Investigating Mechanical Properties of Steel- Nylon Hybrid Fiber-Reinforced Concrete by Using Experimental Design

Pey-Shiuan Song [1,*], Guo-huei Chen [2], and Ma-chine Hsie [2]

[1] Department of Civil Engineering & Environmental Resource Management, Dahan Institute of Technology
[2] Department of Civil Engineering, National Chung Hsing University

ABSTRACT

This paper investigated the mechanical properties of steel-nylon hybrid fiber-reinforced concrete. There was one type of nylon fiber (N) and four types of steel fibers (S), of which, S1, S2, and S3 were hooked-end fibers and S4 was crimped fiber. The respective contents of nylon fibers were 0 kg/m^3, 0.6 kg/m^3 and 1.2 kg/m^3, and the contents of steel fibers were 0 kg/m^3, 10 kg/m^3 and 20 kg/m^3. The L_{27} orthogonal array and ANOVA method were adopted to analyze the interaction effects on the mechanical properties of hybrid fiber-reinforced concrete. The results showed the nylon fibers contributed the most to compressive strength, and S2 fibers contributed the most to splitting tensile strength and modulus of rupture. N×S1 reached a very significant level of compressive strength; N×S2 reached a very significant level of splitting tensile strength; N×S3 reached a very significant level of modulus of rupture.

Keywords: nylon fibers, hybrid fiber-reinforced concrete, modulus of rupture

應用實驗設計探討鋼-尼龍混合纖維混凝土之工程性質

宋佩瑄[1,*], 陳國輝[2], 謝孟勳[2]

[1*]大漢技術學院土木工程與環境資源管理系
[2]國立中興大學土木工程系

摘　　要

本文探討鋼-尼龍混合纖維混凝土之工程性質。試驗採用 1 種尼龍纖維(N)與 4 種型式鋼纖維(S)。鋼纖維 S1、S2、S3 為端勾型，S4 為褶皺型。尼龍纖維含量水準為 0 kg/m^3，0.6 kg/m^3，1.2 kg/m^3，鋼纖維含量水準為 0 kg/m^3，10 kg/m^3，20 kg/m^3。研究使用 L_{27} 直交表與變異數分析方法探討鋼-尼龍混合纖維之交互作用效果對混合纖維混凝土之工程性質影響。結果顯示，抗壓強度以尼龍纖維貢獻最大，劈裂抗拉強度與破裂模數以 S2 貢獻最大。抗壓強度以 N×S1 達顯著水準，劈裂抗拉強度以 N×S2 達顯著水準，破裂模數以 N×S3 達顯著水準。

關鍵詞：尼龍纖維，混合纖維混凝土，破裂模數

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Ⅰ. INTRODUCTION

Concrete is a relatively brittle material. To improve its engineering properties, adding fiber materials is the ideal solution. Nowadays, many types of fibers are available, such as steel fibers, carbon fibers, polypropylene fibers, nylon and glass fibers, etc. Adding a single type of fiber into concrete has limited functions, thus many current researches are oriented to the development of hybrid fiber in concrete to obtain better material properties. Fine and highly flexible fibers can control the dry shrinkage and micro-cracks, while the thick and highly stiff fibers are able to sustain the macro-cracks resulting from high stress. Further, these two types of fibers can complement each other and further improve the engineering properties of concrete.

Among the studies on hybrid fibers, most studies focused on steel and polypropylene fibers. Song et al. [1] indicated the steel-polypropylene hybrid fiber-reinforced concrete has a better first-crack and failure strengths than the steel fiber-reinforced concrete. Banthia and Nandakumar [2] found that adding steel fibers and polypropylene fibers to mortars can effectively restrict the growth of cracks. Yao et al. [3] tested the steel-polypropylene hybrid fiber-reinforced concrete and steel-carbon hybrid fiber-reinforced concrete, indicating the latter has better compressive strength and flexural toughness. Sun et al. [4] suggested hybrid fibers combined with expansive agents provide better shrinkage resistance and impermeability than mono-incorporation of single fibers or expansive agents. Qian and Stroeven [5] pointed out K_{1C} and the fracture toughness of a proper hybrid fiber system can be higher than that of a mono-fiber system. Qian and Stroeven [6] used the L_9 orthogonal array for four factors to analyze the mechanical properties of steel-polypropylene hybrid fiber-reinforced concrete. The result showed that the short fibers significantly influence compressive strength, whereas the long fibers give rise to the splitting tensile strength. However, the L_9 orthogonal array was unable to further explore the interaction effects of different fibers on the engineering properties of concrete.

The polypropylene fiber belongs to the polymer material. Nylon fiber, another polymer material, on the other hand possesses better engineering properties, and has been gradually applied in concrete projects [7-13]. There are limited studies focused on the mechanical properties of steel-nylon hybrid fiber-reinforced concrete therefore this paper investigates the mechanical properties of four types of steel fibers and nylon fibers added into concrete. This study adopted the L_{27} orthogonal array and ANOVA method to explore the interaction effects of steel and nylon fibers on the mechanical properties of concrete, including compressive strength, splitting tensile strength and modulus of rupture (MOR).

Ⅱ. EXPERIMENTAL PROGRAM

2.1 Materials

The materials consisted of normal Type I Portland cement, gravel having a maximum size of 2.54 cm, and river sand having a fineness modulus of 2.88. The proportion of cement, water, and fine aggregate and coarse aggregate were 350: 180: 880: 970 kg/m^3. There were four types of steel fibers (S). S1, S2 and S3 were hooked-end steel fibers with lengths of 32 mm, 40 mm, and 60 mm respectively, and the S4 was crimped steel fiber with a length of 50 mm. The nylon fiber (N) was a monofilament with a length of 19 mm. Their physical characteristics are listed in Table 1. The content levels of various steel fibers (V_f) were 0 kg/m^3, 10 kg/m^3 and 20 kg/m^3, and the content levels of nylon fiber were 0 kg/m^3, 0.6 kg/m^3 and 1.2 kg/m^3 as shown in Table 2.

Table 1. Physical characteristics of the fibers

Fiber type	Steel	Steel	Steel	Steel	Nylon
Fiber no.	S1	S2	S3	S4	N
Fiber geometry	hooked-end	hooked-end	hooked-end	crimped	monofilament
Fiber Length(mm)	32	40	60	50	19
Diameter(mm)	0.5	0.5	0.9	1.14	0.023
Aspect Ratio	64	80	67	44	528
Number / kg	18000	15000	3200	3100	37×10^6
Tensile Strength(MPa)	＞ 1100	＞ 1100	＞ 1100	966-1242	896
Modulus (Youngs）(GPa)	200	200	200	200	5.17
Specific Gravity	7.8	7.8	7.8	7.8	1.16

Table 2. Main control factors and factor levels

Control factor	Level 1	Level 2	Level 3
N (kg/m^3)	0	0.6	1.2
S1 (kg/m^3)	0	10	20
S2 (kg/m^3)	0	10	20
S3 (kg/m^3)	0	10	20
S4 (kg/m^3)	0	10	20

2.2. Mixing and Curing

The mixing process began with dry mixing of the coarse and fine aggregates for one minute, then cement was added to the mix for 1 minute, followed by adding water to the mix for 2 minutes. Finally, the fibers were evenly spread over the concrete and mixed for 3 minutes. The mixed fiber concrete was poured into 150mm×300mm cylindrical molds for testing the compressive and splitting tensile strengths. It was poured into 150mm×150mm×530mm rectangle molds for testing the modulus of rupture. All molds were removed after 24 hours, and the specimens were allowed to cure in a water cabinet at 23 ±1°C. All tests were performed after the samples had cured for 28 days. In this study, every test result was an average of 12 replicate tests.

2.3. Test Methods

The ASTM C39 test method was used to determine the compressive strength of cylindrical specimens [14]. The cylindrical specimens were loaded in a universal hydraulic testing machine under a load control, at a rate of 0.3 MPa/s, until the specimen failed. The ASTM C496 test method was used to measure the splitting tensile strength of cylindrical specimens [15]. The continuous load was increased at a rate of 0.9 MPa/s until the specimen failed. The ASTM C293 test method was used to determine the modulus of rupture of the rectangular specimens [16]. The load was increased at a rate of 0.9-1.2 MPa/min and the maximum load was measured.

2.4. Experimental Plan

This study adopted the L_{27} Orthogonal Array to conduct the experiment planning, and the orthogonal array is shown in Table 3. The ANOVA technique was used to analyze the main and interaction effects of steel and nylon fibers on the engineering properties of concrete. The interaction factors included N×S1, N×S2, N×S3 and N×S4.

Ⅲ. RESULTS AND DISCUSSION

3.1. Compressive Strength

Table 4 shows the compressive strength, splitting tensile strength and MOR of various types of steel-nylon hybrid fiber concrete. Table 5 shows the level effects of fibers on compressive strength and the results are plotted in Fig.1. The difference between the maximum and minimal value of the nylon fibers on compressive strength was 4.43 MPa, S1 was 2.67 MPa, S2 was 2.57 MPa, S3 was 1.38 MPa, and S4 was 0.62 MPa. When adding nylon fiber from 0 kg/m^3 to 0.6 kg/m^3, the compressive strength increased 3.09 MPa. This is in comparison to 1.34 MPa when adding nylon fiber from 0.6 kg/m^3 to 1.2 kg/m^3. Thus, adding more nylon fiber to the concrete improved the compressive strength with minimal effects.

Table 3. Orthogonal array for $L_{27}(3^{13})$ with factor assignment for the experiments

Mix. no.	N	S1	NxS1		S2	NxS2		S3	NxS3		S4	NxS4	
	1	2	3	4	5	6	7	8	9	10	11	12	13
M 1	1	1	1	1	1	1	1	1	1	1	1	1	1
M 2	1	1	1	1	2	2	2	2	2	2	2	2	2
M 3	1	1	1	1	3	3	3	3	3	3	3	3	3
M 4	1	2	2	2	1	1	1	2	2	2	3	3	3
M 5	1	2	2	2	2	2	2	3	3	3	1	1	1
M 6	1	2	2	2	3	3	3	1	1	1	2	2	2
M 7	1	3	3	3	1	1	1	3	3	3	2	2	2
M 8	1	3	3	3	2	2	2	1	1	1	3	3	3
M 9	1	3	3	3	3	3	3	2	2	2	1	1	1
M 10	2	1	2	3	1	2	3	1	2	3	1	2	3
M 11	2	1	2	3	2	3	1	2	3	1	2	3	1
M 12	2	1	2	3	3	1	2	3	1	2	3	1	2
M 13	2	2	3	1	1	2	3	2	3	1	3	1	2
M 14	2	2	3	1	2	3	1	3	1	2	1	2	3
M 15	2	2	3	1	3	1	2	1	2	3	2	3	1
M 16	2	3	1	2	1	2	3	3	1	2	2	3	1
M 17	2	3	1	2	2	3	1	1	2	3	3	1	2
M 18	2	3	1	2	3	1	2	2	3	1	1	2	3
M 19	3	1	3	2	1	3	2	1	3	2	1	3	2
M 20	3	1	3	2	2	1	3	2	1	3	2	1	3
M 21	3	1	3	2	3	2	1	3	2	1	3	2	1
M 22	3	2	1	3	1	3	2	2	1	3	3	2	1
M 23	3	2	1	3	2	1	3	3	2	1	1	3	2
M 24	3	2	1	3	3	2	1	1	3	2	2	1	3
M 25	3	3	2	1	1	3	2	3	2	1	2	1	3
M 26	3	3	2	1	2	1	3	1	3	2	3	2	1
M 27	3	3	2	1	3	2	1	2	1	3	1	3	2

Table 4. Strength test results for hybrid fiber-reinforced concrete

Mix. no.	Compressive strength (MPa)	Splitting tensile strength (MPa)	Modulus of rupture (MPa)
M1	35.46	2.74	5.07
M2	37.11	3.39	6.46
M3	38.60	4.16	8.14
M4	36.90	3.54	6.73
M5	38.36	3.67	7.35
M6	38.59	3.71	7.24
M7	38.07	3.80	7.40
M8	38.76	3.79	7.72
M9	39.19	4.02	7.85
M10	37.32	2.83	5.52
M11	39.20	3.60	7.02
M12	42.45	4.32	8.56
M13	39.75	3.71	7.29
M14	40.89	3.90	7.51
M15	40.54	4.00	7.62
M16	42.76	4.01	7.78
M17	41.67	4.08	7.94
M18	44.24	4.36	8.26
M19	37.97	2.91	5.51
M20	40.93	3.66	7.40
M21	43.41	4.54	9.13
M22	41.01	3.79	7.44
M23	42.21	4.03	8.25
M24	43.57	4.24	7.95
M25	43.16	3.98	8.42
M26	43.63	4.25	8.10
M27	45.00	4.54	8.48

Table 5.The level effects of fibers on compressive strength

Level	N	S1	S2	S3	S4
Level 1 (0 kg)	37.89	39.16	39.16	39.72	40.07
Level 2 (10 kg / 0.6 kg)	40.98	40.20	40.31	40.37	40.44
Level 3 (20 kg / 1.2 kg)	42.32	41.83	41.73	41.10	40.69
E1 (Level 2 – Level 1)	3.09	1.04	1.15	0.65	0.37
E2 (Level 3 – Level 2)	1.34	1.63	1.42	0.73	0.25
E3 (Level 3 – Level 1)	4.43	2.67	2.57	1.38	0.62

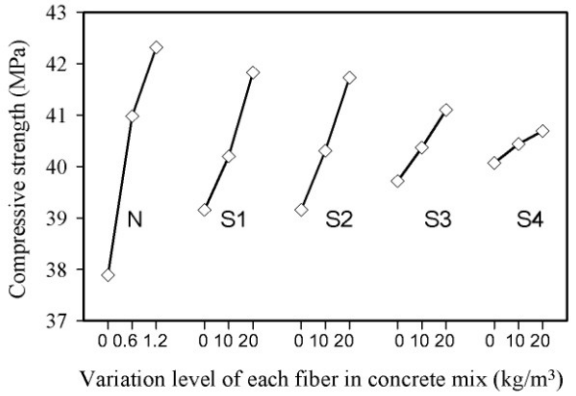

Fig. 1. Main effect plot on compressive strength

Table 6 shows the analysis of variance for compressive strength, indicating the factors of N, S1, S2, S3 and N×S1 are very significant (p value < 0.01), and S4 is significant (p <0.05). Table 7 shows the analysis of variance for compressive strength after pooling, and the contribution ratio of different factors was 38.220, 13.284, 12.224, 3.344, 0.520, 1.086, for N, S1, S2, S3, S4 and N×S1, separately and the order contribution ratio was N>S1≒S2>S3>N×S1>S4. The results indicate the nylon fibers have advantages over steel fibers for compressive strength. The reason is the nylon fibers have high tensile strength and fine thinness. They can easily form the network structure and lower the concrete stress concentration at the crack tips, thus increasing the compressive strength [7]. As for the steel fibers, all hooked-end steel fibers have better ability to improve the compressive strength than crimped steel fibers, which is in accordance with the research of Soroushian and Bayasi [17]. In addition, the shorter hooked-end steel fibers more significantly influence compressive strength, which agrees with the result of Qian and Stroeven [6].

Fig.2 shows the interaction effects of compressive strength between S1 and N fibers. When adding S1 fibers with 0 kg/m^3 and 10 kg/m^3, the L1 and L2 lines are roughly parallel to each other, thus showing no significant interaction effects have yet occurred. However, when adding S1 fibers with 20 kg/m^3, the L3 and L2 lines are not parallel to each other. This shows when the S1 fibers reach 20 kg/m^3 and the nylon fiber reaches 0.6 kg/m^3, significant interaction occurred, thus the two types of fibers complement each other to increase compressive strength.

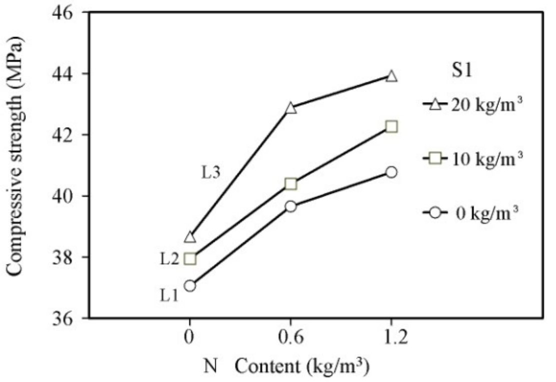

Fig. 2. Response of interaction on compressive strength between S1 and N fibers.

3.2. Splitting Tensile Strength

Table 8 shows the level effects of fibers on splitting tensile strength, and the results are plotted in Fig. 3. The difference between the maximum and minimal value of nylon fibers for splitting tensile strength was 0.35 MPa, S1 was 0.52 MPa, S2 was 0.73 MPa, S3 was 0.43 MPa and S4 was 0.35 MPa. For the steel fibers, the effects of adding the fibers from 0 kg/m^3 to 10 kg/m^3 and from 10 kg/m^3 to 20 kg/m^3 had the same improvement, showing a roughly linear relationship. For the nylon fibers, adding more fibers into the concrete has a limited improvement on splitting tensile strength.

Table 6. The ANOVA table for compressive strength

Factor	SS	DOF	V	F	p
N	1114.055	2	557.027	202.721	0.000
S1	390.891	2	195.446	71.129	0.000
S2	360.137	2	180.069	65.533	0.000
S3	102.605	2	51.303	18.671	0.000
S4	20.691	2	10.346	3.765	0.024
N×S1	42.744	4	10.686	3.889	0.004
N×S2	24.467	4	6.117	2.226	0.066
N×S3	21.462	4	5.365	1.953	0.102
N×S4	6.993	4	1.748	0.636	0.637
Error	816.084	297	2.748		
Total	2900.129	323			

Table 7. The ANOVA table for compressive strength after pooling

Factor	pooling	SS	DOF	V	F	p	rho (%)
N	no	1114.055	2	557.027	198.067	0.000	38.220
S1	no	390.891	2	195.446	69.496	0.000	13.284
S2	no	360.137	2	180.069	64.029	0.000	12.224
S3	no	102.605	2	51.303	18.242	0.000	3.344
S4	no	20.691	2	10.346	3.679	0.026	0.520
N×S1	no	42.744	4	10.686	3.800	0.005	1.086
N×S2	yes	-	-	-	-	-	-
N×S3	yes	-	-	-	-	-	-
N×S4	yes	-	-	-	-	-	-
Error		869.006	309	2.812			31.322
Total		2900.129	323				

rho (%) = contribution ratio = (V-V(error)) (DOF) / Total(SS)

Table 8. The level effects of fibers on splitting tensile strength

Level	N	S1	S2	S3	S4
Level 1 (0kg)	3.64	3.57	3.48	3.62	3.67
Level 2 (10kg / 0.6kg)	3.87	3.84	3.82	3.84	3.82
Level 3 (20kg / 1.2kg)	4.00	4.09	4.21	4.04	4.02
E1(Level 2 –Level 1)	0.22	0.27	0.34	0.23	0.15
E2(Level 3 –Level 2)	0.13	0.25	0.39	0.20	0.20
E3(Level 3 –Level 1)	0.35	0.52	0.73	0.43	0.35

Table 9. The ANOVA table for splitting tensile strength

Factor	SS	DOF	V	F	p
N	6.797	2	3.399	120.752	0.000
S1	14.640	2	7.320	260.076	0.000
S2	28.924	2	14.462	513.838	0.000
S3	9.875	2	4.937	175.423	0.000
S4	6.707	2	3.353	119.144	0.000
N×S1	0.209	4	0.052	1.856	0.118
N×S2	0.729	4	0.182	6.471	0.000
N×S3	0.084	4	0.021	0.747	0.561
N×S4	0.038	4	0.009	0.336	0.853
Error	8.359	297	0.028		
Total	76.362	323			

Table 9 states the analysis of variance for splitting tensile strength. S1, S2, S3, S4, N and N×S2 are very significant ($p < 0.01$). Table 10 shows the analysis of variance for splitting tensile strength after pooling, and the contribution ratio of the different factors was 8.827, 19.098, 37.804, 12.858, 8.710, 0.807, for N, S1, S2, S3, S4 and N×S2, separately and the order contribution ratio was S2>S1>S3> N≒S4>N×S2. This shows that the contribution of steel fibers for splitting tensile strength is roughly in direct proportion to the aspect ratio of fibers. The fibers with a greater aspect ratio have more advantage over embedded depths in concrete [18]. When the specimen cracks, a greater aspect ratio of the fibers produces more bridging effects, thus preventing macro-crack from concrete splitting and increasing the splitting tensile strength.

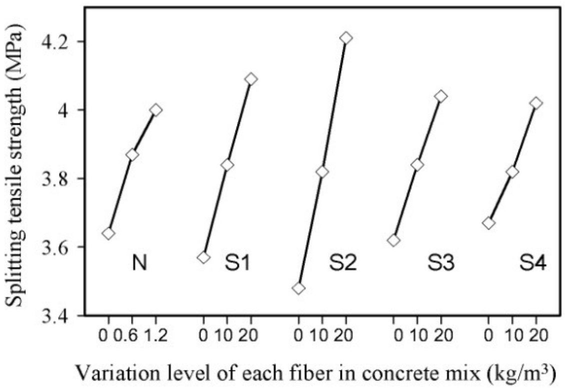

Fig. 3. Main effect plot on splitting tensile strength

The interaction effects on splitting tensile strength between S2 and N is shown in Fig. 4. When the addition of S2 fibers reached 20 kg/m^3, and the N fibers was 1.2 kg/m^3, the hybrid fibers showed significant interaction effects. These two different types of fibers in concrete mitigate the fracture mechanics at different stages under the splitting tensile stress. When the first crack occurred in the concrete matrix, the fine and numerous nylon fibers in the concrete would bridge the cracks and restrict the growth of cracks. When stress continuously damaged the specimen, the nylon fibers bridging effect would gradually transfer to the steel fibers to make the concrete more resistant to the pulling stress, further increasing the splitting tensile strength.

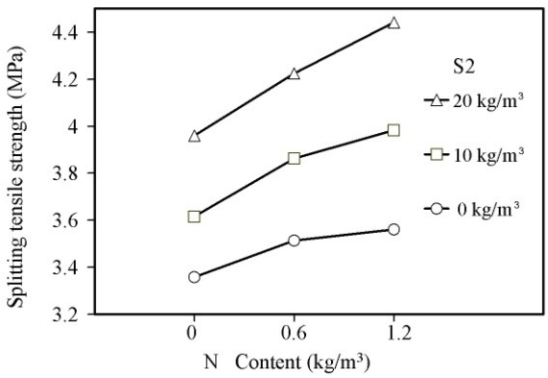

Fig. 4. Response of interaction on splitting tensile strength between S2 and N fibers.

3.3. Modulus of Rupture (MOR)

Table 11 shows the level effects of fibers on the MOR. Fig. 5 illustrates the difference between the maximum and minimal value of nylon fibers on the MOR was 0.75 MPa, S1 was 1.02 MPa, S2 was 1.34 MPa, S3 was 1.09 MPa and S4 was 0.81 MPa. For the steel fibers, the effects of increasing the fibers from 0 kg/m^3 to 10 kg/m^3 and from 10 kg/m^3 to 20 kg/m^3 showed nearly the same improvement on MOR, with a linear relationship.

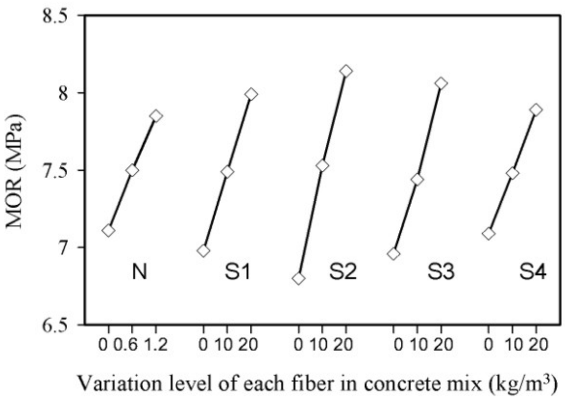

Fig. 5. Main effect plot on MOR

Table 12 represents the analysis of variance for the MOR. S1, S2, S3, S4, N and N×S3 reached a very significant level ($p < 0.01$). Table 13 indicates the analysis of variance for MOR after pooling, and the contribution ratio of different factors was 9.264, 17.149, 30.026, 20.162, 10.722, 0.836, for N, S1, S2, S3, S4 and N×S3, separately and the order contribution ratio was S2>S3>S1>S4≒N>N×S3. The contribution of MOR for each steel fiber was directly proportional to the aspect ratio, and this was in accordance with Yazıcı et al. [18].

Table 10. The ANOVA table for splitting tensile strength after pooling

Factor	pooling	SS	DOF	V	F	p	rho (%)
N	no	6.797	2	3.399	120.844	0.000	8.827
S1	no	14.640	2	7.320	260.285	0.000	19.098
S2	no	28.924	2	14.462	514.241	0.000	37.804
S3	no	9.875	2	4.938	175.568	0.000	12.858
S4	no	6.707	2	3.354	119.244	0.000	8.710
N×S1	yes	-	-	-	-	-	-
N×S2	no	0.729	4	0.182	6.480	0.000	0.807
N×S3	yes	-	-	-	-	-	-
N×S4	yes	-	-	-	-	-	-
Error		8.690	309	0.028			11.896
Total		76.362	323				

rho (%) = contribution ratio = (V-V(error)) (DOF) / Total(SS)

Table 11. The level effects of fibers on MOR

Level	N	S1	S2	S3	S4
Level 1 (0kg)	7.11	6.98	6.80	6.96	7.09
Level 2 (10kg / 0.6kg)	7.50	7.49	7.53	7.44	7.48
Level 3 (20kg / 1.2kg)	7.85	7.99	8.14	8.06	7.89
E1(Level 2 –Level 1)	0.39	0.51	0.73	0.47	0.39
E2(Level 3 –Level 2)	0.36	0.51	0.61	0.62	0.42
E3(Level 3 –Level 1)	0.75	1.02	1.34	1.09	0.81

Table 12. The ANOVA table for MOR

Factor	SS	DOF	V	F	p
N	30.196	2	15.098	130.791	0.000
S1	55.702	2	27.851	241.269	0.000
S2	97.357	2	48.679	421.692	0.000
S3	65.449	2	32.725	283.486	0.000
S4	34.913	2	17.457	151.224	0.000
N×S1	0.276	4	0.069	0.599	0.664
N×S2	0.337	4	0.084	0.730	0.572
N×S3	3.163	4	0.791	6.850	0.000
N×S4	0.593	4	0.148	1.285	0.276
Error	34.285	297	0.115		
Total	322.271	323			

Table 13. The ANOVA table for MOR after pooling

Factor	pooling	SS	DOF	V	F	p	rho (%)
N	no	30.196	2	15.098	131.450	0.000	9.264
S1	no	55.702	2	27.851	242.483	0.000	17.149
S2	no	97.357	2	48.679	423.816	0.000	30.026
S3	no	65.449	2	32.725	284.914	0.000	20.162
S4	no	34.913	2	17.457	151.984	0.000	10.722
N×S1	yes	-	-	-	-	-	-
N×S2	yes	-	-	-	-	-	-
N×S3	no	3.163	4	0.791	6.885	0.000	0.836
N×S4	yes	-	-	-	-	-	-
Error		34.285	309	0.115			11.842
Total		322.271	323				

rho (%) = contribution ratio = (V-V(error)) (DOF) / Total(SS)

Fig.6 illustrates the interaction effects of MOR between S3 and N. When adding of S3 was 20 kg/m^3, and N was 1.2 kg/m^3, the hybrid fibers reached a significant interaction effect. This is because when a load is placed on the specimen, the hybrid fibers can withstand the tensile stress of the tensile zone below the neutral axis. When the nylon fibers failed, the steel fibers could keep bridging and disperse the stress of the macro-cracks until the fibers could no longer sustain the stress. Therefore, the interaction effects of the fibers could further improve the MOR.

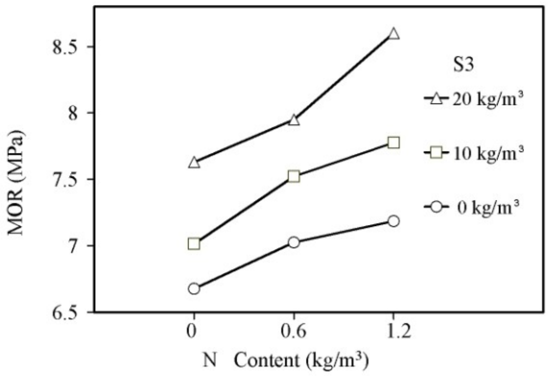

Fig. 6. Response of interaction on MOR between S3 and N fibers.

Ⅳ. CONCLUSIONS

1. Adding fibers into concrete can improve its engineering properties. The nylon fibers contribute the most to compressive strength, and the S2 fibers contribute the most to splitting tensile strength and modulus of rupture.
2. Based on ANOVA, the contribution ratio of different factors on compressive strength was 38.220, 13.284, 12.224, 3.344, 0.520, 1.086, for N, S1, S2, S3, S4 and N×S1, separately and the order contribution ratio was N>S1≒S2>S3>N×S1>S4. The contribution ratio of different factors on splitting tensile strength was 8.827, 19.098, 37.804, 12.858, 8.710, 0.807, for N, S1, S2, S3, S4 and N×S2, separately and the order contribution ratio was S2>S1>S3>N≒S4>N×S2. The contribution ratio of different factors on MOR was 9.264, 17.149, 30.026, 20.162, 10.722, 0.836, for N, S1, S2, S3, S4 and N×S3, separately and the order contribution ratio was S2>S3>S1> S4≒N>N×S3.
3. Steel and nylon fibers have interaction effects, and combination of different fiber types can improve the mechanical properties of concrete. N×S1 reaches a very significant level of compressive strength, N×S2 reaches a very significant level of splitting tensile strength, and N×S3 reaches a very significant level of MOR.

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