EFFECT OF STEEL FIBER ON ENGINEERING PERFORMANCE OF HIGH-STRENGTH CONCRETE

ẢNH HƯỞNG CỦA SỢI THÉP ĐẾN ĐẶC TÍNH KỸ THUẬT CỦA BÊ TÔNG CƯỜNG ĐỘ CAO

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Abstract - This research investigated significant effects of steel fiber on engineering properties of high-strength concrete. The mix proportions were designed relied on the Densified Mixture Design Algorithm (DMDA) method in which fly ash (FA) had filler and pozzolanic effects. The water-to-binder ratio (w/b) was kept at 0.27 to achieve high strength while the superplasticizer was added to ensure the workability of high-strength concrete. Slump, compressive strength, ultrasonic pulse velocity (UPV) and electrical surface resistivity (ESR) tests were examined. All of the steel fiber concrete specimens performed exceptional engineering properties. The greatest compressive strength obtained in this study was 74.9 MPa when steel fiber accounted for 5% by weight of fine aggregate. The amount of steel fiber was proportional to strength, UPV but inversely related with workability and ESR of the high-strength concrete.

Key words - High-strength concrete; steel fiber; compressive strength; electrical resistivity; UPV

Tóm tắt - Nghiên cứu này khảo sát sự ảnh hưởng của sợi thép đối với tính chất của bê tông cường độ cao. Các cấp phối được thiết kế dựa trên phương pháp DMDA. Theo phương pháp này, tro bay đóng vai trò vừa làm đặc chắc các lỗ rỗng giữa các hạt cốt liệu, vừa tham gia phản ứng pozzolanic. Tỉ lệ nước trên chất kết dính ở tất cả cấp phối đều là 0,27 nhằm tạo ra bê tông cường độ cao. Trong khi đó, phụ gia siêu dẻo được bổ sung để đảm bảo độ sụt của bê tông tươi. Các thí nghiệm độ sụt, cường độ nén, vận tốc xung siêu âm, và điện trở suất bề mặt cho thấy các tính chất rất khả quan của bê tông cường độ cao bổ sung sợi thép. Cấp phối với 5% sợi thép cho cường độ nén lớn nhất với 74,9 MPa. Thông qua các thí nghiệm, tăng hàm lượng sợi thép gia tăng cường độ nén và vận tốc xung siêu âm nhưng làm giảm độ sụt và điện trở suất bề mặt của bê tông cường độ cao.

Từ khóa - Bê tông cường độ cao; sợi thép; cường độ nén; điện trở suất bề mặt; vận tốc xung siêu âm

1. Introduction

Being early developed in the late 1950s, high-strength concrete, defined as having a compressive strength over 40 MPa, was expected to adapt to the growing demands of construction industry thanks to the very low permeability, high durability and high strength [1, 2]. These outstanding properties facilitated high strength concrete in numerous applications in construction industry such as high-rise structures, long-span bridges, dams, and marine structures. Notably, high strength concrete allowed reducing dimensions of columns and beams, thereby maximizing space for use. A variety of designs in which steel fibers was added to improve mechanical properties has been established for decades. A study of Holschemacher et al. indicated that the incorporation of high-strength fibers improved the ductility and load bearing capacity [3]. Rossi et al. also further figured out the ability of reducing macro cracks development by utilizing steel fibers [3, 4]. Moreover, integrating steel fiber in self-compacting concrete (SSC) also drew attention from numerous scholars to achieve needed workability and strength simultaneously [5]. This study focused on the significant influence of 6cm-long steel fiber on some fresh and hardened properties of high-strength concrete. The fresh and hardened properties were examined via the relevant tests named slump test, compressive strength test, UPV test, and ESR test.

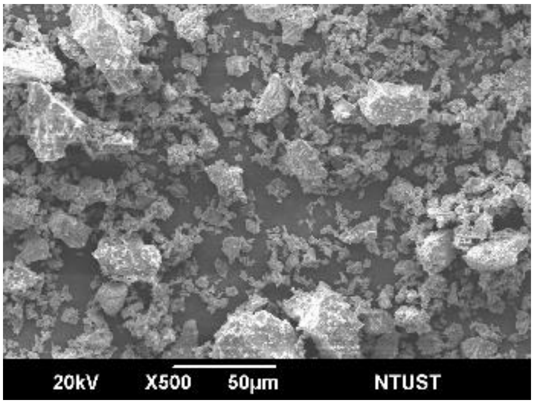
2. Materials and test methods

2.1. Material properties

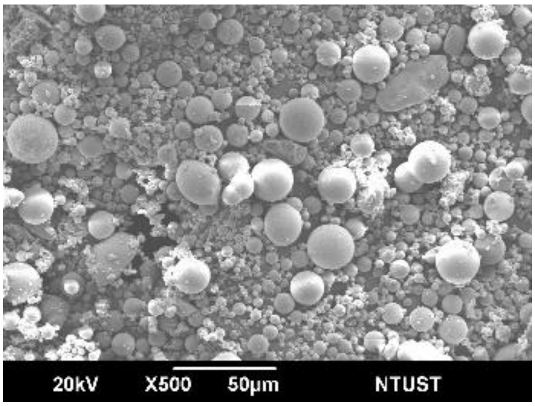
The raw materials used to produce steel fiber high-strength concrete come from Taiwan. The physical properties and chemical compositions of all materials are listed in Table 1. The binder used in the concrete were type I Ordinary Portland Cement (OPC), class F fly ash (FA), and ground granulated furnace slag (GGBFS). Figure 1 showed the Secondary Electron Microscopy (SEM) image of raw materials, in which, the FA particles exhibited the sphere shape and smooth surface, while the OPC and GGBFS presented the irregular shape particles. The mixing water used was local tap water. The superplasticizer (SP) was added to improve the workability of concrete samples. The fine and coarse aggregates were imported from Mainland China with the physical properties as shown in Table 2. Straight steel fibers of 6cm in length and 0.84mm in diameter (as shown in Figure 2) were added to study the influence of this material on engineering properties of high-strength concrete.

Table 1. *Physical properties and chemical compositions of raw materials*

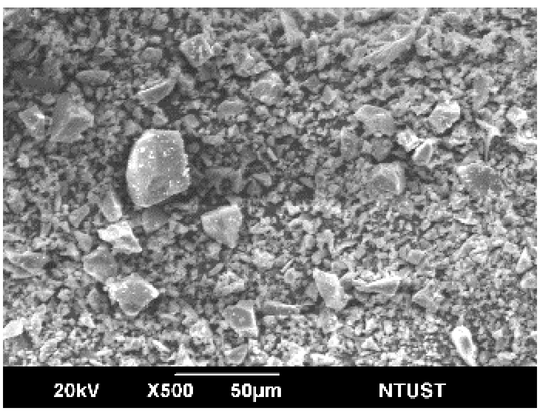
Items		OPC	FA	GGBFS
Physical properties	Specific gravity	3.15	2.08	2.98
	Mean particle size (μm)	19.04	21.8	14.56
Chemical composition (%)	SiO_2	12.5	63.9	33.39
	Al_2O_3	4.60	20.0	14.39
	Fe_2O_3	3.30	6.64	0.19
	CaO	68.8	3.84	41.08
	MgO	5.8	1.25	7.22
	K_2O	-	1.08	0.6
	Others	5.0	1.68	3.13



a. OPC



b. FA



c. GGBFS

Figure 1. *SEM image of raw materials*

Figure 2. *Steel fiber*

The mix proportion were designed based on the densified mixture design algorithm method (DMDA) developed by Prof. Hwang. The method designation originated the hypothesis that the physical properties will be optima when the physical density is high [6]. According to DMDA, the proportion of FA content was determined at 7.3% of the weight of sand and FA. While the ratio of (sand + FA)/ (sand + FA + coarse) by weight was used 0.53. This method helped limit the cement paste content without affecting design properties such as strength and workability. To achieve high compressive strength, pozzolanic materials such as FA, GGBFS were added. In this circumstance, FA played both as filler and pozzolanic material. The water-to-binder (w/b) ratio was kept at 0.27.

2.2. Experimental programs

Table 2. *Physical properties of the aggregate*

Items	Water absorption (%)	Specific gravity (g/cm^3)
Fine aggregate	1.4	2.60
Coarse aggregate	1.0	2.7

Firstly, a part of water was added into a mixer and then cement, FA, and GGBFS was added in 3 min to make a homogeneous paste. The fine and coarse aggregates were sequentially added into the mixer in 6 min and the water and SP were mixed with them to produce the fresh concrete. The slump test was examined after mixing. The fresh concrete was then poured into 100x200mm-cylinder molds. All the specimens were demolded after 24 hours of casting and were water cured in a pool at 25 ± 2^{0}C until their testing age. For each mixture, three cylinder samples were used to determine the compressive strength, UPV test according to ASTM C39 [7], ASTM C597 [8], respectively. The ESR test was measured by a meter, which was manufactured by the CNS Company in UK.

Table 3. *Mix-proportion for the preparation of concrete samples*

Mixtures	Concrete ingredient proportion (kg/m^3)							
	Sand	Coarse	GGBFS	FA	Cement	SP	Fiber	Water
HS0	892	854	152	71	300	4.7	0	136
HS2.5	892	854	152	71	300	4.7	22.3	136
HS5	892	854	152	71	300	4.7	44.6	136

3. Results and discussion

3.1. Fresh properties of steel fiber high-strength concrete

Table 4 shows the slump results of steel fiber concretes. With low water-to-binder ratio (0.27), the fresh high-strength concrete was characterized by high viscosity causing the reduction in slump values [3]. However, in this study, the fresh property of concrete was significantly improved due to superplasticizer. The slump value observed in high-strength mixture without the incorporation of steel fiber was approximately 250mm. As can be seen from the Table 4, increasing amount of steel fiber resulted lower slump value. However, the reduction speed of slump was not stable with the increased proportion of steel fiber. When the additive 2.5% steel fiber slightly reduced the slump flow value by 12%, the incorporation of 5% steel fiber significantly chopped down the slump flow results to merely 100mm, making a reduction of over 60%. The increasing steel fiber content blocked the relative movement of the aggregates, thereby reducing the slump values [9]. This such influence was noticeable in the mixture with 5% steel fiber.

Table 4. *Fresh properties of steel fiber high-strength concrete*

Mixtures	Slump (mm)
HS0	250
HS2.5	220
HS5	100

3.2. Compressive strength development

Figure 3 demonstrates the compressive strength development of high strength concrete in 28 curing days. Initially, the compressive strength of the three mixtures were around 20MPa on the 1st day and increased rapidly to exceed 65 MPa on the 28th day. The high strength of concrete can be attributed to the high density of concrete matrix which was primarily designed relied on DMDA [6]. The low w/b ratio (0.27) which was applied in previous research [5] has been proved to simultaneously foster the chemical reaction between water and binder, and to effectively mitigate voids in concrete matrix. Furthermore, the additive of steel fiber further strengthened high-strength concrete with the increments could be up to 14% compared to conventional high-strength concrete.

As can be seen from Figure 3, the differences in strength between HS0 and the other two steel fiber concretes broadened with aging time. During the curing period, 5% of steel fiber was considerably effective to boost the strength of concrete, approximately to 75 MPa on 28th day, around 14% higher than the reference high-strength concrete, whereas the strength in the counterpart with 2.5% of steel fiber increased by 3%. The results confirms numerous studies conducted by other scholars [10, 11]. Aside with low water-to-binder ratio, the increment in the amount of steel fiber led to the decrease in porosity as well as the considerable increase in the cohesive strength at the steel-fiber-matrix interfacial [11].

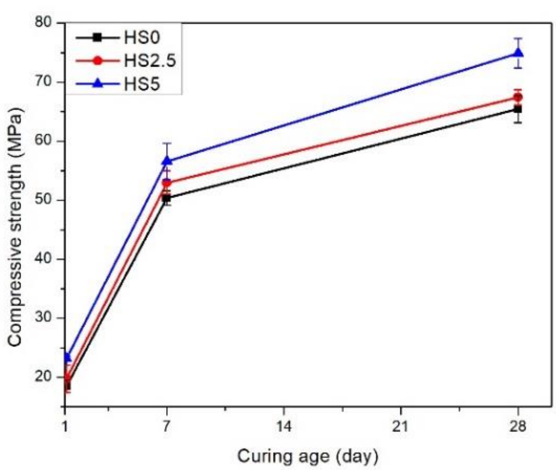


Figure 3. *Compressive strength of steel fiber concrete*

3.3. Ultrasonic pulse velocity (UPV)

The UPV test is a non-destructive method to assess the uniformity of concrete. The average pulse velocity values collected from this test depend on several factors, including the homogeneity and porosity of test samples [12]. Figure 4 illustrates the UPV values on the 7th day and on the 28th day. Obviously, UPV values grew up with curing time and the increase of UPV values were proportional to the steel fiber contents. An increase by approximately 7-11% was observed in the UPV values in later age. Additionally, the influence of steel fiber contents on UPV values was not considerable. On the 7th day, UPV rose by merely 50 m/s for every 2.5% steel fiber added in the mixtures. However, this difference became more considerable in later stage. On 28th day, the UPV values recorded soared from over 4850 m/s (in HS0) to over 5250 m/s (in HS5), in the range of excellent condition. This record correlated to the corresponding compressive strength results [13]. The trend of UPV values can be associated to the high density of concrete matrix which could be achieved by DMDA method, the adequate w/b ratio, and the increasing content of steel fiber. It can be seen that the developments of UPV and compressive strength were quite similar [13].

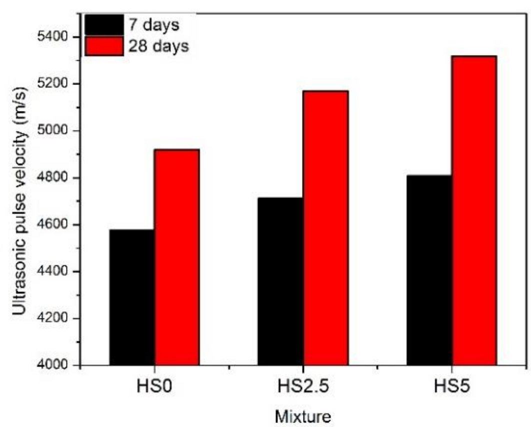


Figure 4. *UPV value of steel fiber concrete*

3.4. Electrical surface resistivity (ESR)

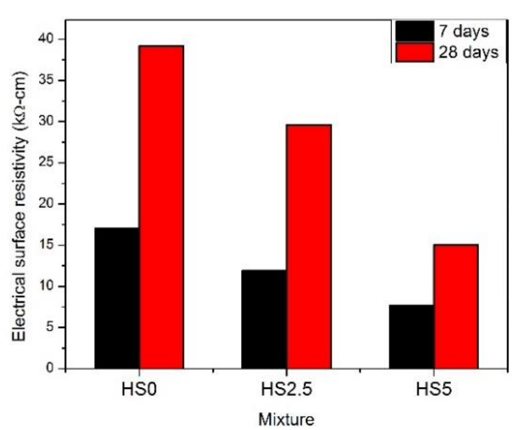


Figure 5. *ESR value of steel fiber concrete*

ESR measurements were conducted to quantify the resistance of materials to the passage of electrical current. While solid material has high ESR, pores that are partially or fully saturated with water have low resistivity. Thus, the pore solution may be considered as the principal electrical conductor. Therefore, measuring the ESR provides information on the microstructure quality of concrete, which is useful for estimating concrete durability [14]. As can be seen from Figure 5, the ESR of concrete samples doubled after 28 days of curing. Along curing time, the pozzolanic reaction produced more hydration products to densify the microstructure of concrete, hence, increased electrical resistivity [15].

On the other hand, the electrical resistivity of high-strength concrete with steel fiber is obviously less than that of non-steel fiber high-strength concrete due to the fact that steel fibers possess higher conductivity [2]. Increasing amount of steel fiber in the mixture, likewise, reduced the electricity resistance. In this study, adding steel fibers of 2.5% by weight of sand would cause the reduction of resistivity by over 25%. When the percentage of steel fiber reached 5%, the electricity resistance collapsed, remaining just nearly 38% compared to the conventional high-strength concrete. Apparently, the effect of steel fiber on electrical resistivity was opposite to that on compressive strength or UPV value.

4. Conclusions

This study explored the influence of steel fiber content on some fresh and hardened properties of high-strength concrete. It was pronounced that the addition of 5% steel fiber by weight of fine aggregate significantly affected the engineering performance of the high-strength concrete. The compressive strength and UPV could rise by 14% and 8%, respectively, in comparison with the conventional high strength concrete. Increasing steel fiber content enhanced the compressive strength, ultrasonic pulse velocity but had a negative impact on slump and electricity resistance.

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