

## EFFECTS OF BLENDING FIBERS ON TENSILE RESISTANCE OF ULTRA HIGH PERFORMANCE FIBER REINFORCED CONCRETE UNDER IMPACT

### ẢNH HƯỞNG CỦA VIỆC PHỐI HỢP CÁC LOẠI SỢI ĐẾN SỨC KHÁNG KÉO CỦA BÊ TÔNG SỢI TÍNH NĂNG CỰC CAO DƯỚI TẢI VÀ CHẠM

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#### ABSTRACT

The effects of blending fibers including two types of macro fiber, steel (S-) and polyamide (P-), and one type of micro fiber, polyamide (p-), on direct tensile behavior of ultra-high-performance hybrid-fiber-reinforced concrete (UHPHFRC) at high strain rates (10 and 47 s<sup>-1</sup>) were investigated. The volume content of macro fiber was maintained as 1.0%, whereas that of micro fiber varied from 0.0 to 1.5%. The UHPHFRCs with steel macro fibers (S-UHPHFRC) produced much higher rate sensitive tensile behavior than those with polyamide macro fibers (P-UHPHFRC). As the volume content of micro polyamide fibers increased, P-UHPHFRC produced higher rate sensitivity on post cracking tensile strength whereas S-UHPHFRC showed lower sensitivity. A proper amount of micro polyamide fibers, 0.5% in this study, would noticeably improve the impact resistance of S-UHPHFRCs, especially for strain capacity and peak toughness.

**Keywords:** blending fibers; high strain rates; ultra high performance fiber reinforced concrete; impact resistance, toughness.

#### TÓM TẮT

Bài báo khảo sát ảnh hưởng của việc phối hợp các loại sợi bao gồm 2 loại sợi lớn, thép (S-) và polyamide (P-), với một loại sợi nhỏ, polyamide (p-), đến ứng xử kéo trực tiếp của bê tông sợi tính năng cực cao (UHPHFRC) dưới tác dụng của tải và chạm với tốc độ cao, 10-47 s<sup>-1</sup>. Hàm lượng sợi lớn là 1%, hàm lượng sợi nhỏ từ 0.0 đến 1.5%. Kết quả cho thấy UHPHFRC với sợi thép nhạy với tải tốc độ cao hơn với sợi polyamide. Khi hàm lượng sợi polyamide tăng lên, độ nhạy về tốc độ tải của sức kháng kéo sau nứt của P-UHPHFRC tăng theo, trong khi đối với S-UHPHFRC lại giảm đi. Nếu đưa vào một lượng thích hợp sợi nhỏ polyamide, 0.5% trong nghiên cứu này, sức kháng chống va chạm của S-UHPHFRC sẽ cải thiện đáng kể, đặc biệt là đối với khả năng biến dạng và năng lượng phá hủy của nó.

**Keywords:** sự phối hợp các loại sợi; tải va chạm tốc độ cao; bê tông sợi tính năng cực cao; sức kháng chống va chạm, năng lượng phá hủy.

#### 1. INTRODUCTION

The 9/11 attacks threw whole the world into shock due to its malicious cruelty and destructive disaster. Such unprecedented attacks highlighted several concerns relating specifically to important structures under tremendous loading conditions. One of the concerns is urgent development of construction materi-

als with high impact resistance for more efficient protection against high velocity projectiles and explosives.

Many researchers have demonstrated that ultra high performance fiber reinforced concrete (UHPFRC) is one of promising construction materials with high impact resistant

[1-5]. Since UHPFRC is an achievement of a cross-century challenge began in 1930s in finding methods of increasing the mechanical strength of concrete, it is considered as one of the greatest breakthroughs in concrete technology at the end of the 20<sup>th</sup> century [6].

However, current UHPFRCs mostly utilize steel fibers which are vulnerable to corrosion under marine environments where most of severe infrastructure located near (e.g. nuclear power plants, high-rise buildings) or under (e.g. oil rigs, bridges) the sea. The corrosion of steel fibers in cementitious composites noticeably reduce the strength over time [7]. Moreover, if steel fiber reinforced concrete is used in certain applications such as tunnels of high speed railway or the runway of airport, it may have the safety problem due to effect of steel fibers on the magnetic and electric fields [8, 9]. Finally, since the cost for 1% steel fibers as volume content is generally higher than that of matrix [10], there is an essential requirement to minimize the cost of the composite for practical applications. Thus, recent UHPFRCs are oriented to minimize the amount of steel fibers but enhancing their mechanical resistance.

Achieving an optimal UHPFRC with the desired properties but at least cost is today technical challenge [11]. Up to now, most research on the mechanical behavior of UHPFRCs has been focused on mono UHPFRCs which is usually obtain separate purpose based on material type of used fibers. Therefore, to achieve the above mentioned UHPFRCs with multi-purposes, a nearly-40-year-old idea of using more than one type of fiber as reinforcement (hybrid fiber composite) [12], albeit during a long period of relative inactivity but appears recently as a renewed interest [13], is proposed in this research. The term "hybrid" is generally used to denote the combination of different types of material to construct a new one that will remain the constituents' advan-

tages but not their disadvantages [14].

Many attempts have been devoted on developing hybrid UHPFRCs, and, consequently it was found that the hybrid steel-steel fiber UHPFRCs exhibited improvement of not only flexural strength [15] but also tensile strength [16]. While the superior direct tensile behavior of hybrid UHPFRCs is mostly based on their responses measured at static rate, it has been expected that they would produce higher tensile resistance even at higher strain rates. On the other hand, polyamides (PA) fibers, well known as nylon and anti corrosion materials, have become more attractive in recent years as reinforcements for cement based material since they can provide effective, relatively inexpensive reinforcement for concrete [17-20]. Therefore, if PA fibers are further optimized for partially or entirely alternatives to steel fibers, a greater improvement of concrete without increasing the reinforcement cost could be obtained [21].

Thus, in this study, in order to gear toward a low cost UHPFRC with high impact resistance in a corrosion environment, the effects of two types of blending fibers including 1) macro PA and micro PA fibers and 2) macro steel and micro PA fibers, on the impact direct tensile behavior of hybrid UHPFRCs are investigated. There are several questions have been raised: which type of hybrids can generate superior tensile resistance (high strength and strain capacity) at high strain rates, how much of micro PA fibers are suitable, and, what is the role of micro PA fibers in enhancing rate sensitivity? Those questions motivated us to carry out this research with following specific objectives: 1) the strain rate effects on tensile behavior of mono UHPFRCs reinforced by steel fiber or PA fiber, 2) the strain rate effects on tensile behavior of hybrid UHPFRCs, 3) the role of micro PA fiber in hybrid UHPFRCs under high rate loading.

## 2. EXPERIMENTAL PROGRAM

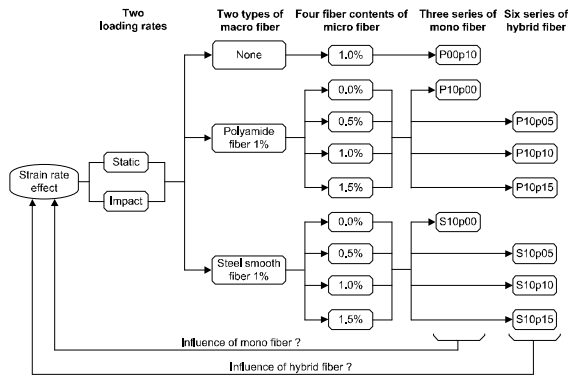


Fig. 1. Details of the experimental program

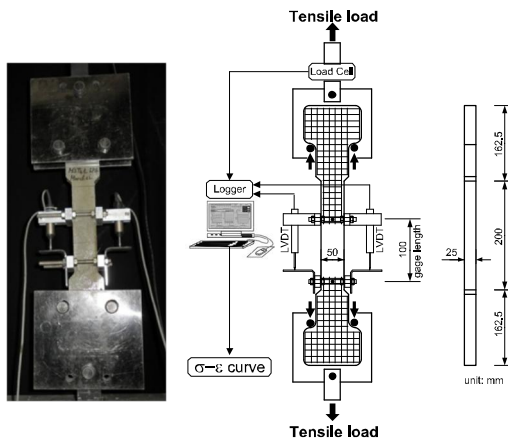


Fig. 2. Test set-up and geometry of specimen for static test [23,24]

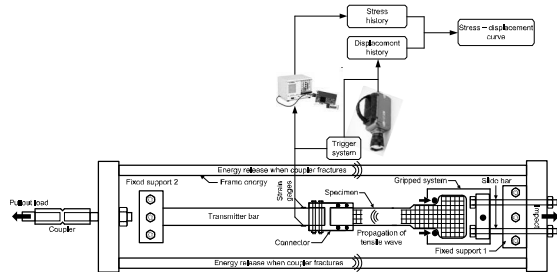


Fig. 3. Test set-up and geometry of specimen for impact test [23, 24]

An experimental program was designed to investigate the effects of blending fibers on direct tensile behavior of hybrid UHPFRCs. The program included 1) three series of mono UHPFRCs to investigate the strain rate effect of separate fiber types: micro polyamide (p), macro polyamide (P) and macro smooth steel (S) on direct tensile behavior, 2) three series

of hybrid P-p UHPFRCs and 3) three series of hybrid S-p UHPFRCs to investigate the role of adding p fibers to strain rate effect on direct tensile behavior of UHPFRCs using P or S fibers. A flowchart in Fig. 1 summarized this program with describing of test series designation. Static tests were performed using a universal test machine with a strain rate of  $\dot{\epsilon} = 0.000167s^{-1}$  by applying displacement speed of 1 mm/min. for the tensile specimen with 100 mm gauge length, while high rate tests were done using a SEFIM [22] with the strain rates varied between  $10 s^{-1}$  and  $47 s^{-1}$  according to the different capacities of coupler.

The test set-up and geometry for both static and impact test were described in Figs. 2 and 3, respectively. All bell-shaped specimens with cross section of  $25 \times 50$  mm and 100 mm gauge length were used for both static and impact tests.

## 3. TEST RESULTS AND DISCUSSION

Four following tensile parameters were analyzed to evaluate the rate effects on the tensile resistance of UHPFRCs: 1)  $\sigma_{pc}$ , the post cracking strength, is the peak stress value in the stress versus strain curve, 2)  $\epsilon_{pc}$ , the strain capacity, is the strain at peak stress 3) the peak toughness  $T_{pc}$ , the absorbed energy per unit volume of material, is defined as the area under the tensile stress versus strain curve until post cracking strength point, and 4) the dynamic increase factors, DIFs, are the ratio between dynamic and static response for above three parameters.

The effects of fiber materials (steel and polyamides) and size (micro p and macro P) on the tensile behavior of mono UHPFRCs at high strain rates are first analyzed as comparative cases for hybrid UHPFRCs. Then, the strain rate effects of two different hybrid P-p and S-p UHPFRCs are comparatively discussed by using dynamic increase factors (DIFs) of post cracking strength, strain capacity and peak toughness, respectively. Finally, the role of micro p- fiber added in hybrid UH-

PFRCs is discussed regarding their impact resistance. It should be noted that two following terminologies would be used in discussion: 1) rate sensitivity implies the values of DIF; and 2) impact resistance implies the values of tensile parameters at high rates.

### 3.1 Strain rate effects on tensile behavior of mono UHPFRCs

Since both mono p- UHPFRCs and hybrid P-p UHPFRCs did not exhibit strain hardening regimes at static rate as at higher strain rates, it is not consistent to establish DIFs of strain capacity as well as toughness. Thus, the rate sensitivity of those UHPFRCs was evaluated only for post cracking strength.

The strain rate effects on the post cracking strength of mono UHPFRCs including P00p10, P10p00 and S10p00 are evaluated based on their DIFs provided on graph plotted in dots with respect to strain rates as shown in Fig. 4. In the figure, although the dots disperse in a wide range from 1 to 4, they still could be distributed into three distinct zones according to the material types of fiber: the highest zone for S10p00, then lower zone for P00p10 and the lowest zone for P10p00. This means, for mono UHPFRC reinforced with same 1% volume fraction of fibers: 1) steel fibers produce the highest rate sensitivity on post cracking strength, 2.96, and more clearly pronounce (nearly twice) than PA fibers regardless any type of fiber length; and, 2) short micro p fibers are more rate sensitivity on post cracking strength than long P macro fibers, 1.64 and 1.09, respectively.

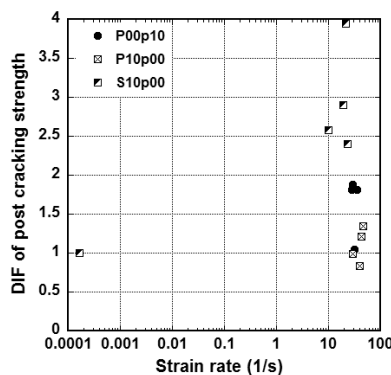


Fig. 4 Strain rate effect of mono UHPFRCs

For the first issue, there are two viewpoints to explain: 1) based on the phenomenon of fiber breakage during impact testing, that, steel fibers in high strain rate specimens are pulled out, not breakage as PA fibers, thus they produced higher rate sensitivity as demonstrated in [5]; 2) based on different bond characteristics due to the difference between the elastic modulus of two fiber material types [25], which, in this case, steel fibers with higher elastic modulus would exhibit more favorable bond characteristics than PA fibers, thus, they produce higher rate sensitivity [23]. For the second issue, the higher rate sensitivity of UHPFRCs reinforced by micro p- fibers compare to those reinforced by macro P- fibers is thought to be originated from the higher interfacial bond strength [23] of p fibers due to their smaller diameters, larger number and relatively smaller distance between fibers [26].

Besides, for the impact resistance, the experimental results show that, P00p10 produces higher post cracking strength, 6.82 MPa, but lower strain capacity, 1.34%, than P10p00 (4.25 MPa and 3.02%, respectively). It demonstrates that UHPFRCs reinforced by short micro fibers would enhance the tensile strength while those reinforced by long macro fibers would enhance the ductility. Moreover, for micro p fibers, since the enhancement of post cracking strength is more prevailed than strain capacity, thus, leading to the peak toughness is more pronounced, 72.59 kJ/m<sup>3</sup> for P00p10 and 66.70 kJ/m<sup>3</sup> for P10p00. Micro fibers, by virtue of its fine size, result in enhancing surround surface area between fibers and matrix, thus, they provide an increase of tensile strength, but a decrease of strain capacity.

### 3.2 Strain rate effects on tensile behavior of hybrid P-p UHPFRCs

As above mentioned, due to inconsistency on tensile performance between static and impact, strain rate effects on tensile behavior of hybrid P-p UHPFRCs would be evaluated on post cracking strength only. These effects

are provided in Fig. 5, in which, it presents all results in dots with respect to strain rates.

In general, there is an increasing trend of rate sensitivity (DIF) on post cracking strength, from 1.09 to 1.56, as increasing in the volume content of micro p- fibers, from 0% to 1.5%, respectively. It should be noticed that, the comparison here is relative since these average values obtained from the various strain rates between 10 and 47 s<sup>-1</sup>. One exception of decreasing rate sensitivity in the case of 1% maybe came from the reason of the scatter in experimental work. While the rate sensitivity was strongly enhanced from 1.09 to 1.43 when adding 0.5% p fibers, that was enhanced more weakly when adding more 1% p fibers, from 1.43 to 1.56. This observation demonstrated that the adding micro p fibers would improve the rate sensitivity on post cracking strength, and this improvement will be gradually reduced as amount of micro fiber increases.

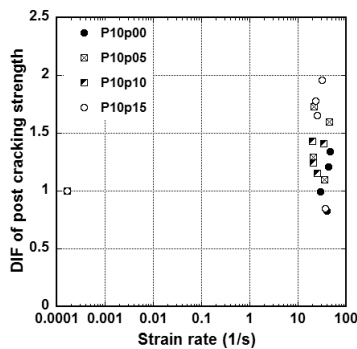


Fig. 5 – Strain rate effect of hybrid P-p UHPFRCs

The addition of micro p fibers not only results in the enhancement of total interfacial bonding due to increasing amount of fibers, but also increasing the friction of matrix. Therefore, the individual bonding between each macro P fiber and surrounding matrix is improved. Consequently, the rate sensitivity of material is enhanced since the bond between fibers and matrix is the key factor leading to the dynamical resistance enhancement at high rate loading as shown in [23]. However, this enhancement of rate sensitivity is reduced as adding too much micro fibers. There might be three following reasons: 1) micro p fibers, if

too much, would absorb much water needed for hydration, leading to reduce the quality of surrounding matrix strength; 2) too much micro p fibers may result in increasing the porosity at interfacial transition zones (ITZs); 3) group effect, i.e., if the number of fiber is high, the amount of matrix surrounding the fiber is not be enough to maintain the interfacial bonding as strong as in the single pullout case, which could lead to dilute or eliminate rate sensitivity [24].

### 3.3 Strain rate effects on tensile behavior of hybrid S-p UHPFRCs

Strain rate effects on tensile behavior including post cracking strength of hybrid S-p UHPFRCs are described in Fig. 6.

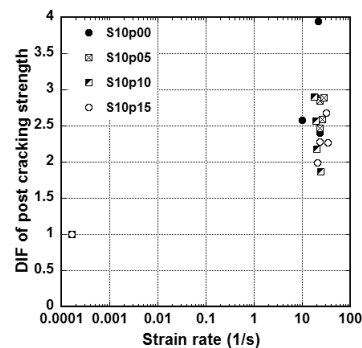


Fig. 6 – Influence of volume contents of micro fiber on DIF of post cracking strength

For the post cracking strength, while the DIFs of hybrid P-p UHPFRCs ranking from 1 to 2, as shown in Fig. 12a, those of hybrid S-p ranking in a higher value, from 2 to 3 as shown in Fig. 6. This indicated that, the macro S fibers contribute much higher rate sensitivity than macro P- fibers in hybrid UHPFRCs, as same as mono UHPFRCs. In other hand, while an increasing of adding micro p- fibers results in the enhancement of rate sensitivity on post cracking strength of hybrid P-p UHPFRCs (Fig. 5), it does opposite tendency for that of hybrid S-p ones. This decreasing phenomenon has been Park *et al.* [27] pointed out that the adding of micro fibers resulted in the shrinkage reducing of surrounding matrix, leading to the reducing the interfacial bonding, thus, reducing the rate sensitivity.

Unlike DIFs of post cracking strength, those of strain capacity and peak toughness are distributed in a much wider ranging, from 2 to 7 for strain capacity and from 3 to 11 for peak toughness. Especially, from the distribution of dots for each serie, it can be seen that the more adding micro p- fibers, the more concentrating of dots. This means, the micro p- fibers provided a positive effect on reducing the scatter in high strain rates testing. Adding micro p- fibers might lead to the enhancement of viscosity for the mortar during mixing, thus, remaining the anti-sinking environment for steel fibers which are very easy to slip in wet mortar. Such improvement of uniform fiber distribution in hybrid nylon steel fiber reinforced concrete has also been mentioned in [28].

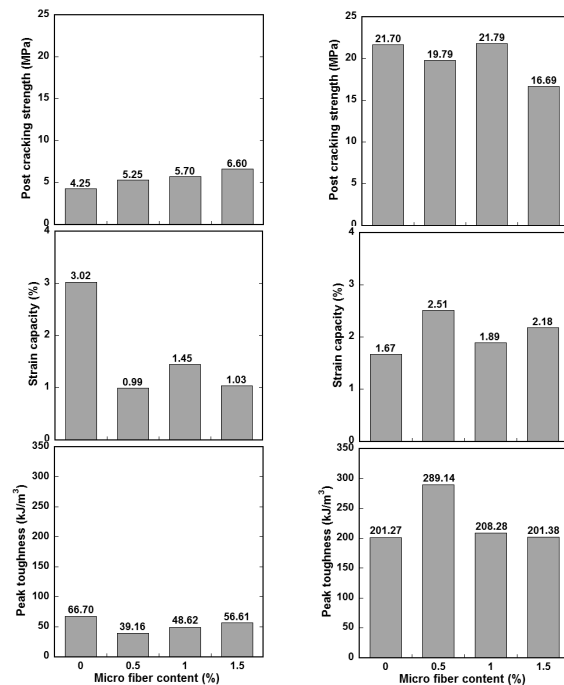
It is also observed that while there is a clear reducing tendency of rate sensitivity on post cracking strength, it is not clear on strain capacity and peak toughness. Not only that, it is very interest that, at the 0.5% of adding micro p- fibers, although the DIF of post cracking strength little bit reduces (from 2.96 to 2.7), those of strain capacity and peak toughness increase strongly (from 3.89 to 5.83 and from 7.02 to 10.09, respectively) and reach to the maximum values. It means that adding 0.5% of micro p- fibers results in an optimal S-p UHPFRCs in rate sensitivity for all post cracking strength, strain capacity and peak toughness.

### 3.3 The role of adding micro p- fibers on the impact resistance of hybrid UHPFRCs

Effect of adding micro p- fibers on the impact resistance of hybrid UHPFRCs is summarized in Fig. 7a for hybrid P-p UHPFRCs and Fig. 7b for hybrid S-p UHPFRCs. In general, the positive effect observed from combination of two types of fiber reinforcements, macro and micro, as in post cracking strength of hybrid P-p, and strain capacity and peak toughness of hybrid S-p, is encourage.

It is clear to observe that adding micro p- fibers from 0% to 1.5% resulted in increasing the post cracking strength of hybrid P-p

UHPFRC, from 4.25 MPa to 6.60 MPa, but decreasing that of hybrid S-p UHPFRCs from 21.70 MPa to 16.69 MPa. The opposite tendency between hybrid P-p and S-p are also observed for strain capacity and peak toughness where the changing trend of strain capacity and peak toughness respect to a concave curve for hybrid P-p, but respect to convex curve for hybrid S-p. Especially, the bottom of the concave curve and the peak of the convex curve are at the same volume content of adding micro fibers, 0.5%. This observation demonstrated that the proper volume content of adding micro p- fiber is different depending on the using type of macro fibers. For steel fibers, the proper volume content is 0.5%, whereas for macro P- fibers, it is not clear. Further studies to investigate the opposite phenomenon between these two fiber types should be performed.



a) Hybrid P-p UHPFRCs

b) Hybrid S-p UHPFRCs

**Fig. 7 – The role of adding micro p fibers on the tensile impact resistance of hybrid UHPFRCs**

## 4. CONCLUSIONS

This work provides experimental results that help to understand the strain rate effects on direct tensile behavior of hybrid UHP-

FRCs. An investigation of blending effects for hybrid UHPFRCs using two types of macro fiber, steel and polyamides in 1% volume content, blended with 0%, 0.5%, 1% and 1.5% micro polyamides fibers, under static and under high strain rate ranging from 10 to 47 s<sup>-1</sup> was presented in this work. The following conclusions can be drawn:

- For mono UHPFRCs, the highest rate sensitivity on post cracking strength is produced by steel fiber, then by micro p- fibers, and lowest one by macro P- fibers. Moreover, at high rate loading, short p- fibers enhance the tensile strength while long P- fibers enhance the ductility.
- For hybrid UHPFRCs, at static rate, a proper amount of adding micro p- fibers,

1% in this case, would improve not only post cracking strength, but also strain capacity and peak toughness. At high strain rate, there are four notices as following: 1) the hybrid S-p specimens almost produce significantly higher impact resistance than corresponding hybrid P-p ones; 2) the adding micro p- fibers provide a positive effect on reducing the scatter in composites; 3) as volume content of adding micro p- increases, while rate sensitivity on post cracking strength of hybrid P-p UHPFRCs increases, that of hybrid S-p decreases; 4) an optimum hybrid S-p UHPFRC for impact resistance could be obtain with a suitable amount of adding micro p- fibers (0.5% in this case).

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