Potential use of spherical glass sourced from cathode ray tube funnel glass for the application as coarse aggregate in concrete

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Managing discarded waste cathode ray tube (CRT) funnels glass has become a major concern worldwide because it has toxic effects on the environment and human health if the hazardous lead leached to the surroundings. The common way of recycling this waste is by crushing it, where it was used as an alternative fine aggregate for concrete production. But the crushing technique has led to the formation of micro-cracks in the funnel glass products, causing to high lead leaching rate. On the other hand, recycling the CRT funnel glass waste through melting and annealing operations in producing the spherical CRT glass (GS) has proven will not danger the environment due to the leaching of lead. Therefore, this paper explored the feasibility of using GS as partial (20%, 50%) and full replacements (100%) of natural coarse aggregates in concrete. The workability, density, compressive strength, and splitting tensile strength were investigated. Given the importance of materials and exposure, the influence of silica fume content and CRT concrete strength subjected to high temperature were evaluated. Overall, the inclusion of GS increased the workability and decreased the density, but reduced the compressive and tensile strength. The use of GS as coarse aggregates should be limited to below 50% due to its negative impacts on the strength aspects have become obvious. However, the results show that the CRT concrete made with 20% GS and 10% silica fume have comparable properties with the control, 52 MPa where only 7% lower than control concrete. The addition of silica fume able to counteract the negative effect of GS.

Keywords: Waste glass, cathode ray tube, lead, concrete, strength

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1. Introduction

Given the advance of electrical and electronic technology that causes an increasing amount of CRT waste, using CRT waste glass especially funnel components as coarse aggregates may be of great importance in environmental terms. Waste CRT glass is classified as hazardous solid waste because it contains a high concentration of lead oxide (PbO), where the funnel components contain approximately 25% PbO. The leaching of PbO can seriously dangers human health and pollute the environment [1, 2]. Past studies [3, 4] reported that in 2014, the production of CRT waste globally reached 6.3 million tons per annum.

Various methods have been proposed for the recycling of CRT waste glass. Using waste materials in concrete production has been a common approach nowadays to achieve sustainable development, but only if it does not negatively impact the concrete properties. Considering that coarse aggregates occupy almost 40% of concrete, replacing CRT waste glass with them could be a fulfilling choice. The common way of recycling CRT funnel glass is by crushing the glass to a size less than 4.75 mm and use as fine aggregates in concrete production.

However, the crushing method cause formation of micro-cracking within the glass that results in a high lead (Pb) leaching rate [2, 5, 6]. The leaching of hazardous Pb will affect the environment such as acidification, reduce abiotic resources, and eutrophication. Besides that, the exposure to the toxic Pb will cause miscarriage, damage the brains, kidneys, and nervous system. Liu et al. [7] found that the Pb leaching values of mortar specimens containing crushed CRT glass as fine aggregate (size $<$ 5 mm) are significantly higher than the allowable limit (5 mg/L). The Pb leaching rate of CRT concrete increases with the increased content of crushed CRT glass. However, they also discover that the addition of fly ash and soaked the crushed CRT glass with 5% dilute nitric acid could significantly reduce the Pb leaching rate and be below the allowable limit.

Concerning the high Pb leaching rate of crushed CRT glass aggregate, the author's earlier work [8] discovered that by using a new recycling method that is melting and annealing techniques in recycling CRT funnel glass waste to formed spherical CRT glass (GS) has significantly reduced the Pb leaching rate. The annealing process has pointedly reduced the internal pressure, which then strengthens the final product and obtains a high strength aggregate. The results of the toxicity characteristics leaching procedure (TCLP) test show that the leaching rate of Pb from GS and concrete specimens containing 100% GS as coarse aggregates were below the allowable limit (5 mg/L), as they were only at 0.30 mg/L and 0.516 mg/L, respectively [8].

However, research on the effects of using GS as aggregates to concrete performances has not been extensively studied. The use of different recycling techniques of CRT glass causes the glass to have its own physical, mechanical and chemical properties, which differ from the crushed CRT glass and natural aggregates, where it will surely affect concrete properties when it is use as an alternative replacement of the natural aggregates. Other than that, in order to use the GS as coarse aggregates effectively, it is necessary to develop a stronger cement matrix to obtain high-quality concrete.

The silica fume (SF) was commonly used to enhance the bond between the materials and it acts as a void filler in the concrete mixtures [9–11]. Commonly, the used of SF is limited to 10% replacement because of the higher content of SF could significantly reduce the workability and concrete strength. Meanwhile, past studies [12, 13] reported that the use of SP dosage should be limited to 2.4% of the cementitious content due to the excessive dosage of SP would increase the content of entrapped air, which then reduces the strength of concrete. Therefore, to fill this gap in the literature, this study used GS to substitute natural coarse aggregates at various percentage replacement.

In this study, CRT concrete was produced by replacing natural granite with 20%, 50%, and 100% of GS to investigate the effect of replacement levels on workability, hardened density, compressive strength, and splitting tensile strength of concrete. The influence of silica fume and CRT concrete strength subjected to high temperatures were also analysed. This study mainly aims to reduce the CRT glass wastes' quantity in the environment and propose alternative construction materials.

2. Methodology

In order to investigate the effectiveness of recycling the spherical CRT glass as a replacement of natural coarse aggregates, experimental work was conducted. Different amounts of GS were added in concrete specimens by fully or partially substituting natural coarse aggregates and properties were assessed.

2.1. Materials and mix proportions

In this study, Ordinary Portland cement (OPC) of ASTM type-I with a 42.5 grade was used as the primary binder. Silica fume (SF) with a density of 2.2 was added as supplementary cementitious materials to replace 10% of the cement. In addition, polycarboxylate ether superplasticizer (SP) was added to enhance the workability of CRT fresh concrete, at a dosage rate of 2%. River sand with specific gravity 2.67 was used as fine aggregates and obtained locally. Meanwhile, the coarse aggregates that were used in this study are divided into two types, i.e. granite (natural coarse aggregate) was used for control specimens, and GS (CRT funnel glass) was used for CRT concrete specimens. Fig. 1 shows the coarse aggregates used in this study.

The GS was produced by Nippon Electric Glass (NEG) Malaysia from the discarded waste CRT glass. NEG has processed the funnel component of waste CRT glass to form spherical glass (GS), which was made through melting, annealing, and cooling process [14]. By using the laser cutting method, the funnel component of CRT glass is extracted and it was melted at temperature 1300°C for 16 hours using the melting furnace machine. After that, the molten glass was poured into a marble mold and subjected to annealing and cooling process. GS is in the form of spherical shape with size fixed 19 mm. Besides that, GS has lower value of specific gravity (2.43), unit weight (1409.25 kg/m^3), and percentage absorption (0.03%) compared to granite at 2.64, 1619.65 kg/m^3, and 0.23%, respectively [14].

The purpose of this study is to experimentally investigate the effects of using GS as a full or partial replacement of natural coarse aggregates, and the influence of silica fume to the performances of CRT glass concrete. Table 1 shows the mix proportions of concrete specimens. The concrete mix proportion are designed closely followed the ACI 211.1 guidelines [15]. The difference in the mixture compositions were the quantities of GS, NCA, sand, cement, and silica fume. Meanwhile, other constituents contain the same quantities, with water/cement ratio and/or water/binder ratio is 0.31. The mixtures are referred to as control-1 and control-2 which are the conventional concrete mixtures without any recycled CRT glass (i.e. GS) for comparison purposes.

On the other hand, specimens GS0.2, GS0.5, and GS1.0 indicated ratios of coarse aggregates are 0.2GS:0.8Granite, 0.5GS:0.5Granite, and 1.0GS:0Granite, respectively, which it is also similar to specimens GS0.2-SF, GS0.5-SF, and GS1.0-SF. The only difference that the specimens GS0.2-SF, GS0.5-SF, and GS1.0-SF contained with SF. To better characterize the size distribution of the coarse aggregates in concrete specimens, the grading curves are shown in Fig. 2. The curve clearly indicates that only the grading of coarse aggregates in control specimens are within the upper and lower limit of BS 882:1992 [16]. Meanwhile, both specimens GS0.2 and GS0.5 have larger sizes that exceed the lower limit. Eight batches of concrete were mixed separately. After casting, all specimens were cured for 7 and 28 days in water.

2.2. Experimental methods

The experimental study included the slump test [17], density test [18], compressive strength [19], and splitting tensile strength [20] tests at room temperature. A total of ninety-six (96) specimens were cast, cured, and tested to determine the workability and mechanical strength of CRT concrete. Two types of molds of a cube size 150 mm and cylinder at diameter of 100 mm and height of 200 mm were cast in this study. In addition, high-temperature exposure of CRT concrete specimens was also carried out to investigate the durability properties.

It was performed using an electric furnace at the Laboratory of Material and Structures, National University Malaysia. The specimens were heated at 200°C, 400°C, 600°C, and 1000°C, where after reached the temperature, it was maintained for 2 hours to ensure that the specimens were heated evenly and achieved a thermally stable state. The heating rate was set at 9°C/ min according to ASTM E119 [21]. After that, the temperature of the specimens was slowly cool down to room temperature. The strength of 96 concrete specimens that heat-exposed was tested to determine the effects of high temperature on the compressive strength of CRT concrete. For each temperature, 3 specimens were tested and the average of the three results was recorded.

3. Results and discussion

3.1. Workability

Fig. 3 shows the workability of concrete with GS and without GS. Control-1 exhibited a slump of 72 mm whereas concrete with 20% GS, 50% GS, and 100% GS had a slump value of 75 mm, 78.9 mm, and 87.5 mm, respectively. The slightly increased slump value was shown in mixtures containing 20% GS as coarse aggregates. However, by replacing completely the use of natural coarse aggregate by GS has significantly increased the slump value by 21.5%. The increasing trend can be due to the smooth surface and nearly zero water absorption of GS compared to granite used as coarse aggregates in the study. A similar increase pattern was observed by Zhao and Poon [2] and Hui et al. [22] and Tian et al. [23] on the workability of CRT mortar.

They reported that due to the nature of glass with smooth surface texture and impermeable have increased the slump value of mortar when the crushed CRT glass partially replaced the natural sand as fine aggregates. Figure 3 also indicated the influence of SF on the workability of concrete. The concrete mixtures containing 10% SF showed even lesser slump values, where Control -2, GS0.2-SF, GS0.5-SF, and GS1.0-SF had a slump value of 69 mm, 74.5 mm, 76.8 mm, and 83.5 mm. The finer particle size of SF caused the increased amount of water needed for the mixtures to obtain a higher slump value.

However, from observations, the use of SF may reduce the risk of material segregation of CRT concrete mixtures. It is because of the bigger sizes and smooth surface texture of GS resulting in the weaker cohesion between the GS and the cement paste. This was in agreement with the book of Neville [24]. In addition, all the CRT mixtures were in the range of a targeted slump of 70 -80 mm, except for mixtures whose volume replacement of GS is 100% (GS1.0 and GS1.0-SF).

3.2. Density

Table 2 indicates the hardened density of CRT concrete specimens. Control -1 and Control-2 concrete showed 2396 kg/m^3 and 2410 kg/m^3 density, whereas the density of CRT concrete specimens was in the range of 2390 kg/m^3 to 2285 kg/m^3. The density of concrete decreased significantly with an increase in the quantity of GS as coarse aggregates, which is up to 4.7% reduction with the use of 100% GS as coarse aggregates. This decreasing trend was attributed to the lower specific gravity of GS compared to granite [2]. GS had a specific gravity of 2.43 and 7.9% lowered than granite at 2.64. The hardened density of concrete

Fig. 1. Coarse aggregates used in this study

Table 1. Material proportions of concrete specimens

Mix	Cement	SF	Coarse aggregates (kg/m^3)		Sand	Water	SP
notations	(kg/m^3)	(kg/m^3)	NCA	GS	(kg/m^3)	(kg/m^3)	(kg/m^3)
Control-1	545.8	0	1049.5	0	642.9	169.2	10.9
GS0.2	545.8	0	839.6	182.6	654.5	169.2	10.9
GS0.5	545.8	0	524.8	456.6	672.0	169.2	10.9
GS1.0	545.8	0	0	913.2	701.1	169.2	10.9
Control-2	491.2	54.6	1049.5	0	622.8	169.2	10.9
GS0.2-SF	491.2	54.6	839.6	182.6	634.5	169.2	10.9
GS0.5-SF	491.2	54.6	524.8	456.6	651.9	169.2	10.9
GS1.0-SF	491.2	54.6	0	913.2	681.1	169.2	10.9

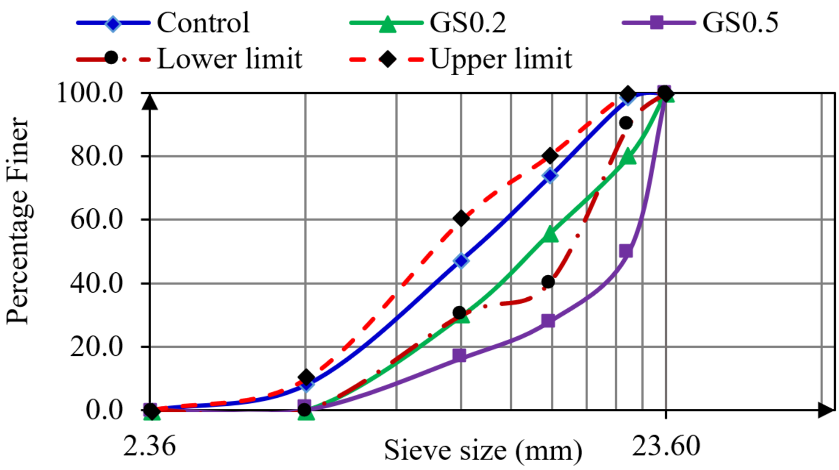


Fig. 2. Size distribution of coarse aggregates

Table 2. Hardened density of CRT concrete

Specimen	Average hardened density (kg/m^3)	Percentage difference
Control-1	2396	0
GS0.2	2350	1.94
GS0.5	2310	3.65
GS1.0	2285	4.74
Control-2	2410	0
GS0.2-SF	2390	0.83
GS0.5-SF	2381	1.21
GS1.0-SF	2366	1.84

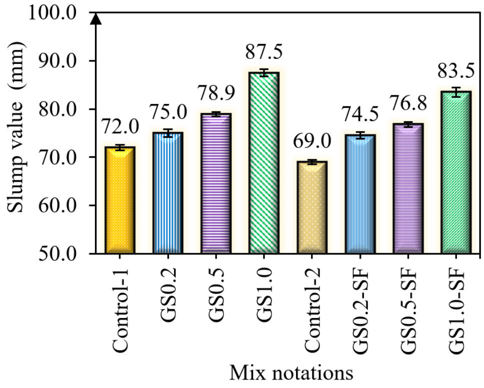


Fig. 3. Slump values of CRT concrete mixtures

specimens was measured at 7 and 28 days. Table 2 also shows that the addition of SF has increased significantly the density of concrete specimens, up to 3.5%. Blending SF with concrete mixtures containing GS has increased the density because of the finer particles of SF results in good packing density [7].

3.3. Compressive strength

The compressive strength results of the CRT concrete with different replacement levels of GS and content of SF under different curing ages (7, 28, 56 days) are shown in Fig. 4. Each value given in the figure is the average of all three specimens. Fig. 4. shows that the development of compressive strength mainly depends on the curing age and addition of SF. The compressive strength of CRT concrete increases with the addition of SF concrete, up to 40%.

The use of SF not only leads to a reduction in cement quantity in CRT concrete production but also increase significantly the compressive strength. The enhancement of concrete compressive strength is mainly because of the pozzolanic and filler effect of SF [25, 26]. However, the strength values of CRT concrete are lower than control concrete at all curing ages. The compressive strength of CRT concrete with no SF at 28 days of GS0.2, GS0.5, and GS1.0 is approximately 9%, 17%, and 24% lower than that of the Control-1 specimens. The highest compressive strength of CRT concrete with no addition of SF is 38.7 MPa, which is exhibited by GS0.2 specimens. On the other hand, the compressive strength of CRT concrete specimens with 10% SF at 28 days of GS0.2-SF, GS0.5-SF, and GS1.0-SF are around 7%, 14%, and 18% lower than that of the Control-2 specimens.

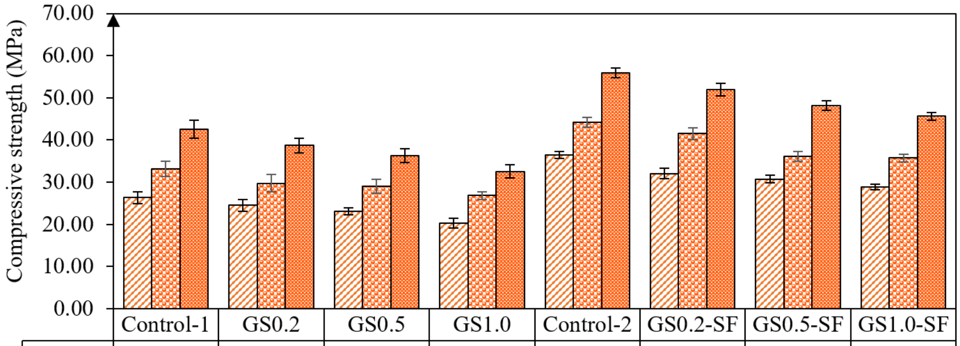
The decreasing trend in the compressive strength of CRT concrete with increasing percentage replacement is mainly attributed to the smooth surface texture and spherical shape of GS as coarse aggregates, which weaken the bonding between coarse aggregates and cement paste. Thus, the high content of GS as coarse aggregates has increased the point of weakness and failure of CRT concrete. This behavior is similar to the findings from past studies [2, 27–29],that used crushed glass as aggregates, where they reported that the smooth surface texture of the glass is the main reasons that cause concrete strength decreases.

As shown in Fig. 4, the compressive strength tends to decrease significantly when the GS content exceeds 20%, and the maximum strength is 52 MP$_a$ by GS0.2-SF specimens. Hence, the compressive strength of CRT concrete with the percentage replacement of GS 20% and SF 10% has able to lower the gap of strength differences, at only 7% lower than the control concrete (56 MP$_a$). This study has shown that by adding 10% of silica fume and limit the GS content to only 20%, the CRT concrete will develop strength sufficient and comparable to the conventional concrete.

3.3.1. Compressive strength after exposure to high temperature

The compressive strength of CRT concrete specimens after was subjected to high temperatures ranging from ambient temperature to 800°C at an exposure time of 2 hours is shown in Fig. 5 As expected, the compressive strength of CRT concrete specimens decreased with an increase in temperature, which is up to 82%. The reduction of compressive strength is due to the disintegration of C-S-H gel and decomposition of calcium hydroxide (CH) that results in bonding strength between the GS and cement paste decreases [30, 31].

In addition, control specimens show a lesser loss in strength at only 69%, compared to CRT specimens. This behavior is similar to the past studies where the free water retained in the mixture containing GS as coarse aggregates are more readily dissipate at high temperatures. It is because of the impermeable nature of the glass, as GS has nearly zero water absorption rate at 0.03% [32]. However, it also can be seen in Fig. 5 that for GS0.2-SF, GS0.5-SF, and GS1.0-SF specimens, the compressive strength increases when the specimens heated to 200°C and 400°C, up to 12%.



	Control-1	GS0.2	GS0.5	GS1.0	Control-2	GS0.2-SF	GS0.5-SF	GS1.0-SF
7 day	26.35	24.53	23.12	20.28	36.44	32.05	30.72	28.88
14 day	33.10	29.75	29.04	26.81	44.19	41.55	36.10	35.74
28 day	42.54	38.70	36.29	32.51	55.94	52.00	48.17	45.66

Mix notations

Fig. 4. Compressive strength of CRT concrete

The increase in strength is might due to the progression of cement paste hydration because of the loss of moisture [33].

3.4. Splitting tensile strength

Fig. 6 indicates the splitting tensile strength of CRT concrete with various replacement ratios of GS as coarse aggregates (20%,50%, and 100%) at 7, 14, and 28 days. The splitting tensile strength increases with the increase of curing ages. However, the concrete splitting tensile strength decreased significantly with an increase in the quantity of GS as coarse aggregates, up to 45% lower than control specimens. Reduction in splitting tensile strength of CRT concrete with full replacement of GS (100%) shows the lowest strength at only 1.85 MP_a, which is exhibited by GS1.0 specimens.

Similar to the compressive strength, the incorporation of smooth surface texture of GS as coarse aggregates has decreased the concrete splitting tensile strength [2, 29]. But, as shown in figure 6, it can be clearly seen that the splitting tensile strength of CRT concrete increases with the addition of SF. Specimens GS0.2-SF shows the highest splitting tensile strength at 3.35 MP_a, where it only 19% lower than control concrete specimens. The 10% content of SF has enhanced the compactness and bonding between GS and cement paste, which enhanced the splitting tensile strength of CRT concrete.

4. Conclusions

In this study, the effect of recycling waste CRT funnel glass as coarse aggregates on the properties of concrete was investigated. To this purpose, CRT funnel glass waste was processed to produce GS and replaced granite at 20%, 50%, and 100%. In addition, the influence of SF on the CRT concrete performances was evaluated. Although the hardened density was reduced successively with the increase in GS content, the increase of workability was noticed in the mixtures with a high content of GS.

The incorporation of GS had a significant impact on concrete strength, mainly due to the spherical shape and smooth texture of the GS. The use of GS as an alternative replacement of natural coarse aggregates was proven to decrease the concrete strength, i.e. compressive and splitting tensile, up to 45% lowered than conventional concrete. Other than that, with an increase in replacement rate, compressive strength and splitting tensile strength of concrete can reduce, and measures need to be taken to improve the strength by the addition of SF.

The addition of SF in CRT concrete can significantly enhance CRT concrete performances. This study also found that when the CRT concrete is subjected to high temperatures up to 400°C, the compressive strength can be increased by up to 12%. The optimum content of GS as coarse aggregates has determined to be 20% of coarse aggregates weight.

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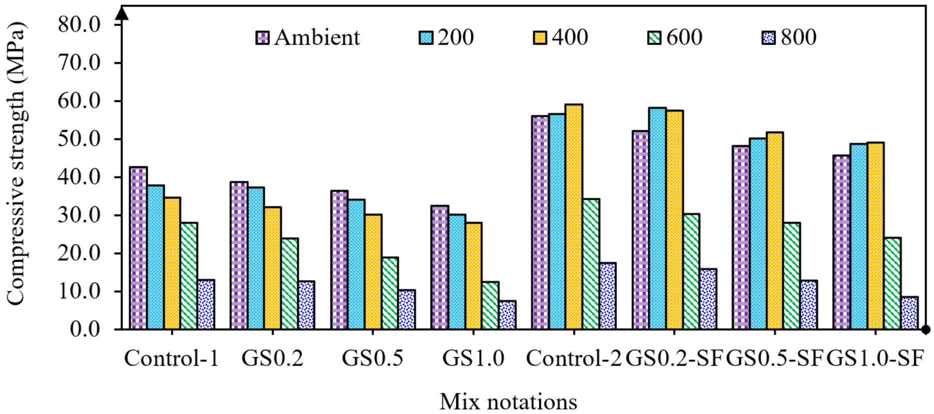
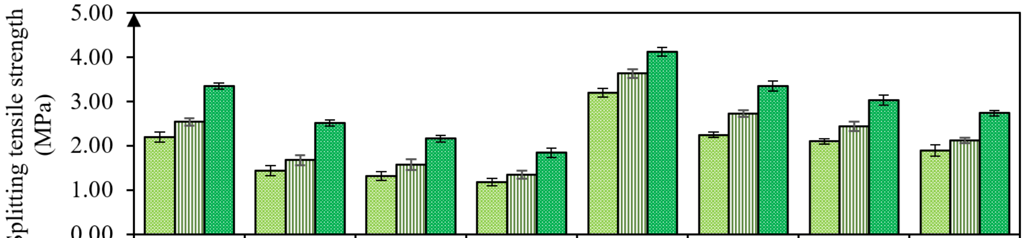


Fig. 5. Compressive strength of CRT concrete after exposure to high temperatures



	Control-1	GS0.2	GS0.5	GS1.0	Control-2	GS0.2-SF	GS0.5-SF	GS1.0-SF
7 day	2.20	1.44	1.32	1.18	3.20	2.25	2.10	1.90
14 day	2.54	1.68	1.57	1.35	3.64	2.73	2.44	2.12
28 day	3.36	2.52	2.16	1.85	4.12	3.35	3.03	2.74

Mix notations

Fig. 6. Splitting tensile strength of CRT concrete

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