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NEW CEMENTITIOUS COMPOSITE DEVELOPMENT WITH THREE DIMENSIONAL FABRIC MESHES

JI WOON PARK[*], JEONGUN LEE[**], HYUN SU MOON[***], AND YUN MOOK LIM[†]

[*] Department of Civil and Environmental Engineering, Yonsei University
50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea
e-mail: jwp1021@yonsei.ac.kr

[**] Department of Civil and Environmental Engineering, Yonsei University
50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea
e-mail: dns1823@yonsei.ac.kr

[***] Department of Civil and Environmental Engineering, Yonsei University
50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea
e-mail: smilefou@yonsei.ac.kr

[†] Department of Civil and Environmental Engineering, Yonsei University
50, Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea
e-mail: yunmook@yonsei.ac.kr

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Abstract: In previous researches for the last couple of decades, various types of fibers have been studied, mainly discontinuous short fibers with random distribution for the convenience of mixing processes. In somehow, there were few applications of continuous fibers as the reinforcements in composites compared to the short fibers, even though there are strong points for the composite behaviors. One of the main reasons for these less application of continuous fibers is that it is almost impossible to hold individual fibers during the casting. However, in these days, the technology allows the manufacturers to weave fibers as fabrics in three dimensions. In this way, the orientation and distribution of fibers can be controlled in spaces. Therefore, in this study, these fabrics were utilized as the reinforcements in the cementitious composites. First, the potential of these fabric products is studied by inserting them in composite specimens as reinforcements. Second, provided that the possibility of the products is confirmed, the optimization study of the fabric is discussed.

1 INTRODUCTION

The fiber reinforced composites (FRCs) with brittle matrixes have been widely used in the engineering fields. Among numerous kind of FRCs, this study focused on fiber reinforced cementitious composites (FRCCs). To attain superior mechanical properties of the FRCCs, various studies and approaches have been conducted. Many researches with respect to the volume fraction, interface properties and distribution of the fibers in FRCCs were carried out to investigate the relationships between the fiber characteristics and the composites. Most of these researches focused on the short-fiber-reinforced composites rather than composites with continuous fibers. These discontinuous fiber composites tend to fail in tension softening with the first crack initiation [1]. In addition, it is hard to achieve satisfactory fiber distribution and is impossible to specify the orientations of the fibers [2].

There were numbers of studies to overcome these limits of the random discontinuous fiber composites. Specific conditions for these composites are already examined to assure them to have desirable features, such as multiple cracking and strain hardening through multiple researches [1, 3-5]. Moreover, studies with respect to controlling and investigating the distributions and orientations of the fibers in FRCCs were conducted with utilization of extrusion-manufacturing [6, 7] and specialized tests such as image scanning [8-10]. However, these approaches require complicated calculation and analyzation steps with several assumptions.

In contrast, composites with aligned continuous fibers is proven to have multiple cracking and strain-hardening behavior under even undemanding conditions [1]. By utilizing continuous fibers, the desirable features of FRCs can be attained with less volume fractions and without the consideration of fiber pull-out. Furthermore, the specified orientation and uniform distribution of fibers can be assured in the case of aligned continuous fiber composites. The problem of the aligned continuous fiber composites is that they are difficult to manufacture. However, these days, they can be made more conveniently through the recently developed manufacturing technologies such as three dimensional printing, weaving, and foaming. This study aims to identify the possibility of these 3D manufactured fabrics as reinforcements in FRCCs, since the fabrics are expected to behave as aligned continuous fibers.

2 EXPERIMENT CASES

Several bending specimens was casted and tested utilizing three different reinforcing fabric materials. First, the 3D printed randomly distributed fiber matrix had been tested and the results were published in the previous study [11]. Second case has different specimen dimensions matched with the thickness of the utilized commercial fabric samples. This cases represent the utilization scheme of 3D weaving. Lastly, the third case specimens used 3D foamed reinforcements, having same dimensions with the second case.

2.1 3D printed fiber matrix

The geometries of the printed fiber meshes are illustrated in Figure 1. The geometries could be divided in two groups which are the idealized mesh shape and the mesh replicating randomly distributed fibers. The material used in the fabrication was VisiJet M2 RWT plastic which has tensile strength of 33-42MPa. The printed fiber meshes and the specimen had dimensions of 220×50×50mm. 3-point bending test was conducted.

2.2 3D air mesh

In this case, three dimensionally weaved fabrics were inserted in the bending specimens. The fabric called '3D air mesh' composed of polyester is the ready-made merchandise which is commonly available in the markets. The material is expected to have tensile strength of around 50MPa. The exact structure and shape are shown in Figure 2(a).

Two kinds of specimens were tested which have 7mm and 15mm thickness respectively. The dimensions of the specimens were chosen to be 470×100×10mm and 470×100×18mm for the thin and thick fabric materials. Note that these specimens were for 4-point bending tests, unlike the previous case. Fiber volume fraction of the composites with 15mm-thick air mesh was 2% and volume fraction with 7mm thick air mesh was around 3%.

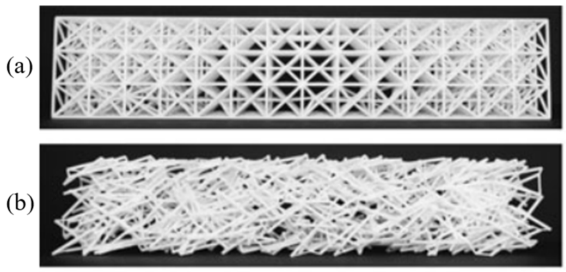
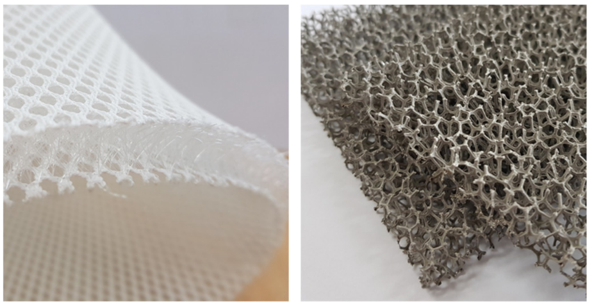


Figure 1: 3D printed fibers: (a) ideally distributed mesh and (b) replication of randomly distributed fibers.



(a) (b)

Figure 2: Reinforcements in the case 2 and 3: (a) 3D air mesh and (b) metal alloy foam

In addition, two different cementitious matrixes were tested, which are cement-only paste and mortar. The mixing ratio is chosen in consideration of the viscosity of the mix which is thin enough to infiltrate into the air meshes. The w/c ratio was 0.4 for both mixes.

2.3 Metal alloy foam

Metal foams have hollow spheres giving them relatively high strength considering their low density. They can be utilized to various fields due to their good energy absorption and heat transfer characteristics [12]. In this study, a single kind of metal alloy foam is used as reinforcements in bending specimens.

The specimen size was identical with the previous 3D air mesh case. The parent material of the metal foam was Nickel-based alloy (NiCrAl). Cell size of the metal foam was claimed to be 6mm by the manufacturer (Alantum). The volume fraction is expected to be around 2%. Figure 2(b) shows the shape of the utilized metal alloy forms. The thickness of the metal alloy foam and the specimens were identical as 10mm in this instance. Two specimen types with different matrixes were tested to coincide with the previous cases.

3 RESULTS AND DISCUSSION

3.1 Results of 3D printed fiber matrix

3-point bending test was conducted with the composites reinforced with 3D printed fibers in the previous study. Instron 3369 instrument with load capacity of 50kN was used. The tests proved that it is possible to control and determine orientations and distributions of the fibers regardless of the structural complexity of the fabricated composites. A tendency was shown that there were a relationship between fiber distribution and major crack orientation by analyzing fiber locations.

In fact, the specimens showed brittle failure and only slight improvements of the flexural strength due to the lack of fiber strength. The 3D printed fibers demonstrated less tensile strength than its parent material. There were previous studies reporting that the mechanical properties of 3D printed material significantly depend on the building direction while utilizing the 3D printer [13]. However, these underperforming results are expected to be advanced in near future with the technical improvement of 3D printing materials.

3.2 Results of 3D air mesh

The composite specimens were tested, which are reinforced with three dimensionally weaved fabric, namely the 3D air mesh. A simple configuration of the 4-point bending test is illustrated in Figure 3(a). MTS 322 was utilized for the test. Both displacement and load were measured through the instrument and the data was filtered using Butterworth filter design parameters and zero-phase digital filtering function in MATLAB (Figure 4).

The specimens showed extremely improved elongation capacities as can be seen in Figure 3(b). In case of the test condition in this study, the composites did not catastrophically failed even at 60mm vertical displacement. The test ended at the displacement of 60mm due to the limitation of the current test settings, however, most of the specimens were still in strain-hardening zone. The long hardening section in load-deflection curve in Figure 4 suppose that the composites behave almost in ductile manner. Multiple cracking could be also observed at the bottom surface of the specimens (see Figure 5). These desirable improvements in these composites, i.e. multiple cracking and strain hardening, are attained by the benefit of utilizing continuously aligned fibers. The continuity and alignment of fibers gives the beneficial features even in relatively low fiber strength and volume fraction conditions.

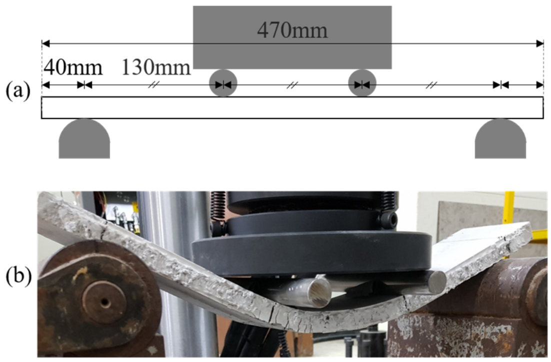


Figure 3: Bending test: (a) Test configuration and (b) an example of the tested specimen.

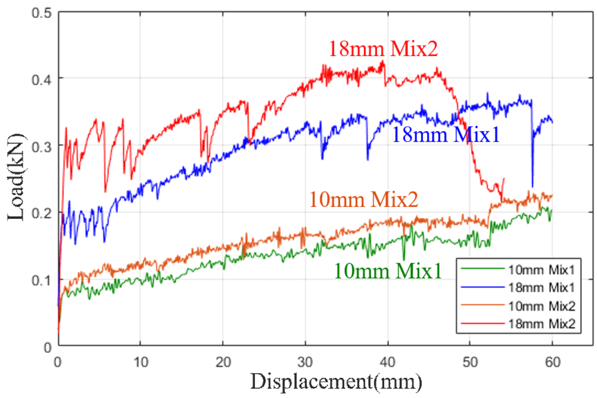


Figure 4: Load-deflection curves of composite specimens with 3D air mesh. (Mix 1 and 2 indicate cement paste and mortar respectively.)

Naturally, the 18mm-thick specimens showed higher load capacity than the thinner 10mm specimens. Nevertheless, the 10mm-thick specimens with 7mm air mesh showed higher bending strength development, if the results are converted with respect to the maximum bending stress linearly by flexural formula. The results of thin specimens with 7mm air mesh are calculated the composites to demonstrate maximum bending stress of 8-9MPa, while estimating the cases with 18mm to demonstrate 4-5MPa. This gap between these two different outcomes results from the differences in terms of volume fraction of the fibers. It is obvious that the larger fiber volume fraction leads to the higher bending strength.

Furthermore, comparing two different matrixes, it is evident that the stronger matrix that contains sand have higher strength than the other. In case of the 18mm-thick specimens, it can be confirmed that the mortar matrix needs more energy to start a fracture. The first crack strength of mix 2, i.e. the mortar matrix, is higher than mix 1 in Figure 4. However, if composites' matrix toughness increased, volume fraction should be increased likewise to satisfy the condition of the pseudo strain-hardening. A simple illustration of the equation from Li and Wu in case of randomly distributed short fibers is as below [3]:

$$V_f \geq V_{f,critical} \propto G_{tip} \qquad (1)$$

V_f, $V_{f,critical}$, and G_{tip} indicates the fibers' volume fraction, the critical volume fraction, and the matrix toughness, respectively. The inequation should be satisfied to attain strain-hardening of fiber reinforced composites. In terms of this study's experiment, it seems both cases with two different matrix satisfied the condition as they showed multiple cracking behaviors and apparent pseudo strain-hardening. However, the specimen with mortar matrix showed slightly larger sizes of cracks than the one with weaker matrix. Meanwhile, the number of the cracks in case of the specimen with cement paste matrix surpass that of the other with mortar. This fracture tendency is displayed in Figure 5.

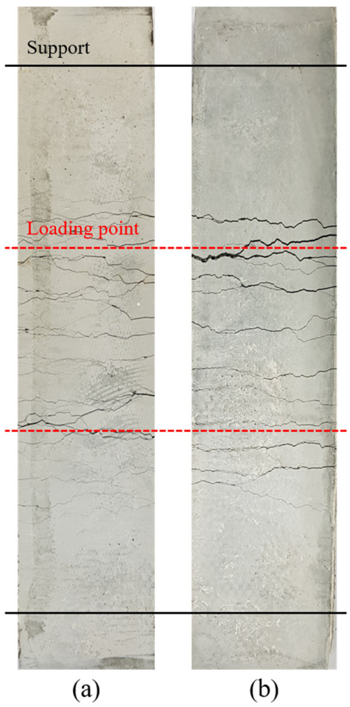


Figure 5: Examples of fractures in specimens: 18mm-thick specimens (a) with cement paste matrix and (b) with mortar matix.

In addition, incidental specimens were also tested, utilizing two dimensionally weaved fabrics. Here, 2D mat of aligned glass fibers were used. Two mats were inserted for one same size 10mm-thick bending specimen. In case of these specimens, it was hard to cast the matrix assuring the mats to locate at exact depth. Moreover, the specimens showed brittle failure.

3.3 Results of alloy foam

The bending tests of the specimens with metal alloy foams will be conducted by the end of this month, April 2019. The tests will be carried out under same test settings with the configuration in Figure 3(a). The results and discussion of the tests will be organized near future and presented at the conference (FraMCoS-X) in June.

4 CONCLUSION

Intending advantages are discussed in this study which can be attained by utilizing recent manufacturing technologies to produce FRCCs. Three-dimensional fabrication methodologies were suggested such as 3D printing, 3D weaving, and 3D foaming. This paper presumed that the products from the suggested methods would interact as continuously aligned fibers in composites. Three kinds of the composite specimens were made in the laboratory. Printers and fabric materials were used that are already available in the markets.

By adopting these three dimensionally aligned fiber fabrics, the fiber orientations and distributions could be precisely controlled and conceived. Also, multiple cracking and pseudo strain-hardening behavior can be obtained conveniently by the benefit of aligned continuous fibers. However, there should be more detailed researches with respect to the conditions for the strain-hardening in these composites. Equations regarding volume fractions, matrix toughness, fiber stiffness, and strength should be derived. Moreover, application of optimization scheme is needed to fabricate more efficient 3D fiber fabrics. This optimization will be achieved by controlling the fiber material, alignment, and distribution in the 3D space.

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