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*Research Article*

# Mechanical and durability properties of self-compacting concrete with recycled concrete aggregate, silica fume and nanosilica

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***Abstract***

*The current study addresses the effect of substitution of silica fume and nanosilica on the mechanical and durability properties of self-compacting concrete containing recycled coarse aggregate (RCAs). A self-compacting concrete (SCC) was prepared by the incorporation of silica fume and nanosilica as a replacement of cement. Two series of concrete mixtures were prepared in the laboratory. In these series, RCAs with the replacement of 25%, 50%, 75%, and 100 % respectively were used with and without supplementary cementitious materials (SCMs). J-ring and Slump flow tests were conducted to investigate the fresh properties SCC. The incorporation of supplementary cementitious materials enhanced the properties of SCC and the result showed that the use of these cementitious materials can reduce water absorption and chloride diffusion up to a great extent. The mechanical and durability properties of SCC were determined by different tests like compressive strength test, water absorption test, and rapid chloride migration test. The use of cementitious materials showed a better result after 90 days of compressive strength. The test results indicate that silica fume and nano-silica were very effective and have great resistance against chloride diffusion.*

***Keywords**: Recycled concrete aggregate, Silica fume, Self-compacting concrete, Water absorption, Chloride diffusion*

## 1. Introduction

last several decades, with the advancement of new technologies the researchers have found a method to make the concrete that can be easily placed in form due to its weight is known as self-compacting concrete (Loukili, 2011). The major advantage of SCC is ease in implementation without vibration as it doesn't need any vibration during concreting (O. Kebaili*et al*, 2015).In 2017 more than 5.5 billion tons of concrete was produced which released 0.83 tons of $Co_2$ and consumed almost 5 billion tons of limestone and river sand and caused a serious environmental problem(Y.Y. Hu, 2018). This CO2 was produced as a result of concrete production and transportation which is about 10 % of manmade CO2 (K. Kuder*et al*, 2012).However, during construction and demolition, the quantity of waste has also been increased from the last two decades. In 2015, during construction and demolition, almost 3.9 billion tons of waste was produced and this creates serious environmental problems (M. H. Fu, 2016).

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However, it is possible to produce recycled aggregate concrete by using recycled aggregate which can minimize the use of natural resources, C&D waste, and can contribute to both natural resources and environmental preservations. Hence it is an efficient technique to foster the production of sustainable concrete (C. J. Shi et al, 2016).From the last two decades, a lot of experimental research work has been done on the hardened properties of recycled aggregate concrete (RCA), the structural performance of RCA elements and structures. Mostly researches showed that concrete containing RCAs can cause a high rate of water absorption, porosity, and can lower the mechanical strength. For some years several improvement techniques such as heat grinding, mechanical grinding, pre-soaking in water, and carbonation treatment were used to enhance the properties of RCAs (Wu *et al*, 2017; M. Amario*et al*, 2017). Previous researches showed that SCC can be made with RCAs by adopting the appropriate preparation methods, controlling the w/c ratio, and proper use of admixtures (I. González-Taboada*et al*, 2017). The compressive strength of SCC may be reduced because of high water absorption and porosity of RCSs which can also increase the interface transition zone. There are Three ITZ defined in recycled aggregate concrete (RAC) are transition layer between old and new mortar, transition layer between old mortar and aggregate and transition later between new mortar and recycled aggregate. In concrete, the location of ITZ is the weakest point and the possibility of increasing or decreasing the resistance depends on the recycled concrete aggregate and that concrete where those RCAs were obtained (M. Nili*et al*, 2019; C. S. Poon *et al*, 2004). Some researchers found that by increasing the quantity of RCAs in SCC it may decrease the compressive strength while some found that it has been increased because of non-hydrated cement of mortars on fine recycled aggregates (L. Evangelista *et al*, 2007). Many researchers found that adding supplementary cementitious minerals such as nanosilica, fly ash, and silica fume can modify hardened properties of concrete(S. A Santos *et al*, 2018; S. C. Kou *et al,* 2016; K. Kapoor*et al*, 2016). Silica fume has been extensively used in SCC to modify the mechanical strength of concrete, apart from its strength development SF is also an effective material to modify the durability of concrete and is more resistant to freezing and thawing and sulfate attack (M. I. Khan *et al*, 2011; D. Wang *et al*, 2017). This is because of its very fine particles that act as filler material and can enhance the hardened properties of concrete (H. Yazıcı*et al*, 2007). In 2015, Farahani that showed in seawater tidal zone that by increasing the quantity of SF and decreeing the w/c ratio can reduce the depth of chloride ions penetration into concrete as an increment of SF and control w/c has an indirect relationship with the chloride penetration of ions (A. Farahani*et al*, 2015).

With the advancement of nanotechnology, a lot of nano materials have been developed for producing high-performance concrete (HPC) (L. G. Li *et al*, 2017; H. E. D. Ahmed *et al*, 2017). Between these nano-silica is finer than all and has very high pozzolanic reactivity. Because of the quality of being finer than SF, nanosilica with its ultra-fine particles can fill even the small pores to improve the imperviousness and structural properties of concrete as the addition of NS can improve the resistance of water into concrete(T. Ji, 2005). Abd El-Aleem found that replacing 5 % silica fume with cement can improve the microstructure of the past by making it densify (S. Abd El-Aleem*et al*, 2014). In 2014, H. Du found that adding 0.3 % of NS as a replacement of cement can significantly reduce chloride diffusion (H. Du *et al*, 2014). D. Adak investigated that the addition of 6 % NS in geopolymer mortar can significantly increase the chloride resistance of concrete (D. Adak*et al*, 2014). Ghafari stated that by adding NS in HPC the rate of steel bars corrosion can be minimized up to a certain extent (E. Ghafari*et al*, 2015)

A nanomaterial can also be used with other cementitious materials such as fly ash to improve the hardened properties of concrete. In 2016, Mohsen stated that the addition of fly ash and NS 28% and 2% respectively in SCC can improve the water absorption and chloride ions penetration (E. Mohsen*et al*, 2016). In 2017, Li investigated that incorporation of NS and SF can further enhance the resistance against the chloride, water absorption, carbonation resistance, and sulfate attack (L.G. Li *et al*, 2017). In 2018, Ramezanianpour stated that adding 2 % NS and 5% SF can improve the chloride resistance in concrete to a great extent (A. A. Ramezanianpour *et al*, 2018). In 2018, Massana stated that combine the use of NS and SF in concrete can significantly modify the freeze and thaw properties of concrete (J. Massana*et al*, 2018). Thecollective use of NS and SF can modify the microstructure of the ITZ zone and minimize the porosity, however, the coupled effects of nanomaterials and supplementary cementitious material are still complicated and still needs to be an improvement (B. Zhang *et al*, 2018).

## 2. Research Objective

The major objective of this study is to determine the effect of combined usage of SF and NS on the mechanical and durability of SCC with the different replacement of RCAs. As we know the use of SCC has been an increase for some decades and also many studies have been done on the durability of SCC but very few studies have been done on the use of RCAs in SCC (K. Kapoor*et al*, 2016).A previous study demonstrated that the use of RCAs in SCC has an adverse effect on the properties of concrete while this effect can be compensated by using SF and NS. Nanosilica plays a vital role in filling the void between particles because of its ultra-fine particles (A. M. Said *et al*, 2012).Further, as we know by replacing the cement with SF and NS can also contribute to saving energy and environmental pollution. The use of RCAs can also lessen the usage of natural resources. So, the use of SF, NS, and RCAs can produce an environmentally friendly clean product.

## 3. Experimental program

The material used in this experimental work includes nanosilica, silica fume, ordinary Portland cement (OPC), water, lime powder, polycarboxylate superplasticizer to reduce water content, and to make concrete SCC.SF and NS were obtained from China while other materials were obtained from a local manufacturer company in Islamabad, Pakistan. RCAs were obtained from the waste of different demolished buildings and then crushed it in the laboratory to obtain RCAs of different sizes. Waste concrete was crushed manually by a hammer as well as by a crushing machine. Properties of cement and SF including chemical and physical are shown in table 1.

**Table 1.** Chemical and physical and of cement and silica fume

| Chemical properties | Silica fume (%) | Cement (%) |
|---|---|---|
| SiO2 | 85–95 | 21.27 |
| CaO | | 62.95 |
| Fe2O3 | 0.4–2 | 4.03 |
| Al2O3 | 0.5–1.7 | 4.95 |
| MgO | 0.1–0.9 | 1.55 |
| Na2O | 0.15–0.2 | 0.49 |
| K2O | 0.15–1.02 | 0.65 |
| SO3 | | 2.26 |
| C3A | | 6.3 |
| LOI | 3.5 | 2.11 |
| Physical properties | | |
| Specific gravity | 2.21 | 3–3.1 |
| Specific surface (cm2 /gr) | 14,000 | 2910 |
| Setting Time (min) | | Initial- 154 |
| | | Final- 195 |

## 4. Mix proportions

Coarse aggregate was replaced with a different percentage of normal coarse aggregate between 0%, 25%, 50%, 75%, and 100%. The amount of SF and NS was kept constant 8% and 1% for some cases while for some cases the amount was kept zero to know the influence of NS and SF on the characteristics of concrete. Before using RCAs, they were kept in water to isolate impurities to get a better quality of RCAs. During wetting, the amount of water absorbed by RCAs was calculated and also added to the mixing table. In all the cases the quantity of cement was kept 420 kg/m3 while the w/c ratio was kept 0.41. Two cases A, A1 was prepared with normal coarse aggregate as a reference concrete to compare the result with other cases containing RCAs. As shown in Table 2, in the first series no cementitious material was used while in series two the cementitious material was used to check different properties of SCC. J-ring test result showed that height was reduced from 10mm to 2 mm by incorporation SF and NS in concrete as shown in Table 3.

**Table 2.** Mixtures Proportions

| Mix Series | Mix Code | W/b | W(kg/m3) | Cement | SF | NS | CNA | FNA. | CRA. | LP | SP (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| References | A | 0.41 | 175 | 420 | 00 | 00 | 526.2 | 1032.5 | 00 | 172 | 1.00 |
| | A1 | 0.41 | 175 | 382.2 | 33.6 | 4.2 | 526.2 | 1032.5 | 00 | 172 | 1.02 |
| Series 1 | B25 | 0.41 | 175 | 420 | 00 | 00 | 401.4 | 1032.5 | 119.5 | 172 | 1.07 |
| | B50 | 0.41 | 175 | 420 | 00 | 00 | 263.1 | 1032.5 | 239.1 | 172 | 1.10 |
| | B75 | 0.41 | 175 | 420 | 00 | 00 | 131.6 | 1032.5 | 358.7 | 172 | 1.05 |
| | B100 | 0.41 | 175 | 420 | 00 | 00 | 00 | 1032.5 | 478.2 | 172 | 1.01 |
| Series 2 | C25 | 0.41 | 175 | 382.2 | 33.6 | 4.2 | 401.4 | 1032.5 | 119.5 | 172 | 1.02 |
| | C50 | 0.41 | 175 | 382.2 | 33.6 | 4.2 | 263.1 | 1032.5 | 239.1 | 172 | 1.10 |
| | C75 | 0.41 | 175 | 382.2 | 33.6 | 4.2 | 131.6 | 1032.5 | 358.7 | 172 | 1.10 |
| | C100 | 0.41 | 175 | 382.2 | 33.6 | 4.2 | 00 | 1032.5 | 478.2 | 172 | 1.00 |

**Table 3.** Properties of fresh SCC mixes

| Mix Series | Mix Code | Slump flow (mm) | T50 (s) | T final (s) | J-ring (mm) | J-ring | SP (%) |
|---|---|---|---|---|---|---|---|
| References | A | 600 | 4.4 | 30 | 590 | 9 | 1.00 |
| | A1 | 600 | 5.0 | 30 | 585 | 2 | 1.10 |
| Series 1 | B25 | 575 | 4.6 | 31 | 560 | 4 | 1.06 |
| | B50 | 590 | 5.0 | 28 | 585 | 6 | 1.10 |
| | B75 | 685 | 4.7 | 32 | 630 | 6 | 1.05 |
| | B100 | 610 | 5.0 | 21 | 570 | 5 | 1.10 |
| Series 2 | C25 | 630 | 5.1 | 29 | 590 | 3 | 1.10 |
| | C50 | 615 | 4.2 | 30 | 600 | 3 | 1.09 |
| | C75 | 610 | 3.3 | 28 | 600 | 4 | 1.00 |
| | C100 | 615 | 5.0 | 23 | 600 | 2 | 1.00 |

## 5. Casting, curing, and testing

The rotary drum mixture was used to mix all the proportions of concrete. First RCAs, sand, binder, and cementitious materials were added and were dried mix for two minutes and then 90 % water was added and then mix for 2 minutes, at the last 10 % remaining water was mixed with superplasticizer and then added into the mixture until 3 minutes more to make concrete homogeneous. After casting the specimens were kept in water for 90 days and a compressive strength test was conducted on 100mm cubes according to ASTM C39 after 28 and 90 days respectively. According to BS 1881 Part122the water absorption test was performed on 75x75mm cylindrical specimens. To check the chloride diffusion rate on a 100x50 mm specimen cylinder the rapid chloride migration test was performed according to ASTM C1202and the influence of NS and SF on the behavior of concrete was recorded.

## 6. Results and discussions

To evaluate the hardened properties of concrete including compressive strength test, water absorption, and rapid chloride migration test was conducted and the influence of SF, NS, and recycled coarse aggregate was calculated. In particular, the combination of cementitious materials and RCAs replacement level was checked in details.

### Compressive strength

The compressive strength test results are shown in figure 1 after 28 and 90 days and are the average value of three specimens. Fig. 1(a) shows that by increasing the replacement level of RCAs the value of compressive strength decreased. A comparison mixture containing cementitious materials and without cementitious materials was made. In fig. 1(b) at the age of 28 days the result shows that there was a reduction in compressive strength 15%, 17%, 14%, and 25% respectively in the mixes in which SF and NS were used with RCAs as compared to the first series. Some researchers showed that reduction in strength at early ages is possible due to SF and NS when used with RCAs but the effect of SF and NS was observed later and they gave better results after 90 days (D. Pedro *at el*, 2017; Ö. Çakır*et al*, 2015). In the first series when the RCAs were increased from 25% to up to 100% the reduction in compressive strength was 31%, 36%, 39%, and 41% respectively at the age of 90 as shown in Fig. 1(a). With the replacement of RCAs, it was found that as the amount of RCAs was increased the value of compressive strength was decreased it is due to weak ITZ between RCAs and mortar and also the formation of cracks in aggregate and also high porosity also affect (M.D. Safiuddin*et al*, 2011). In other words, we can say that by increasing the value of recycled coarse aggregate, the number of boundary layers was also increased and caused a reduction in compressive strength. However, the incorporation of SF in the second series increased the compressive strength slightly more as compared to the first series after 90 days as shown in Fig. 1(b).By the incorporation of RCA's the microstructure of concrete was changed as compared to normal aggregate concrete. The addition of RCAs, the number of boundary layers was increased which causeda reduction in compressive strength (F. Aslani*et al*, 2018).

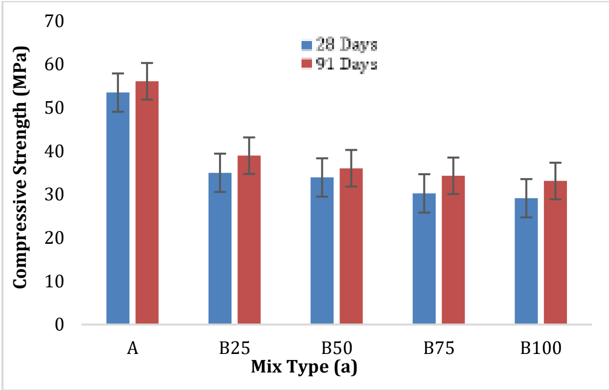


**Figure 1**(a). Effect of RCAs on compressive strength

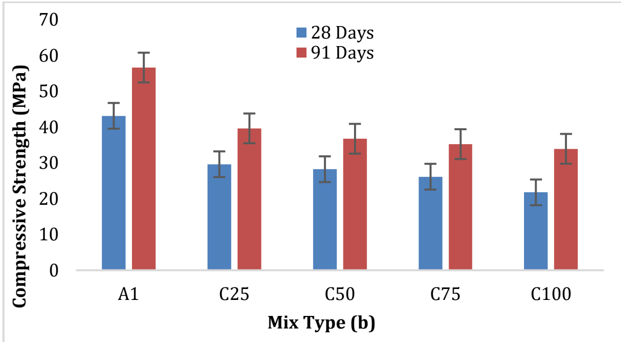


**Figure 1(b).** Effect of RCAs, SF, and NS on compressive strength

### Water absorption

Water absorption test results are shown in Fig. 2that by increasing the value of RCAs from 25%, 50%, 75%, and 100% the rate of water absorption was increased by 2%,11%, 38%, and 40% respectively as compared to reference concrete A. The rate of water absorption increased because the structure of RCAs is porous and it can cause a high amount of water absorption (A.G. Khoshkenari*at et al*, 2014; P.O. Modani*at et al*, 2014). While those cases in which cementitious materials were added the rate of water absorption was decreased. The result shows in Fig.2that reference concrete A1 in which cementitious materials were added they showed almost 40% water absorption reduction as compared to reference concrete A also in the cases containing RCA's the cementitious materials reduced water absorption. While all the other cases in which cementitious material was used with RCAs, they showed 20%, 18%, 36%, and 34% respectively less water reduction as compared to the first series as shown in Fig. 2.

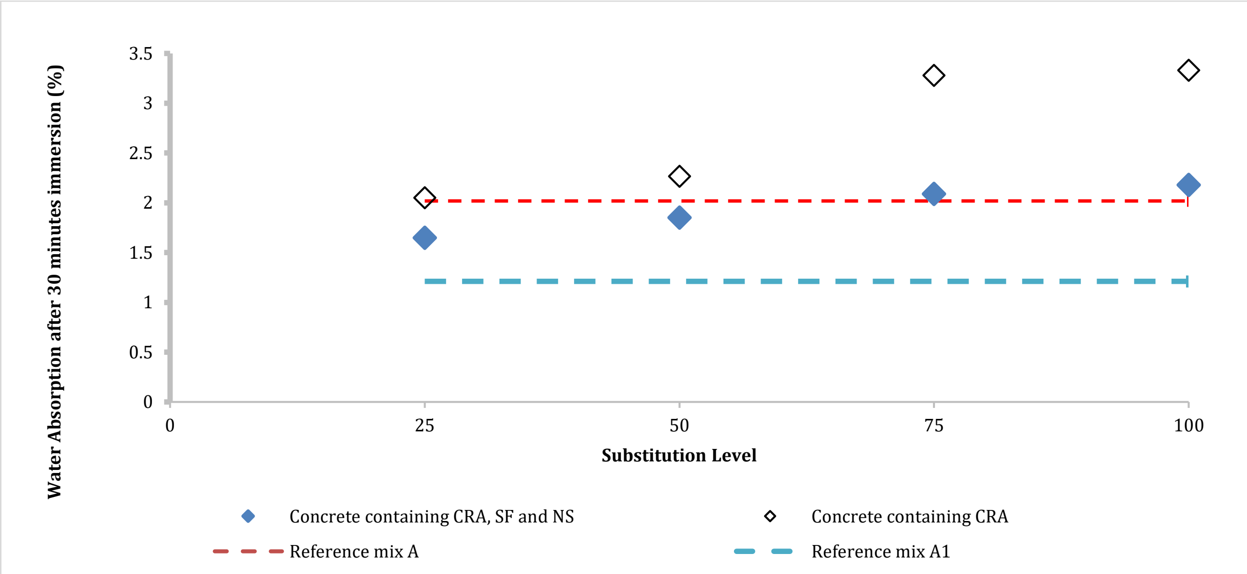


**Figure 2.** Effect of RCAs, SF, and NS on water absorption

## Rapid Chloride Migration Test

Rapid chloride migration test was conducted after 28 days of curing according to ASTM C1202. By substituting the RCAs in the first series the rate of chloride diffusion was also increased as shown in Fig. 3(a).

This increment in the rate of chloride diffusion with the substitution of 25%, 50%, 75% and 100% of RCAs was recorded 12%, 15%, 19%, and 20%, respectively as compared to reference concrete A. The increment in chloride diffusion rate was due to porous structure of concrete that contains RCAs. As stated, that as the value of porosity increased in concrete the value of chloride penetration is also increased (K. Kapoor et al, 2016). But by the addition of cementitious materials, chloride penetration resistance was increased and the diffusion rate was decreased significantly. Comparison of the reference concrete A1 shows that by adding the SF and NS the diffusion rate was reduced up to32 % as compared to reference concrete A. Fig. 3(b) showed that with the addition of cementitious materials, the surface under the curve is less than that of series 1. By adding SF and NS in the second series having RCAs from 25%, 50%, 75%, and 100%, the rate of chloride diffusion was reduced from 37%, 30, 23%, and 20% respectively as compared to the first series. Result also shows that as the value of RCAs was increased, the value of chloride diffusion was also increased. However, by replacing 8 % SF and 1% NS in the concrete containing 25 % RCAs has a very positive effect on increasing the chloride resistance. However, by comparing the results it can be easily seen that adding SF and NS has a very positive effect on reducing and controlling the chloride ions penetrations into the concrete. This is because the addition of SF and NS improves the bond between aggregate and mortar by making it denser and hence diffusion rate was decreased (M.Mastali*et al*, 2016).

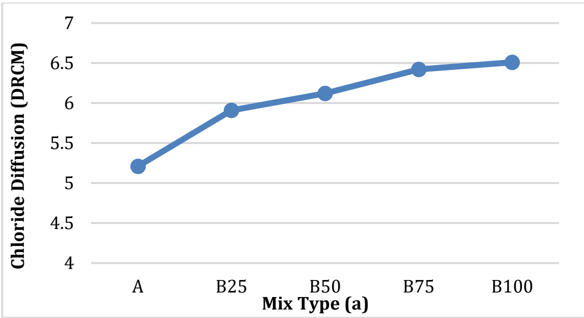


**Figure 3(a).** Effect of RCAs on chloride diffusion

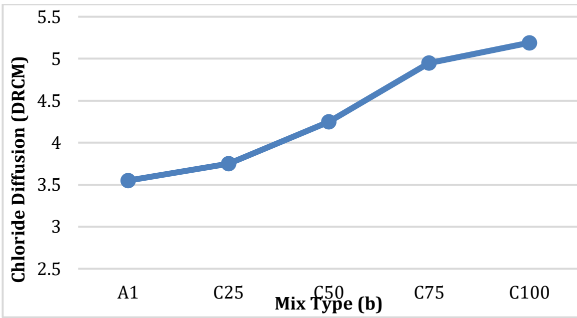


**Figure 3(b).** Combined effect of RCAs, SF, and NS on chloride diffusion

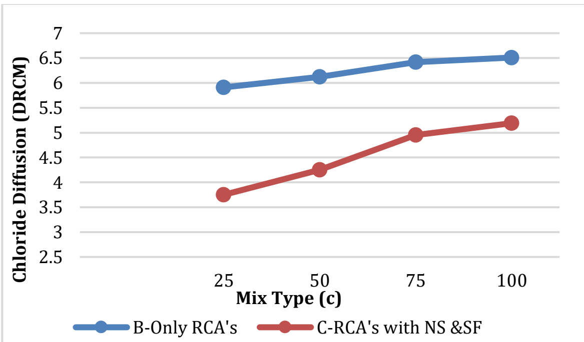


**Figure 3(c).** Chloride diffusion rate between modified and unmodified SCC

## Conclusions

From the results, it can be concluded that the addition of supplementary cementitious materials increased the workability and improved the fresh properties of SCC. Hence it is possible to make the concrete SCC by using RCAs. Due to high water absorption and porosity in the recycled aggregate, the incorporation of RCAs decreased the compressive strength. However, the use of cementitious materials decreased the compressive strength after 28 days but it shows improvement in mechanical strength after 90 days. The substitution of RCAs increased the water absorption rate. However, the addition of cementitious material decreased the water absorption rate up to a great extent. RCAs caused an increase in chloride diffusion rate and also reduced the resistance to chloride penetration in concrete. While the addition of cementitious materials decreased the chloride diffusion as the diffusion rate was significantly reduced and it shows very good results against chloride penetration. This is due to the improvement in the porosity of RCAs. The incorporation of cementitious materials controls the movement of chloride ions and thus in this way it showed great resistance against chloride ions diffusion into the concrete.

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