 80%RH	1	20^{o}C sealed	7	20^{o}C 60%RH

Table 5. Outline of workability experiment.

Exponential paramete r	Level
Viscous agent type	Cellulose type, Bio-saccharide type
Cement type	C rdinary Portland cement (OPC), Low heat Portland cement (LPC)
Fly ash type	FA1, FA2

Table 6. Combination of parameters in workability experiment.

Mix	Cement type	Viscou agent type	Fly ash type	Scope
Control	OPC	Cellulose	FA1	-
LPE	LPC	Cellulose	FA1	Influence of cement type
BS	OPC	bio-saccharide	FA1	Influence of viscous agent type
LPC/BS	LPC	bio-saccharide	FA1	Influence of cement and viscous agent types
LPC/BS/FA	LPC	bio-saccharide	FA2	Influence of fly asy type

increase accompanies increase of yielding stress in fresh status, which deteriorates workability. Hence workability experiment was planed to establish mix design showing good workability with maintaining other material properties. In addition, self-compacting ability is aimed to be realized.

Table 5 is shown outline of the workability experiment. Experimental parameters are: viscous agent type, cement type, and fly ash type. Viscous agent is important to control viscosity and to secure fiber dispersion. Adopted viscous agents are a product belonging cellulose type and one in bio-saccharide type. Cellulose type is widely used in concrete industry, and bio-saccharide type appears appropriate in the current usage due to its thixotrophy property. Cement type is also strongly influence fresh property in ECC. Low heat Portland cement (LPC) was adopted due to its viscosity reducing tendency in addition to ordinary Portland cement (OPC). The last parameter, fly ash type, was selected since fly ash quality is known to be widely spread depending on production source and to affect fresh property. Hence two types of fly ash products, FA1 and FA2, from different source were adopted in the experiment. FA1 is high quality fly ash with ignition loss 0.2%,and FA2 is regular quality with 1.6%.

Table 6 shows five ECC mixes investigated in the workability experiment by combining experimental parameters in Table 5. Comparing the properties of these mixes, effects of cement type, viscous agent type, and fly ash type are expected to be revealed. These mixes are based on W385 in Table 3 but modified to involve 10% air content.

Testing items in workability experiment are slumflow test, V-funnel test (JSCE 1998), and self-compactability test (JSCE 2002). V-funnel test is used to evaluate segregation resistance, and self-compactability test is used to check self-compacting ability beyond obstacles like re-bars. Apparatus of self-compactability test is shown in Figure 2. In this experiment, two levels of anti-flowing obstacles were adopted according to rank 1 (D10-5 rebar), and rank 3 (no rebar).

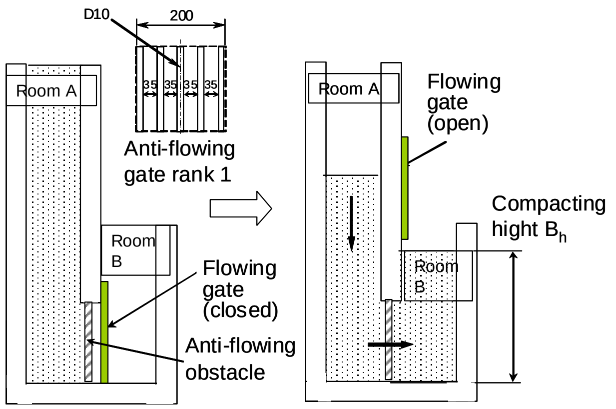

Figure 2. self-compactability test.

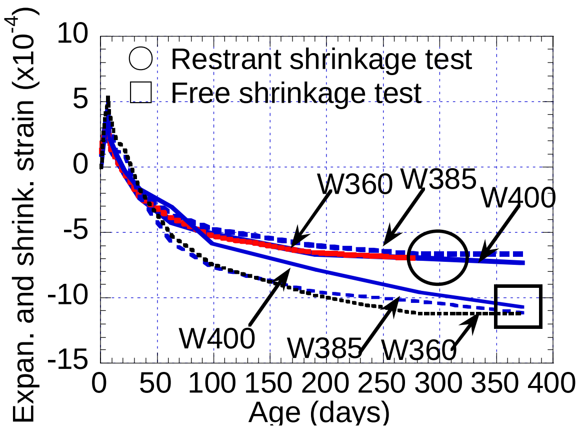

Figure 3. Result of restraint shrinkage and free shrinkage tets.

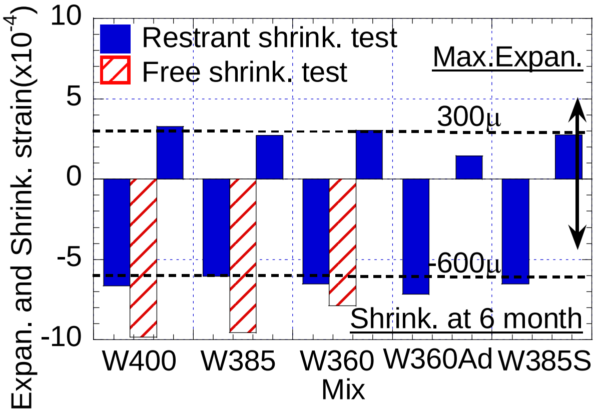

Figure 4. Summary of Initial expansive strain and shrinkage strain result.

Table 7. Summary of material mechanics test result.

Mix	Tension		Compression	
	Tensile strength σ_{cu} (N/mm^2)	Ultimate strain σ_{cu} (%)	Compressive strength σ_b (N/mm^2)	Elastic modulus E_c (N/mm^2)
W400	5.72	3.09	47.6	14.6
W385	6.53	2.40	51.0	15.5
W360	4.82	3.09	39.5	15.3
W360Ad	4.71	1.74	-	-
Normal concrete	-	-	36.4	26.9

3 RESULT AND DISCUSSION

3.1 *Shrinkage cracking experiment*

Table 7 shows material mechanics test results. All ECC mixes in shrinkage cracking experiment showed multiple cracking with over 1.5% of ultimate tensile strain.

Figure 3 shows some results of restraint shrinkage test and free shrinkage test. In both kinds of tests, differences among mixes are minor in Figure 3. The restraint test results tend to be smaller shrinkage strain than free shrinkage strain after one year age. This tendency is reasonable because 0.95% of rebar in restraint test leads to smaller shrinkage than free condition.

Figure 4 summarizes the both of shrinkage tests. Positive side in Y axis shows maximum expansive strain at initial age, and negative side does shrinkage strain at 6 months. All test data in this figure is average of three specimens. Maximum expansive strain data in restraint shrinkage test are almost constant around 300μ independent of mixes, other than W385S with steam curing. This tendency in W385S appears due to lack of hydration water for expansive agent after steam curing, where sealing condition was adopted as shown in Table 4.

In Figure 4, it is shown that shrinkage strain data at 6 months in restraint shrinkage test are also constant, similar to maximum expansive strain, around 600μ although free shrinkage strain data decrease with increasing unit water contents. Shrinkage strain in restraint shrinkage test shows shrinkage restrained force by multiplying elastic modules and section area or rebar. Hence supposed cracking strength is constant, the results in Figure 4 imply influence of unit water content, SRA type, and curing condition on ECC's shrinkage cracking resistance are minor.

Figure 5 depicts data example of stress development in restraint cracking test. Restraint stress in Figure 5 calculated strain measurement data in restraint rebar's gauge multiplied by elastic modulus of rebar. Figure 5 shows that ECC has longer first cracking age than normal concrete while stress profiles are very different between these two materials. Longer first cracking age in ECC depends on larger compressive stress at initial stage, which is due to expansive agent. Furthermore, tensile stress development slopes are almost same between two materi

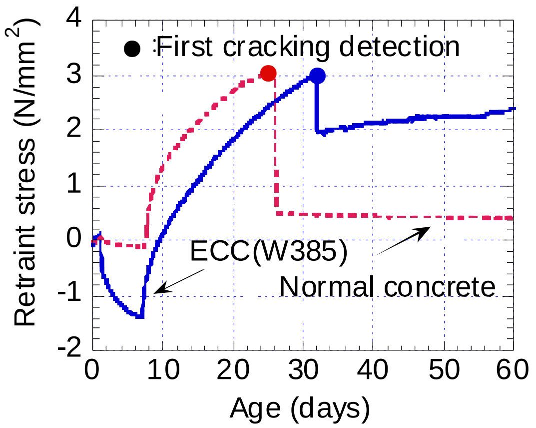

Figure 5. Stress development example in restraint cracking test.

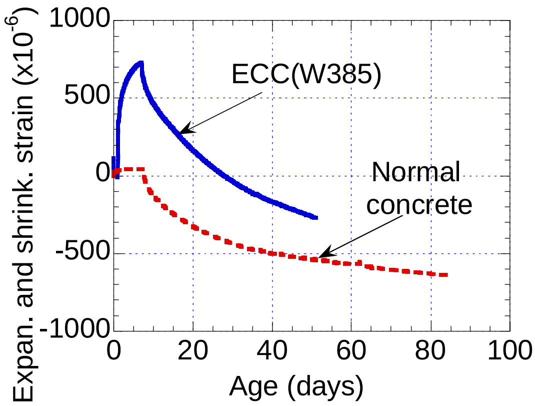

Figure 6. Free expansive and shrinkage strain.

Table 8. Summary of restraint cracking test result.

	ECC	Normal concrete
First cracking age (days)	37.4	26.7
Cracking strength (N/mm^2)	3.23	2.95
Crack opening displacement at 90 day age (mm)	0.06	0.37

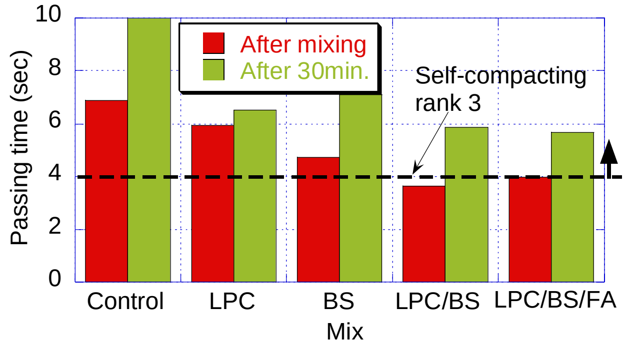

Figure 7. V-funnel test result.

als. This appears due to SRA effects. Figure 6 shows free shrinkage strain of normal concrete simul tane ously measured with restraint cracking test. This figure illustrates adopted normal concrete shows about 650μ at 90 day age, which is not special as concrete.

Table 8 summarizes restraint cracking test results, which are average in three specimens for each condition. This table shows first cracking age is longer in ECC than normal concrete. As a result, ECC in this study demonstrates at least similar restraint shrinkage cracking resistance to normal concrete.

3.2 *Workability experiment*

Figure 7 illustrates V-funnel test results. Passing time in V-funnel test shows segregation resistance, longer time is preferred. Passing time should be longer than 4 sec. to satisfy rank 3 self-compacting condition according to JSCE recommendations (JSCE 1998). As shown in Figure 7, all mixes except LPC/BS demonstrates to satisfy rank 3 requirement. It should be noted that control mix after 30 min. showed substantially long passing time, which infers compacting performance may be deteriorated due to too high viscosity.

Figure 8 shows slump flow results. Rank 3 requirement is more than 500mm, and all mixes showed satisfying this requirement or close to satisfying it.

Figure 9 shows selfcomactibility height results. JSCE's rank 3 requirement is higher than 300mm. Figure 9 demonstrates BS, LPC/BS, and LPC/BS/FA satisfy this requirement, hence showing that BS usage necessary to realize rank 3 self-compacting performance. As a result, ECC mixes using bio-saccharide viscous agent can achieve rank 3 requirement, i.e., semi-self-compacting performance.

4 CONCLUSION

This study aimed at adding shrinkage restraint cracking resistance and workability to ECC. To address two issues, shrinkage cracking experiment and workability experiment were conducted. As a result of these experiments, next conclusions were obtained.

First, even with very high unit water content over 300 kg/m^3, ECC demonstrates comparable shrinkage restraint cracking resistance to normal concrete. This is due to the effects of simultaneous usage of expansive agent and SRA. Second, bio-saccharide viscous agent can improve self-compacting ability maintaining segregation resistance in fresh state and strain hardening tensile mechanical property.

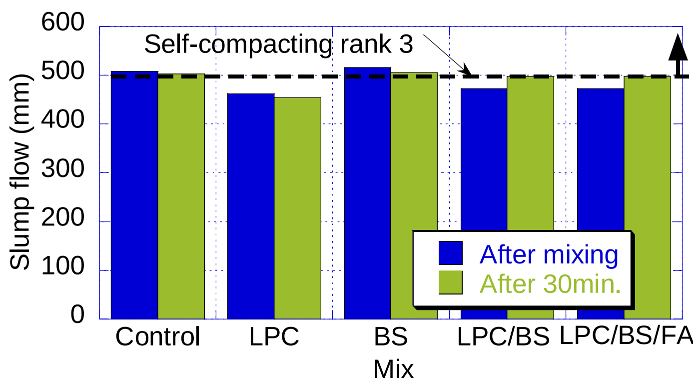

Figure 8. Slump flow result.

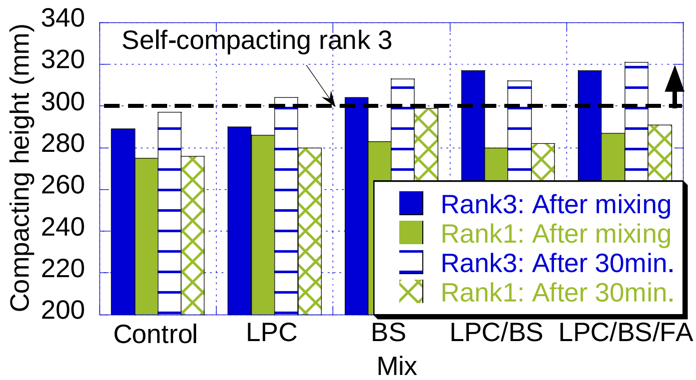

Figure 9. Self- compactability test result.

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