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Abstract

This research studies the mechanical properties of concrete mixtures containing 1% nano-SiO₂ and different content macro-fiber. Steel (ST) fibers and High performance polypropylene (HPP) fibers of the same length and shape were used, a total of 10 concrete mixtures incorporating 1% of nano-SiO₂ by weight of the binder and 0.5%, 1%, 1.5% and 2% macro-fiber by volume of concrete were studied. The experimental results show that addition 1% nano-SiO₂ leads to an improvement in all of the mechanical properties of concrete and the incorporation of steel fiber and HPP fiber improves the mechanical properties of concrete. Furthermore, the tensile strength of concrete mixed with 2% steel fiber increased by 51.4%, and the flexural strength increased by 32.7%, the tensile strength of concrete mixed with 1% HPP fiber increased by 34.5%, and the flexural strength increased by 22.8%. It was also indicated that when the fiber content is 1 vol%, the HPP fiber can replace steel fiber.

1. Introduction

Nowadays, concrete is one of the most widely used building materials because of its low-cost, versatility, good mechanical properties, and abundant material [1–3]. Therefore, improving the mechanical properties and durability of concrete was a major concern for researchers.

The addition of fibers, pozzolanic materials and admixtures in concrete are effective in improving the mechanical Properties and durability of concrete [4, 5]. Among them, Steel fibers, polypropylene fibers, carbon fibers, hybrid fibers and other types of fiber-reinforced concrete (FRC) have been widely studied, especially steel fibers (SF) and polypropylene fibers (PPF) was widely used in practice and research [6–9]. Madandoust et al [10] obviously demonstrate that steel fiber content has an appreciable impact on the compressive strength, tensile strength, flexural strength and elastic modulus of concrete. Moreover, the length, aspect ratio, shape of the fiber in FRC plays an important role in the mechanical properties [11, 12]. Abbass et al prove that hooked ended steel fibers reinforced concrete has higher pullout load and ductility [13], unfortunately, Steel fiber has the shortcomings of high cost, easy corrosion and deformation, while polypropylene fiber has low cost and corrosion resistance. But polypropylene reinforced concrete (PPFRC) has low mechanical properties compared with SFRC.

As a new type of synthetic fiber, High performance polypropylene fiber (HPPF) has the advantages of high strength, high elastic modulus and high dispersion, which has attracted the attention of researchers [14, 15]. He et al compared the influence of PPF and HPPF on the mechanical properties of concrete, and the results showed that the mechanical properties of HPPFRC, including compressive strength, tensile strength, flexural strength and impact resistance higher than PPFRC [16]. Behfaravan et al [17] indicate that HPP fiber can significantly improve flexural toughness, impermeability and chloride ion resistance of concrete. However, the research on HPPFRC is much less sufficient than the research on SFRC. As a substitute for steel fibers, comparative studies on the effect of HPPF and SF on the mechanical properties of concrete with the same geometric parameters are also less.

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Another widely used method to improve the mechanical properties of concrete was the addition of pozzolanic materials. Nano SiO$_2$ (NS) is a commonly used nanomaterial and pozzolanic material, and researchers have conducted numerous studies on the properties of concrete incorporated with nano-SiO$_2$ [18–21]. Due to its small particle size and large specific surface area and surface energy, Nano SiO$_2$ has high pozzolanic activity and filling effect, it can promote cement hydration, accelerate generate C-S-H and fill the micropores and nanopores of cement, and increase the compactness of concrete [22, 23]. Wang et al reported that the addition of 3% NS can effectively improve the compressive strength of light-aggregate concrete and reduce its cracking area due to the ability of NS to enhance the interfacial transition zone of concrete. At present, the combined use of fibers and NS to improve the mechanical properties and durability of concrete is still relatively little studied. The main focus is on fiber and silica fume (SF), and steel fiber and NS. Algburi et al studied that the addition of steel fibers, glass fibers and hybrid fibers to reactive powder concrete, and the results showed that silica fume and fibers have a synergistic effect, and can improve the mechanical properties of concrete to a greater extent [24]. The research results of Zhang et al showed that NS can improve the compressive strength and durability of concrete, and steel fibers can improve the mechanical properties of concrete, but will reduce the permeability of concrete [25].

It is known that the material and geometric parameters of the fibers have a significant impact on the mechanical properties of concrete. The SF have been widely studied on the mechanical properties of NSRC, but the effect of HPP fibers on the mechanical properties of NSRC was less studied, and the comparative study of these two fibers with the same geometric parameters is also less. In this paper, a new sawtooth-shaped HPP fiber was used instead of the traditional wave-shaped, The tests used SF and HPPF of the similar geometric parameters.

| Material | Properties |
|----------|------------|
| SF       | Average fiber length 40 mm, Average fiber diameter 0.8 mm |
|          | Tensile strength ≥600 MPa, Specific gravity 7.8 g cm$^{-3}$, Type Wave-shaped |
| HPPF     | Average fiber length 40 mm, Average fiber diameter 1.0 mm |
|          | Tensile strength 550 MPa, Specific gravity 0.91 g cm$^{-3}$, Type Sawtooth-shaped |
| NS       | Specific surface area 380 ± 30 m$^2$ g$^{-1}$, Mean Particle size 7 nm |
|          | Apparent density 30 wt%, Bulk density 0.05 g cm$^{-2}$, SiO$_2$ content 99.8 wt% |

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to compare the effects of different HPPF and macro-SF contents on the mechanical properties of NSRC and to
determine the optimum admixture of HPPF and macro-SF.

2. Experimental program

2.1. Materials
The study used P.O 42.5 Portland cement (C) produced by Huaxin Cement Co., Ltd, Normal tap water (W),
Crushed limestone as coarse aggregates (CA), Natural sand as fine aggregates (FA), BASF F10 water reducer (WR), A380 Nano SiO2 (NS) produced by Evonik Industries AG, with a mean particle size of 7 nm and a specific
surface area of 380 m² g⁻¹, Steel fibers (SF) and High performance polypropylene fiber (HPPF) produced by
Tianyi Fibers Co., Ltd, the length was 40 mm, aspect ratio was 50 and 40 respectively, SF were wave-shaped and
HPPF were sawtooth-shaped. The major properties of SF, HPPF and NS from manufacturers were presented in

2.2. Mixture proportions
In order to investigate the effect of different contents of SF and HPPF on the mechanical properties of concrete
added with 1% NS , a total of ten mixture with two type fiber and four different fiber volume fraction was
prepared in this paper. W/B was 0.4, Nano-SiO2 as a cement replacement was added 1 wt% of the binder.

Plain concrete mix (PC) were prepared as the contrast sample, three primary parameters were provided in the
experimental program. To be specific, (a) Concrete mixture containing 1% nano-SiO2 (NS), (b) NS mixture
containing 0.5%, 1.0%, 1.5% and 2.0% HPPF-fiber by volume (HPP) and (c) NS mixture containing 0.5%, 1.0%,
1.5% and 2.0% steel fiber by volume (ST). Concrete mixes were presented in table 2.

2.3. Preparation and testing methods
An experimental analysis focused on the mechanical properties of concrete mixture was presented using a total
of 270 specimens. All specimens were made and cured as implied in the Chinese standard GB/T50081-2019,

| Concrete mixture | W/B | C (kg m⁻³) | W (kg m⁻³) | FA (kg m⁻³) | CA (kg m⁻³) | SF (kg m⁻³) | HPPF (kg m⁻³) | NS (kg m⁻³) | WR(%) |
|------------------|-----|------------|------------|-------------|-------------|-------------|---------------|-------------|-------|
| PC               | 0.4 | 432        | 172        | 712         | 1080        | 0           | 0             | 0           | 1     |
| NS               | 0.4 | 428        | 172        | 712         | 1080        | 0           | 0             | 4.3         | 1     |
| ST-0.5           | 0.4 | 428        | 172        | 712         | 1080        | 39          | 0             | 4.3         | 1     |
| ST-1.0           | 0.4 | 428        | 172        | 712         | 1080        | 78          | 0             | 4.3         | 1     |
| ST-1.5           | 0.4 | 428        | 172        | 712         | 1080        | 117         | 0             | 4.3         | 1     |
| ST-2.0           | 0.4 | 428        | 172        | 712         | 1080        | 156         | 0             | 4.3         | 1     |
| HPPP-0.5         | 0.4 | 428        | 172        | 712         | 1080        | 0           | 4.5           | 4.3         | 1     |
| HPPP-1.0         | 0.4 | 428        | 172        | 712         | 1080        | 0           | 9.1           | 4.3         | 1     |
| HPPP-1.5         | 0.4 | 428        | 172        | 712         | 1080        | 0           | 13.6          | 4.3         | 1     |
| HPPP-2.0         | 0.4 | 428        | 172        | 712         | 1080        | 0           | 18.2          | 4.3         | 1     |

Figure 1. The compressive strength of concrete mixture.
that adding nano-SiO₂ to concrete improves its compressive strength. The compressive strength of concrete mixtures at 28 days increases by 6%, 10%, 8% and 6%, respectively, as the SF contents are 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol%. Furthermore, the concrete mix with 1.5% HPP fiber provided the highest 28 days compressive strength of 60.5 MPa and the concrete mix with 1.0% HPP fiber provided the lowest 28 days compressive strength of 58.9 MPa. Compared with PC, the compressive strength of HHP mixtures at 28 days increases by 6%, 10%, 8% and 6%, respectively, as the SF contents are 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol%.

According to GB/T50081-2019, Cubic specimens (150 × 150 × 150 mm) and Beam specimens (400 × 100 × 100 mm) were prepared and the compressive strength test, splitting tensile strength test and flexure strength test was carried out at 3 days, 7 days and 28 days, respectively.

### 3. Results and discussion

#### 3.1. Compressive strength

The results of compressive strength tests and associated standard deviation (expressed as a percentage of the mean value) for different mixture at 3, 7 and 28 days were presented in table 3 and figure 1. The results indicate that adding nano-SiO₂ to concrete improves its compressive strength. The compressive strength of concrete with 1% nano-SiO₂ addition increased by 22%, 11% and 10% at 3 days, 7 days and 28 days, respectively. It’s noted that the compressive strength of concrete added with nano-SiO₂ increases rapidly at the early age and gradually decreases at the later age. Ren et al. [26] have reported similar phenomenon that Nano-SiO₂ particles can react with C-H in cement to generate C-S-H gel at early age and reduce harmful holes in concrete, and improve compressive strength. Their results show that when the nano-SiO₂ replacement amount is 3%, the compressive strength of concrete increases by 16% at 28 days.

HPPF and SF can improve the compressive strength of concrete at all ages. As can be see that the concrete mixture with 1% steel fiber provided the highest compressive strength of 60.6 MPa at the age of 28 days, while the concrete mix with 2.0% steel fiber had the lowest 28 days compressive strength of 58.4 MPa; Compared with PC, the compressive strength of ST mixtures at 28 days increases by 17%, 21%, 19% and 17%, respectively, as the SF contents are 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol%. Compared with NS, the compressive strength of ST mixtures at 28 days increases by 6%, 10%, 8% and 6%, respectively, as the SF contents are 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol%.

#### Table 3. Compressive strength of concrete mixture.

| Concrete mixture | 3d  | 7d  | 28d  | Compared to PC (%) |
|------------------|-----|-----|------|--------------------|
| PC               | 24.4(4%) | 34.7(10%) | 50.0(3%) | 100  | 100  | 100  |
| NS               | 29.9(6%) | 38.6(5%) | 55.4(3%) | 122  | 111  | 110  |
| ST-0.5           | 28.4(14%) | 37.5(3%) | 58.6(6%) | 116  | 108  | 117  |
| ST-1.0           | 33.1(12%) | 38.9(3%) | 60.6(9%) | 135  | 112  | 121  |
| ST-1.5           | 32.7(4%) | 38.1(7%) | 59.7(10%) | 134  | 110  | 119  |
| ST-2.0           | 32.4(5%) | 43.3(12%) | 58.4(10%) | 133  | 125  | 117  |
| HPP-0.5          | 29.1(10%) | 39.6(6%) | 59.5(4%) | 119  | 136  | 119  |
| HPP-1.0          | 30.0(13%) | 40.6(8%) | 58.9(2%) | 122  | 117  | 118  |
| HPP-1.5          | 30.4(5%) | 37.5(7%) | 60.5(7%) | 124  | 108  | 121  |
| HPP-2.0          | 30.0(2%) | 39.2(8%) | 59.1(1%) | 123  | 113  | 118  |

### Table 4. Splitting tensile strength of concrete mixture.

| Concrete mixture | 3d  | 7d  | 28d  | Compared to PC (%) |
|------------------|-----|-----|------|--------------------|
| PC               | 1.40(3%) | 2.03(9%) | 2.62(5%) | 100  | 100  | 100  |
| NS               | 1.60(9%) | 2.10(5%) | 2.80(12%) | 114  | 104  | 107  |
| ST-0.5           | 1.63(15%) | 2.28(4%) | 2.98(3%) | 116  | 112  | 114  |
| ST-1.0           | 1.76(7%) | 2.59(5%) | 3.51(10%) | 126  | 128  | 134  |
| ST-1.5           | 1.94(12%) | 2.59(3%) | 3.84(6%) | 138  | 127  | 147  |
| ST-2.0           | 2.04(8%) | 2.78(6%) | 4.27(7%) | 146  | 137  | 162  |
| HPP-0.5          | 1.78(8%) | 2.15(5%) | 2.96(4%) | 127  | 106  | 113  |
| HPP-1.0          | 2.09(3%) | 2.67(5%) | 3.79(6%) | 150  | 132  | 144  |
| HPP-1.5          | 1.90(7%) | 2.36(18%) | 3.54(12%) | 136  | 116  | 135  |
| HPP-2.0          | 1.84(2%) | 2.35(12%) | 3.25(4%) | 132  | 115  | 124  |
increases by 19%, 18%, 21% and 18%, respectively, as the HPPF contents are 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol%. Compared with NS, the compressive strength of HHP mixtures at 28 day increases by 8%, 7%, 10% and 7%, respectively, as the HPPF contents are 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol%.

The results show that adding SF and HPPF to concrete can slightly improve the compressive strength of concrete, but the effect of different fiber content in concrete on the compressive strength of concrete was not significant. This is due to the fact that SF and HPPF do not act as aggregates to provide support for concrete, but SF and HPPF act as macro-fibers to prevent the generation and expansion of cracks in the concrete matrix and inhibit the development and accumulation of concrete damage [27–29]. Figure 1 also indicate that SF and HPPF have similar compressive strength in this study, The highest compressive performance of ST and HPP is 21% higher than that of PC and 9% higher than that of NC. This is due to similar size, shape and tensile strength of SF and HPPF.

3.2. Splitting tensile strength

Table 4 shows the results and s associated standard deviation (expressed as a percentage of the mean value) of splitting tensile strength for different concrete specimens at 3, 7 and 28 days. The results show that the splitting tensile strength of concrete with addition 1% nano-SiO₂ increased by 14%, 4% and 7% at 3 days, 7 days and 28 days, respectively. Due to the pozzolanic and filling effect of NS increased the compactness of concrete, leading to an increased in the splitting tensile strength of concrete.
Table 5. Flexural strength of concrete mixture.

| Concrete mixture | Flexural strength (MPa) | Compared to PC(%) |
|------------------|-------------------------|------------------|
|                  | 3d | 7d | 28d | 3d | 7d | 28d |
| PC               | 3.06 (5%) | 4.07(4%) | 4.76(5%) | 100 | 100 | 100 |
| NS               | 3.24(2%) | 3.94(16%) | 4.81(6%) | 106 | 97  | 101 |
| ST0.5            | 3.57(12%) | 4.20(5%) | 5.55(8%) | 117 | 103 | 117 |
| ST1.0            | 3.82(7%) | 4.66(4%) | 5.92(6%) | 125 | 115 | 125 |
| ST1.5            | 3.83(7%) | 5.06(4%) | 6.10(4%) | 126 | 124 | 128 |
| ST2.0            | 3.91(4%) | 4.90(9%) | 6.37(6%) | 128 | 120 | 134 |
| HPP0.5           | 3.70(8%) | 4.17(8%) | 5.10(8%) | 121 | 103 | 107 |
| HPP1.0           | 3.97(7%) | 4.90(10%) | 5.91(9%) | 130 | 121 | 124 |
| HPP1.5           | 3.88(8%) | 4.51(10%) | 5.62(10%) | 127 | 111 | 118 |
| HPP2.0           | 3.83(9%) | 4.70(6%) | 5.32(12%) | 125 | 115 | 112 |

Figure 2 show that the incorporation of SF and HPPF has a significant influence on the splitting tensile strength of concrete. The regression analysis showed that the splitting tensile strength of concrete was linearly related to the SF content, and the splitting tensile strength increased by 6.5%, 25.2%, 37.4% and 51.4% for 0.5%,
1.0%, 1.5% and 2.0% of SF content, respectively. The results also indicate that the increased in splitting tensile strength of concrete at 28 days is higher than that in the early age of curing, indicating that add 1% NS can improves the bonding ability between the SF and the concrete matrix.

Figure 2(b) illustrates the relationship between HPP content and splitting tensile strength of concrete. The splitting tensile strength of concrete first increases with the increase of HPP fiber content, and reaches the maximum value of 3.79 MPa for 1.0% of HPP fiber content at 28 days, and then starts to decrease with the increase of HPP fiber content. The splitting tensile strength of concrete containing 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol% HPPF increased by 5.6%, 34.5%, 26.2% and 15.9% at 28 days, respectively. Mixture ST2.0 and HPP1.0 prove the highest splitting tensile strength of 4.27MPa and 3.79MPa, which were 51.4% and 34.5% higher than NS mixture, respectively.

Similar trends have been obtained by other researchers regarding the effect of SF and HPPF on the splitting tensile strength of concrete, Abbass et al indicate that the splitting tensile strength of concrete in a certain range is linearly related to the fiber content, this is consistent with the results in figure 2(a), because of the bridging mechanism of fibers prevent the generation and expansion of cracks in the concrete matrix. However, figure 2(b) show when the HPP fiber content is higher than 1 vol%, the splitting tensile strength decreased. Afrughhsabet et al reported that the splitting tensile strength of concrete not only depended on the fiber content, but also depended on the dispersion of fibers in concrete. Better fiber distribution results in higher mechanical properties. The high content of fiber leads to fiber agglomeration which increases the internal defects of concrete and reduces its splitting and tensile properties. It is worth noting that this phenomenon does not occur with steel fibers reinforced concrete. The higher density of steel fibers results in a more uniform dispersion of steel fibers in the concrete, which is consistent with subsequent observations from the fracture surface of the concrete.

3.3. Flexural strength
Table 5 shows the results and s associated standard deviation (expressed as a percentage of the mean value) of the flexural strength for different mixture at 3, 7 and 28 days. The results show that the flexural strength of concrete with addition 1% nano-SiO2 increased by 6%, −3% and 1% at 3D, 7D and 28D, respectively. It shows that adding 1% nano-SiO2 has no significant effect on the flexural strength.
In this paper, the mechanical properties of NS and SF are investigated, and based on experimental studies and analysis, the following conclusions can be drawn.

4. Conclusions

In this paper, the mechanical properties of NS and fiber-reinforced concrete with different contents of HPPF and SF are investigated, and based on experimental studies and analysis, the following conclusions can be drawn.

Figure 5. Failure modes of concrete specimens under flexural test.

Figure 3(a) show that the incorporation of SF and HPPF has a significant influence on the flexural strength of concrete. The regression analysis showed that the flexural strength of concrete was linearly related to the SF content, and the flexural strength increased by 15.8%, 23.8%, 26.7% and 32.7% for 0.5%, 1.0%, 1.5% and 2.0% of SF content, respectively. On the other hand, figure 3(b) also illustrates the relationship between HPP content and flexural strength of concrete. The flexural strength of concrete first increases with the increase of HPP fiber content, and reaches the maximum value of 5.91 MPa for 1.0% of HPP fiber content at 28 days, and then decrease with the increase of HPP fiber content. The flexural strength of concrete containing 0.5 vol%, 1.0 vol%, 1.5 vol% and 2.0 vol% HPPF increased by 5.9%, 22.8%, 16.8% and 10.9% at 28 days, respectively.

Mixture ST2.0 and HPP1.0 show the highest flexural strength with the value of 6.37MPa and 5.91MPa, which were 32.7% and 22.8% higher than NS, respectively. The results show that when the fiber content was 1 vol%, steel fiber and HPP fiber have similar effects on the flexural strength of concrete, due to the similar length, shape and tensile strength. Conversely, when the fiber content is 1.5 vol% and 2.0 vol%, the improvement of the flexural strength of concrete by SF is much higher than that of HPPF. Similar to the reason that appeared in the aforementioned split tensile test, this is due to the high volume fraction of HPPF cannot be evenly distributed in the concrete, The uneven dispersion of fibers in concrete leads to fiber agglomeration and increases in internal defects in the concrete, reducing the flexural strength of concrete [32].

Figure 4 shows the load-deflection curves for concrete with different fiber contents, it can be observed that as the content of SF in concrete increased, the ultimate load and the deflection corresponding to the ultimate load increased, deflection hardening can be observed as SF content of 1.5% and 2%. The curve starts to show a decreased after the load reaches its first peak, with a gentle decrease and a greater residual load for concrete with a higher SF content, as the load was transferred from the concrete matrix to the bridging fibers, all the concrete in figure 4(a) showed a obvious load increased, The results indicated that steel fibers can effectively enhance the concrete toughness and flexural properties. The load-deflection curves of HPP fibers shown in figure 4(b) were significantly different from that of steel fibers. With the increase of HPP fiber content, the ultimate load increases significantly, but the corresponding deflection was not increased. The curve decreases rapidly after the first peak, which is due to the fact that the modulus of elasticity of HPP fibers is much lower than that of steel fibers, as the load is transferred from the concrete matrix to the HPP fiber, and as the load is transferred from the concrete matrix to the HPP fibers, the load gradually increases and reaches the second peak, where the HPP fiber content is 2.0% and the second peak load is higher than the first peak. The results show that HPPFRC were more ductile and energy absorbing than SFRC.

Figure 5(a) show the failure modes of mixture ST2.0 after the flexural test, the distribution of SF in concrete were even and part of the wave-shaped steel fiber become straight, because of the elastic modulus of the steel fiber were greater than that of the HPP fiber, it contributed more effectively toward arresting the macro-cracks in concrete, steel fiber reinforced concrete shows higher flexural strength. Figure 5(b) show the failure modes of mixture HPP1.0 after the flexural test, HPP fiber had even distribution, fibers were pulled out intact without breakage. Figure 5(c) shows the clustering of HPP fibers in concrete containing 2 vol% HPP fiber, while the mechanical is mainly depended on the distribution and orientation of fibers in concrete [31]. Therefore, High volume fractions of HPPF lead to agglomeration of fibers in the concrete matrix, which increases concrete defects and reduces flexural performance.
The addition of 1% nano-SiO₂ can effectively improve the mechanical strength of concrete, among which, the compressive strength is increased by 10%, the splitting tensile strength is increased by 7%, and the flexural strength is increased by 1% at 28 days, respectively.

The compressive strength of concrete is increased by no more than 10% when the fiber content is 0.5%–2.0%. HPP fibers and steel fibers with any fiber content have no significant effect on the compressive strength of concrete.

The splitting tensile strength and flexural strength of concrete increased linearly with the increased of SF content, when the SF content was 2 vol%, the tensile strength increased by 51.4% and the flexural strength increased by 32.7%.

The splitting tensile strength and flexural strength of concrete first increases, and then decrease with the increase of HPP fiber content. HPP fiber content of 1% has the highest mechanical performance, and its tensile strength and flexural strength were increased by 34.5% and 22.8%, respectively.

HPPRC with 1 vol% HPP fiber content has similar mechanical properties as SFRC with 1% steel fiber content, while presenting higher toughness and residual strength, and can replace the steel fiber in concrete. But SFRC has better mechanical properties at fiber contents of 1.5% and 2.0.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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