

FUNDAMENTAL PROPERTIES OF DIRECT SPRAYED ECC

Tetsushi KANDA*¹, Tadashi SAITO*², Noburu SAKATA*³ and Masanori HIRAISHI*⁴

ABSTRACT: It has been highly expected to utilize ECC, which has metal-like deformation and crack opening restriction ability, as retrofit materials for structures. For this application, direct spray method has been commonly accepted. This study focuses on experimentally clarifying fundamental properties of direct sprayed ECC, which involved high performance PVA fiber. As a result of experiments, it was demonstrated that the direct sprayed ECC can be successfully processed and shows pseudo-strain hardening performance comparable to ordinary cast ECC in literature.

KEYWORDS: ECC, retrofit, direct spray, tensile property, flexural property

1 INTRODUCTION

Engineered cementitious composite (ECC, hereafter) is expected to be utilized as effective retrofit materials as having large deformability and crack width restricting ability[1][2]. When using ECC as the retrofit material on existing concrete structures, this material can follow the movement of the existing foundation. Furthermore, even if cracking stress is exceeded and cracks are formed in the ECC retrofit material, crack width is restricted in small amount, e.g., less than 0.1 mm. This restriction is expected to enhance the durability of retrofitted structures against the attack of harmful substances.

In retrofit construction, concrete or mortar is often processed with direct spray method, generally known as shotcrete. This method has remarkable advantages in process efficiency and cost in some construction conditions. Shotcrete process has been widely applied such as to tunnel lining using conventional fiber reinforced concrete. However, to process ECC with the direct spray method has not been accomplished in previous development. This is because fiber volume fraction in ECCs, typically 1 to 2%, arises processing problems such as fiber ball cramming in pumping system.

This study experimentally investigates newly developed direct sprayed ECC. In experiment, ECC with Polyvinyl alcohol (PVA) fiber is processed with direct spray method and material test specimens are molded, with which tensile and flexural tests are conducted. With the test results, it is demonstrated that direct sprayed ECC has comparable mechanical properties with ordinary cast ECC.

*1 Building Eng. Dept., Kajima Technical Research Institute, Ph.D.

*2 Industrial Goods Development Dept., Kuraray

*3 Civil Eng. Dept., Kajima Technical Research Institute, Dr. Eng.

*4 Civil Eng. Dept., Kajima Technical Research Institute

2 EXPERIMENTAL PROGRAM

2.1 PROCESSING SYSTEM AND METHOD

Figure 1 illustrates processing system for ECC direct spray. In this study, two types of mixers are used, i.e., omni-mixer with 70 litter capacity and concrete mixer having horizontal two scraping axes with 100 litter capacity. As in Figure 1, mixed fresh materials are transferred with mortar pump via flexible tube to spray gun. At reaching spray gun the fresh materials are accelerated in speed with high pressure air and emitted out of the guns. Pumping machine is so called squeeze type with $6 \text{ m}^3/\text{hr}$ of capacity. The flexible tube has 40 mm diameter with 10 m length.

Direct sprayed ECC in this study is processed with approximately 10 mm thickness at once as not involving rapid setting cement or admixture. However, 10 mm thickness layer can be multiplied with certain time interval such as 10 min. to reach further desired thickness. It was experimentally confirmed that this repetition process enables us to achieve up to around 80 mm thickness on both vertical and horizontal surface to be sprayed upward. This level of thickness may be sufficient for ordinary retrofit application.

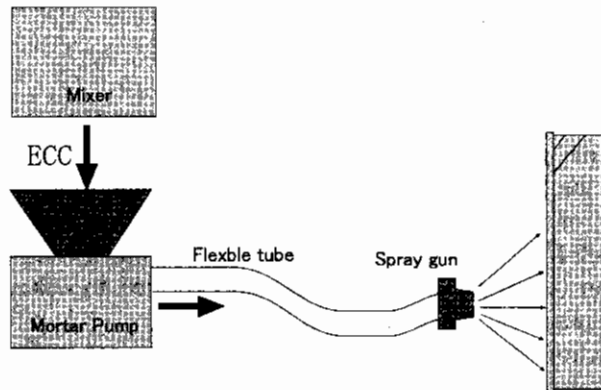


Figure 1 Schematic processing system

2.2 EXPERIMENTAL PARAMETER AND MATERIALS

This study investigates total 4 mixes by the combinations of three experimental parameters, which are named as mix-A, B, C, and D, as shown in Table 1. With those 4 mixes, material test specimens are cast by spray, and tested in tension and flexure.

Table 1 outlines 4 ECC mixes in this study. As depicted in this table, these mixes are different in: cement type, air content after mixing, and mixer type. Two cement types are used, ordinary Portland cement (OPC), and low heat Portland cement (LPC). Air content levels are 15 and 25%, and two types of mixers, as explained in section 2.1, omni-mixer and concrete mixer are adopted.

Cement types are selected depending on applicability in actual construction process. While OPC is normal choice, this cement is not appropriate in hot climate. This is because OPC tends to lead high fresh temperature, which deteriorates fresh flowability and causes troubles in spray process. Contrary to OPC, LPC restricts fresh temperature in low level and may be appropriate to hot environment in summer.

Table 1 Outline of ECC mix

Cement type	Air content (%)	
	15	25
OPC	A, D	B
LPC	C	-

A~C: mixed by omni-mixer

D: mixed by concrete mixer

Concerning mixer type, omni-mixers have been often used for ECC mixing, which are mainly used in this study. However, applicability of the omni-mixers may be questionable in actual retrofit construction site since their system is not compact and their operation requires additional labor compared with concrete mixer. Hence ordinary concrete mixer is added for investigation in this study.

Rather large air content level in this study depends on an ingredient in mix. Mixes in this study involve moisturizing agent with urethane (R-NHCOO-R') to enhance anti-segregation ability and flowability. This moisturizing agent has strong air entraining tendency and normal mixing leads to over 20% of air content.

Table 2 shows the mix proportion of ECCs in this study. The numbers in Table 2 are calculated by neglecting air content. Water by binder ratio (W/B), water content, and fiber volume fraction are constant in all mixes. Adopted binder consists of cement and fly ash (type II specified in JIS A 6201), whose weight ratio is 7:3. Involving in water content, high range water reducer and moisturizing agent are added by 1.1% and 0.8% of binder weight respectively. Adopted fiber is PVA, which has 0.04mm of diameter, 12mm of length, 1600 MPa of tensile strength, and 40 GPa of elastic modulus.

Table 2 Mix proportion

Mix	Water by binder ratio	* Sand by binder ratio	* Water content	Fiber volume fraction
	W/B	S/B	W (kg/m ³)	V _f (%)
A, B, D	0.32	0.41	382	2.1
C	0.32	0.42	382	2.1

*Air content is neglected.

2.3 TESTING PROCEDURE

This study investigates fresh properties and mechanical properties of the mixes. Fresh tests are conducted after mixing and after spraying, concerning temperature, table flow, specific gravity, and air content. Mechanical test specimens are cast by spraying on mold and by placing fresh mix into mold.

Mechanical property is evaluated mainly via tensile tests in this study. Tensile test set-up is illustrated in Figure 2 (a), where specimens have gauge length of 80 mm, width of 30 mm, and thickness of 13 mm. Specimens are cast after mixing by directly spraying on mold,

which are called sprayed specimen. To clarify the effects of spraying process on mechanical properties, tensile specimens are cast by placing fresh mixes in mold (placed specimen). Specimens are de-molded 2 days after cast and cured in sealing condition with 20 °C before testing at 28 day age. Tensile properties are evaluated by the average of at least three specimens.

Flexural tests are utilized in this study to investigate the effects of spraying thickness. Flexural specimens are prepared by three different processes. First two processes are same as tensile specimens (sprayed and placed), and the other is cut out of massive solid (cut-out specimen). Cut-out specimens are prepared with the procedure where: 1) 500 x 500 x 150 mm solids are cast by spraying at once, and 2) 40 x 40 x 160 mm of specimens are cut out of the solids (see in Figure 2 b). Cut-out specimens are named as cut-out-top (from top 50 mm), cut-out-middle (from middle 50 mm), and cut-out-bottom specimens (from bottom 50 mm), depending on the sections where those are in 150 mm of height direction. Flexural tests are conducted by mid-span loading on 100 mm span, where mid-span displacement and load are recorded in the tests. Flexural properties are evaluated by the average of at least three specimens.

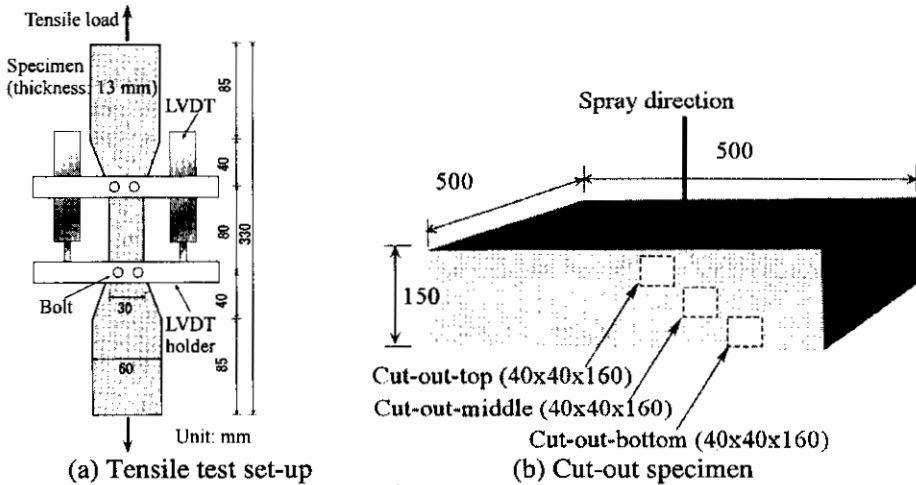


Figure 2 Specimen outline

3 RESULTS

3.1 MIXING AND SPRAYING

Mixing was successfully accomplished in both omni-mixer and concrete mixer. Using omni-mixer, powder materials were first mixed in dry state with 0.5 min., and then liquid materials were mixed with 2.5 min. After mortar was prepared, fiber was placed in the mixer and further continued mixing 3.5 min. When the same procedure as the omni-mixer was adopted, it was found that concrete mixer led to low viscosity in fresh ECC. This resulted in fiber ball formation. Since this is suppose to be by low mixing efficiency, two modifications in procedure were adopted. First is to substantially extend mortar mixing time from 2.5 to 15 min. Second is revising water placement in mortar mixing, where 80% of liquid materials is first added in the same timing as omni case, and the remaining 20% is followed after 4 min. mixing. This modification, which was determined in try and error

operation, led to similar fresh property to omni case and resulted in appropriate fiber dispersion in fresh mix.

Spray process was conducted using 8mm diameter spray gun and material pumping rate 3 little per min. Actual spraying process was illustrated in Figure 3. In the process, sprayed materials using 4 mixes were all stable in 10 mm thickness on vertical surface. Fresh properties after mixing and after spraying are shown in Table 3. In Table 3, table flow value decreases after spraying compared with after mixing, except for mix-C using LPC. This decreasing appears favorable for material stability on sprayed surface. Furthermore, air content decreases to almost constant level among those mixes after spraying independent of the content after mixing. This decreasing appears due to pumping and spraying process, where air tends to be squeezed out. This implies that rather rough control of air content may be sufficient on mixing procedure.



Figure 3 Spraying process

Table 3 Fresh properties

Mix	Sample	Temp. (°C)	Table flow (mm)	Specific gravity (g/cm ³)	Air Content (%)
A	after mix	24.1	181/173	1.85	14.5
	after spray	17.9	163/160	1.98	7.8
B	after mix	23.1	181/177	1.66	25.0
	after spray	19.0	165/162	1.98	8.4
C	after mix	23.3	177/171	1.84	15.0
	after spray	20.7	173/175	2.01	7.0
D	after mix	20.5	184/181	1.87	12.5
	after spray	16.2	168/163	2.00	6.6

3.2 MECHANICAL PROPERTY

All ECC materials in this study demonstrated typical pseudo-strain hardening behavior with large tensile strain capacity nucleating fine multiple cracking. Figure 4 (a) shows the examples of tensile stress-strain relation of sprayed specimens in the tests, and (b) is for placed specimens. As shown in Figure 4 (a), specimens sustained load after first cracking up to ultimate point, which is defined in this study as continuous load decreasing initiates. The strain at these ultimate points (ultimate strain, hereafter) is over large value of 2% in all the specimens in Figure 4 (a). This figure demonstrates that 4 mixes in this study are the first example of sprayed ECC with clear pseudo-strain hardening behavior. Among those mixes, mix-D was mixed with ordinary concrete mixer, and this success contributes to industrializing of spray ECC due to its practicality in mixing procedure. Compared with Figure 4 (a), placed specimens in Figure 4 (b) show inferior strain and stress capacity on ultimate points.

Some examples of flexural test results are illustrated in Figure 5. As shown in Figure 5(a), sprayed specimens demonstrate similar flexural behavior independent of mix types. In the behavior, loads are sustained after cracking up to large mid-span displacement such as 1 mm. Figure 5(b) and (c) show the behavior of placed specimens and cut-out specimens respectively. These two types of specimens showed similar results to sprayed ones in Figure 5 (a).

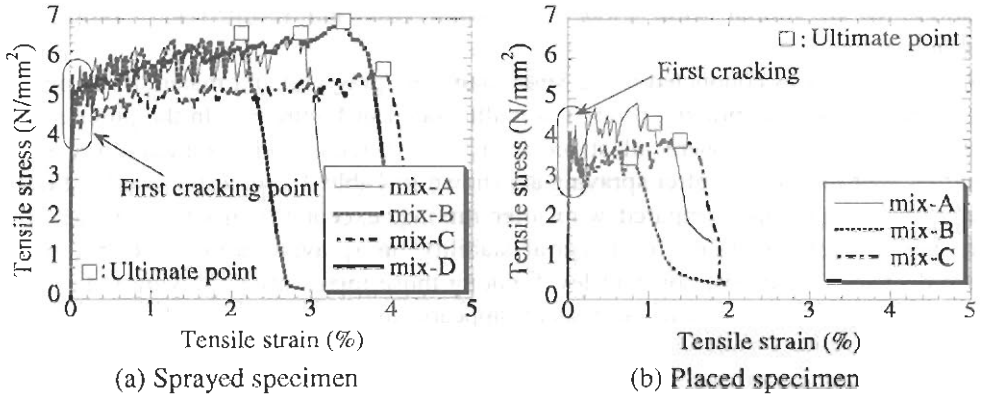


Figure 4 Example of tensile test result

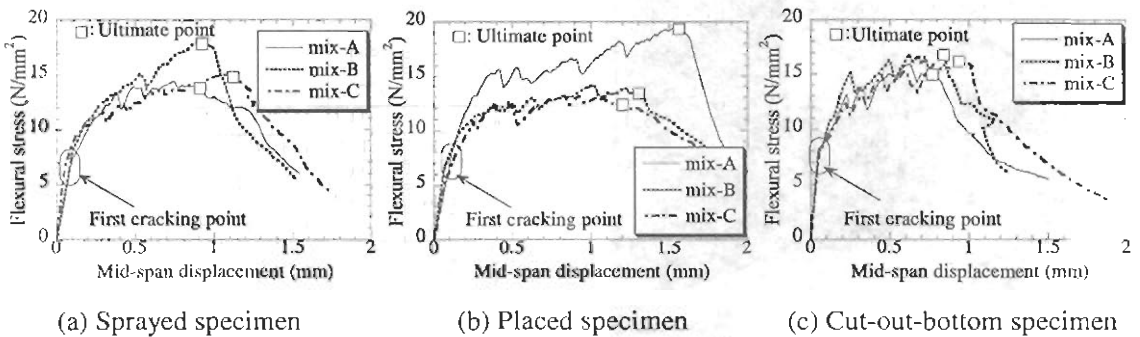


Figure 5 Example of flexural test result

4 DISCUSSIONS

4.1 TENSILE PERFORMANCE

Three characteristic values, first cracking strength, tensile strength, and ultimate strain, are discussed to reveal the effects of experimental parameters on tensile performance in the followings. First cracking strength is defined as first bend over point on stress-strain relation in this study. Since ECC has steady state cracking propagation[3], which occurs without load increase, stiffness change is significant due to first cracking. This enables us to easily detect first cracking point on stress-strain curves.

Figure 6 (a), (b), and (c) illustrate the effects of experimental parameters on tensile performance. Data in Figure 6 are the average of at least three specimens. First, the effects of experimental parameters on sprayed specimens' performance are discussed. In Figure 6 (a) and (b), it is found that differences in stress performance among mixes are not significant. Strain performance in Figure 6 (c) shows certain discrepancy among mixes. However, strain performance tends to involve larger variation than stress performance, and all mixes are considered to exceed the saturation level of multiple cracking nucleation[4]. Hence it can be concluded that the effects of air content, cement type, and mixer type are rather insignificant within the limitation of materials adopted in this study. Justification of this results is discussed below.

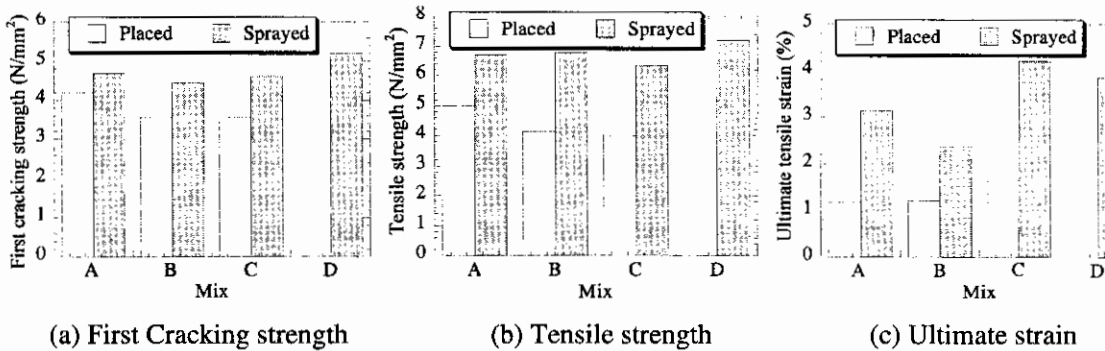


Figure 6 Effect of experimental parameter on tensile property

Air content after mixing was intended to differentiate between mix-A and B. However, this difference diminished after spraying as shown in Table 3. This implies that hardened ECCs in mix-A and B have similar air content. Indeed, specific gravity values of hardened specimens were 1.98 and 1.97 for mix-A and B respectively. Note that the specific gravity was estimated from size and weight of flexural specimens for convenience.

The effects of cement types are to be clarified in comparison between mix-A and C. The discrepancy in chemical characteristics of cement may significantly affect on fiber/matrix interface and fracture toughness in matrix. Specifically, chemical differences affect hydration rate, which is higher in OPC than LPC. However, at 28 day age, where all tests were conducted, the effects of this difference may diminish, thus causing similar performance between mix-A and C.

The effects of mixer types can be revealed via mix-A and D. This study intended to modify mixing procedure with concrete mixer such as to realize similar fresh property to omni case. This modification may have resulted in similar material tensile performance between omni and concrete mixer.

Figure 6 also demonstrates the deviation of performances influenced by casting procedure, i.e., sprayed or placed. All three characteristic values in Figure 6 (a), (b), and (c) reach higher levels in sprayed case than in placed case. This appears due to fiber orientation and air content. In spray process, spray guns are continuously moved parallel to sprayed surface and very thin sprayed layers are accumulated. In the individual thin layers, fibers should be oriented parallel to sprayed surface, i.e., 2-dimension orientation. If sprayed thickness is processed large at once, this orientation trend found to be weak from the observation of the process. This is because sprayed materials are tend to be mixed with previous layers due to sprayed on soft and fresh foundation. However, tensile specimen has thin thickness (13 mm), thus having the stronger tendency of 2-dimension orientation than placed case. This tendency may enhance tensile performance of sprayed specimen. Furthermore, high air content in placed specimens may degrade performance less than sprayed ones.

4.2 FLEXURAL PERFORMANCE

The effects on flexural performance of cement type, air content, casting process, and spraying thickness are discussed. Three characteristic values to represent flexural performance are selected similar to tensile property case: first cracking strength, MOR, and ultimate mid-span displacement. These values are defined in accordance with those of tensile case.

Figure 7 (a), (b), and (c) show the variation of first cracking strength, MOR, and ultimate

mid-span displacement depending on mix type and casting process. Data in this figure are represented by the average of at least three specimens. The deviation of performance between mix-A, B, and C is not significant in these graphs similar to tensile case of Figure 6. However, the effects of casting process appear to be different from tensile case in some aspects. In Figure 7 (a), (b), and (c), sprayed specimens show insignificant superiority to placed ones, contrary to Figure 6. Mix-A and B in Figure 7 (c) demonstrate even lower ultimate displacement in sprayed specimen than placed ones. This may be because less trend of 2-dimension fiber orientation in flexural specimens, having larger spray thickness of 40 mm than in tensile specimen of 13 mm, as described with Figure 6. Furthermore, more flaws may be involved in spray process with large thickness than in placed process, which degrades flexural performance.

The effects of larger processing thickness are to be further discussed with cut-out specimens. Figure 7 (a) and (b) demonstrate insubstantial discrepancy in first cracking strength and MOR between cut-out specimens and the others. However, Figure 7 (c) shows rather clear inferiority in cut-out specimens. Material solids for cut-out specimens were cast by spraying 150 mm thickness at once, and the effects of this process may influence lower deformation ability in Figure 7 (c).

Nevertheless, mechanical properties of sprayed ECC may be accurately reflected by using sprayed specimen in tension or flexure. This is due to the facts that: 1) load-displacement curve of cut-out specimens have essentially the same tendencies as sprayed specimens and placed specimens in Figure 5, and 2) processing thickness in actual retrofit construction, mostly on vertical surface or horizontal surface to be sprayed upward, limits within around 10 mm at once.

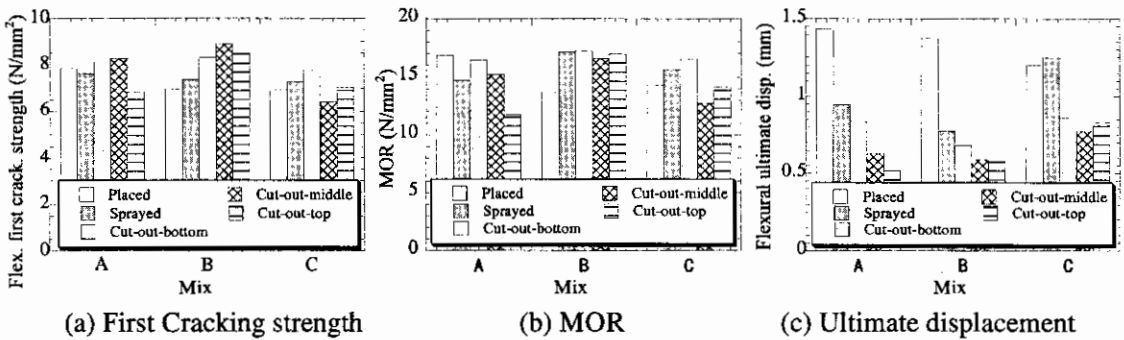


Figure 7 Effect of experimental parameters on flexural property

5 CONCLUSIONS

This study experimentally clarified fundamental mechanical properties of direct spray PVA-ECC and demonstrated first examples of sprayed ECC having pseudo-strain hardening behavior. 4 different mixes were used to cast tensile and flexural test specimens via spraying process. As a result of those tests, sprayed ECC in this study showed pseudo-strain hardening behavior in tension independent of air content after mixing and cement type used. Sprayed ECC with similar mechanical performance was also produced using ordinary concrete mixer instead of omni-mixer. Considering both test data and actual construction process, where 10 mm thickness layers are accumulated, tensile or flexural tests using sprayed specimens in this study appear sufficient to evaluate material performance.

When sprayed ECCs are used for retrofit, retrofitted structural elements are to have higher durability and load resistance. Clarifying these effects are remained in following studies.

ACKNOWLEDGEMENT

Futase-yogyo Co. and Showa-light Co. are greatly acknowledged for their help in material supply and in spraying operation respectively.

REFERENCES

- [1] Lim, Y.M., and Li, V.C., "Durable Repair of Aged Infrastructures Using Trapping Mechanism of Engineered Cementitious Composites," J. Cement and Concrete Composites, Vol. 19, No. 4, 1997, pp. 373-385
- [2] Kamada, T. and Li, V.C., "The Effects of Surface Preparation on the Fracture Behavior of ECC/Concrete Repair System," J. of Cement and Concrete Composites, Vol. 22, No. 6, 2000, pp.423-431
- [3] Li, V.C. and Leung, K.Y., "Steady-State Multiple Cracking of Short Random Fiber Composites," J. of Engineering Mechanics, ASCE, Vol. 118, No. 11, 1992 , pp. 2246-2263
- [4] Kanda, T. and Li, V.C., "Practical Design Guidelines for Pseudo Strain Hardening Cementitious Composites Reinforced with Short Random Fibers," J. Struct. Constr. Eng., AIJ, No. 552, 2002, pp.13-21 (in Japanese)