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Environmental Considerations of Recycled Concrete Aggregates (RCA) for Improved Sustainability of Reinforced Concrete Building Structures

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ABSTRACT

While concrete is one of the most versatile building materials on earth and has facilitated industrial growth in the last century, it is also one of the biggest in terms of environmental impact. Much of the research to date and the state-of-practice pertaining to sustainable use of structural concrete focuses on the partial replacement of cement with industrial by-products. In comparison, conservation of coarse aggregates has been largely ignored in the U.S. even though coarse aggregates make up 40 to 50% of the concrete mix by volume while cement takes only about 10%. The production of natural crushed stone, sand, and gravel in the U.S. accounts for more than half of all mining and more than twice the amount of coal produced. The mining, processing, and transport operations for such large quantities of aggregate consume large amounts of energy and adversely affect the ecology of forested areas and riverbeds. By recycling old concrete as partial or full replacement for natural coarse aggregates in concrete for new construction, it is possible to substantially improve the sustainability of reinforced concrete structures. The current paper presents a study that compares several key variables in natural aggregate and recycled concrete aggregate (RCA) production: production facility land use, water use, transportation distances and energy demand, and overall greenhouse gas emissions. The data used in comparison includes sources from satellite imagery comparisons and data collected in field studies at RCA production facilities.

INTRODUCTION

Concrete has countless application when it comes to using it as a building material, but it also has many negative impacts on the environment. Much of the research to date and the state-of-practice pertaining to sustainable use of structural concrete focuses on the partial replacement of cement with industrial by-products. With infrastructure in the U.S. aging, the need to either repair or completely rebuild concrete structures is inevitable. Urban areas are saturated by buildings and roads that have at least some component of concrete in them, and with coarse aggregates taking about 40 to 50% of a concrete mix by volume. It is only practical to consider ways to recycle the material as opposed to having its end use be occupying landfill space. Construction projects use about 3 billion tons/year of natural aggregates in the U.S. alone (Meininger and Stokowski 2011). To produce this quantity of material, large amounts of energy must be consumed, and the ecology of forested areas and riverbeds are adversely affected. Additionally, mining areas close to or around urban areas have had their reserves rapidly depleted, resulting in the need to transport aggregates over longer distances (Stanczak 2007; Kohler 2006). To improve the sustainability of concrete structures, crushing concrete and using it to partially or fully replace coarse aggregate could have a profound effect on the aggregate market by providing an alternative to conventional natural aggregate. The current paper presents a study that compares several key variables in natural aggregate and recycled concrete aggregate (RCA) production: production facility land use, water use, transportation distances and energy demand, and overall greenhouse gas emissions. The data used in the comparison includes sources such as satellite imagery and data collected in field studies at RCA production facilities. The result is an environmental footprint of RCA facilities that illuminates the sustainability benefits of increased RCA use. The following are specific objectives of the paper:

1. Quantify land use of RCA plants and compare it with natural aggregate producers
2. Water use of RCA vs. Natural Aggregate producers
3. Characterize transport distances associated with each type of facility and the CO2 production due to these distances

The paper is organized as follows: first, using the measured land areas and their associated production values, the area of land it takes to produce one ton of aggregate is evaluated. Then, the respective water consumption for RCA and natural aggregate plants is estimated and compared to production values in order to quantify the amount of water used to produce one ton of aggregate. Finally, transportation distances are presented for arrival and departures for both RCA and natural aggregate producers, while taking into account the type of vehicle and fuel economy to ultimately estimate the CO2 emissions and energy consumption.

DATA COLLECTION

In order to evaluate the practicality of utilizing concrete aggregates on a larger scale, the interworking of RCA production, transportation and use must be quantified and compared to similar measures for NA to definitively say if there are actual environmental benefits associated with RCA. To accomplish this, two recycled concrete aggregate plants were visited on three separate occasions to collect data that would assist in estimating water consumption, transportation characteristics of RCA plants, and material production. Additionally, surveys inquiring about this information were sent to RCA producers, and used as part of the RCA data set. For natural aggregate producers, a company which appears on USGS's top 100 aggregate producers list provided data sheets with transportation and production information. Data to estimate water consumption for natural aggregate producers was taken from USGS publications, as well as their mineral yearbooks. Finally, emission factors for fuel consumption were collected from the EPA's website. Thus, the current paper represents a synthesis of many different data sources to develop a picture of RCA vs. NA use.

LAND USE

The first step in the process was to identify three natural aggregate mine sites and identify an annual production at each site. Once this was complete, a location of each quarry was found using Google Earth. In Google Earth, there are a number of tools that can be used to analyze a map. The tool of interest as it relates to our analysis was the polygon tool. Using the polygon tool, a perimeter was drawn around each mine site that had noticeable differences to the topography as compared to the surrounding area. This was most often identifiable by the lack of vegetation/patchy and random areas of vegetation. Once the polygons had been drawn, they were put in the program EarthPoint, which is a tool that is used in coordination with Google Earth, and the areas were calculated. Figure 1 shows examples for the three sites considered.


Site A Site B Site C

Figure 1. Land Use of Natural Aggregate Mines

Table 1 represents the area of land that a quarry or mine is occupying to produce one ton of aggregate. Natural aggregate producers provided the amount of material produced at each location. The average production of the three locations is 1,996,000 tons which will be used for calculations in later sections. Only the land that was absent of green space was considered to be part of the land use calculation.

Table 1. Natural Aggregate Land Cover Compared to Production Rate (Tons/Area)

Site	Tons	ft^2/Ton	Tons/ft^2	Tons/yd^2	Tons/Acre
A	4,093,000	7.86	0.13	1.14	5,540
B	1,144,000	13.9	0.07	0.65	3,140
C	750,000	12.1	0.08	0.75	3,609
Average	1,996,000	11.3	0.09	0.85	4,096

The same type of analysis was performed for RCA, with production values of RCA Site A estimated based on site visits. Two different estimation values were calculated for site A, one based on bucket loads of a backhoe loader into the concrete crusher and one based on output from the crusher-the two methods agreed within 12% and the average is reported in Table 2. Data for Site B was obtained in a survey. The land used to produce one ton of RCA is summarized below in Table 2.

Table 2. RCA Land Use

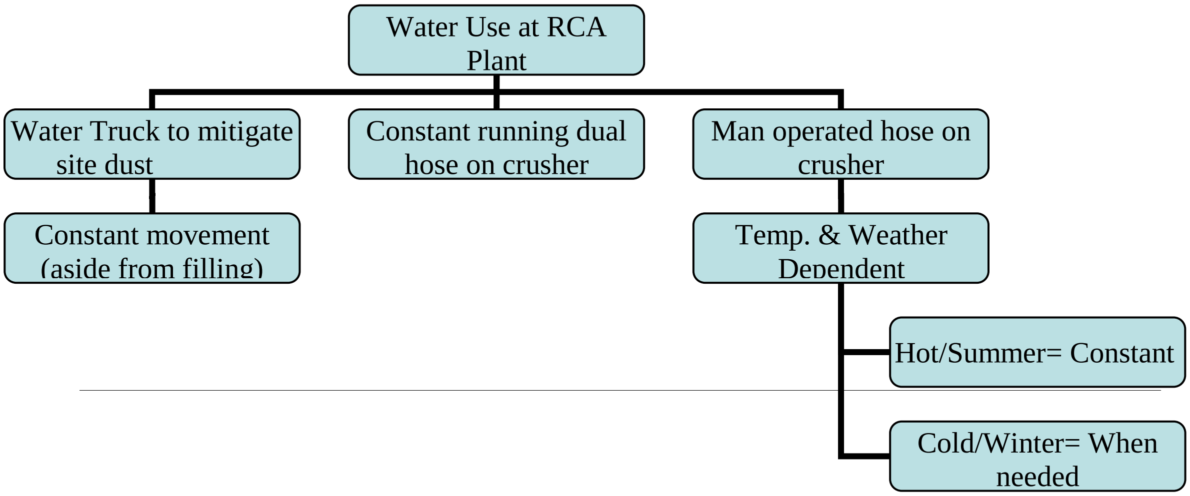
Site	Estimation Source	Tons	ft2/ton	Tons/ft2	Tons/yd2	Tons/Acre
A	Loader & Scale Data	1,022,000	1.2	0.8	7.5	36,300
B	Reported Data	175,000	1.05	0.96	8.61	41,600
	Average	599,000	1.13	0.88	8.10	39,000

Site A was the location that researchers physically studied, and for this reason, it is used as the production value for RCA facilities throughout the paper. For natural aggregate facilities, the average of the three production values listed in Table 1 is the production value for natural aggregate producers.

WATER CONSUMPTION

Recycled Concrete Aggregate. Since water is such a valuable resource, it absolutely falls under the category of things to consider when mapping out an environmental footprint for RCA plants. By taking relatively simple measurements and observing the day-to-day operation of the plants, an estimate of how water is used in production of recycled concrete aggregates was obtained. It was observed that water usage at an RCA production facility essentially falls into three categories including (see Figure 2): (1) water truck consumption used for dust control, (2)water hoses/spouts attached to crushers, and (3)man operated hoses used to spray material as it's loaded in the crusher. Although different RCA plants may have slightly different operating procedures, for this paper it is assumed that the RCA plant visited is representative.

Figure 2. Sources of Water Consumption at Visited RCA Plant



For the water truck consumption estimation, a Ledwell 4000 gallon water truck was used in the model based on visual observation on site at the RCA facility. The Ledwell 4000 is used for the estimations below. The truck has a total of three discharge points, and a capability to discharge water at 350 gpm. Water consumption was evaluated at 1/3, 2/3, and full discharge capacity of the trucks capability. For water consumption, and for all the upcoming estimates, it was assumed that a workday was 10-hours; a workweek was 50-hours, and 250 workdays in a year. Table 3 shows calculations to determine water use by this truck assuming that it is in operation for different times in a given week. During the project team site visits, the truck usage was temperature and (especially) precipitation dependent.

Table 3. Tgal (1000 Gallons) of Water Consumed in a Year by Water Trucks at RCA Plants

Operation (min/wk)	Tgal/Yr @ Full Cap.	Tgal/Yr @ 2/3 Cap.	Tgal/Yr @ 1/3 Cap.	Avg.
3,000	54,500	35,300	17,700	35,800
2,250	40,910	26,500	13,200	26,900
1500	27,300	17,700	8,820	17,900
750	13,600	8,820	4,410	8,940
			Average	**22,400**

The average value of the possible scenarios was used as a representative estimate for water truck consumption at an RCA plant. The yearly total was estimated to be 22,400 Tgal/year (thousand gallons per year).

The water estimation for the dual hose attached to the crusher is simpler, with fewer variables to consider. For example, the operator of the crusher stated that the hoses are always running as long as the crusher is running, meaning that no dead time need be accounted for between the water being on and off. The two valves were at a location on the crusher that would be unsafe to visually observe the flow rate; instead, it was compared to the hose that the operator was using to add additional water to the recycled material. The flow rate for the man-operated hose was measured and found to be 0.14 gallons/second. The total discharge rate for the two crusher hoses was simply multiplied by two since there were two separate points of discharge. Table 4 presents these calculations and shows an estimate of 1,860 Tgal/year for the crusher hoses.

Table 4. T gal Produced in a Year by Water Used by Dual Hose attached to Crusher at RCA Plants

Discharge Points	Discharge Rate gal/s	Flow Time/ Week (s)	% of Time Crusher's in Operation	Time/Year in Operation (s)	Tgal/Year
2.00	0.14	180,000	0.75	6,750,000	1,863

Based on a survey of temperatures and rainfall by season in the U.S., it was assumed that the manually operated hose was used 100% for summer months, 75% for spring and fall months, and 50% in the winter months. Our observations during site visits informed these assumptions- on visits with cool temperatures and slight rainfall, the hose was virtually never used. On hot dry days, it was almost constantly deployed. Rainfall was assumed approximately evenly distributed through the year, resulting in approximately 50 workdays per season where the manual hose was utilized with a flow rate of 0.14 gal/s. With these assumptions, the manual hose was estimated to use 707 Tgal/Year. The total water usage at the RCA plant can be determined by summing the quantities from the three sources. This yields an estimated yearly water usage of 25,000 Tgal/year for this facility, which produced 1,022,000 tons of RCA. The yearly total of water used at an RCA facility can now be used to estimate the amount of water it to produce one ton of aggregate. Using the production estimation for site A, it takes 24.5 gal/Ton of RCA produced. Also, site B in table 2 was reported from an RCA producer who also indicated that the company uses 700 gallons of water per day of operation. For site B, it takes one gallon per ton of recycled concrete aggregate. The difference between the two values is expected to come from the different geographical locations where the amount of rain and temperature in the region can play a huge role. Furthermore, Site A was located in an urban area where dust control is tightly regulated, whereas Site B is located in a more rural area. The layer of the two values (24.5 gal/Ton) is used throughout the rest of this paper.

Natural Aggregate. Using information published by various sources, the amount of water used in the production of natural crushed and broken stone is presented.

1) According to the USGS, mining operations in the US in 2005 used a total of 2,310 million gallons per day of freshwater (assumed to be for the 250 workdays in a year and not for the full 365 days)
2) In their minerals yearbook for 2005, data was collected for "MATERIAL HANDLED AT SURFACE AND UNDERGROUND MINES IN THE UNITED STATES IN 2005, BY COMMODITY AND STATE". It was reported that the total number of active mines was 14,445.
3) USGS also reported that of the 14,445 active mines, 3,171 (or 22%) were crushed stone mines and 9,975 were sand and gravel mines for the construction industry (69%)

Based on the information, water consumption for crushed stone and sand and gravel mines was estimated to be 39,976 Tgal per year. USGS reports that the total production for sand, gravel and crushed stone mines was 3,395,000 thousand tons. Dividing the total production by the number of mines yields 258,253 tons of material produced per mine. Finally, dividing the amount of water used by the annual production of a mine results in 155 gallons of water used to produce one ton of material for NA producers.

TRANSPORTATION

Transportation of aggregates plays a large role in their environmental impact due to energy demand and associated CO2 production. Figure 3 shows a schematic of the transportation operation necessary to produce and use natural aggregate and RCA. As mentioned, the goal of the study was to compare transportation distances of RCA and natural aggregate plants. From these transportation distances an estimation of CO2 emitted can be found. The RCA plant crushed and sold the material all at one location, which is not typical of natural producers. The values presented in the following graphs for RCA plants are representative of one-way travel. Anecdotally, it is typical that quarries and mines are relatively far from urban centers where both demolition and new construction are concentrated, while RCA facilities tend to be closer.

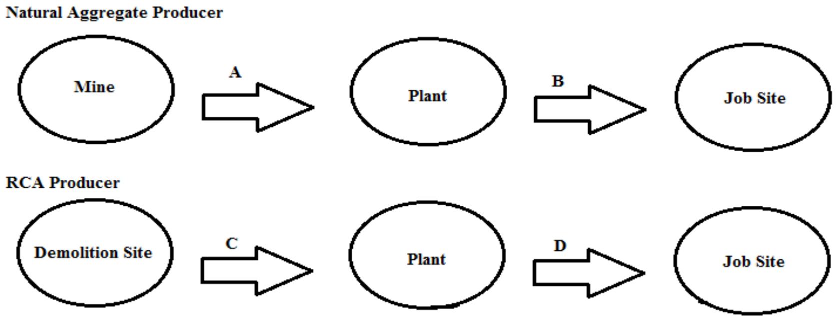
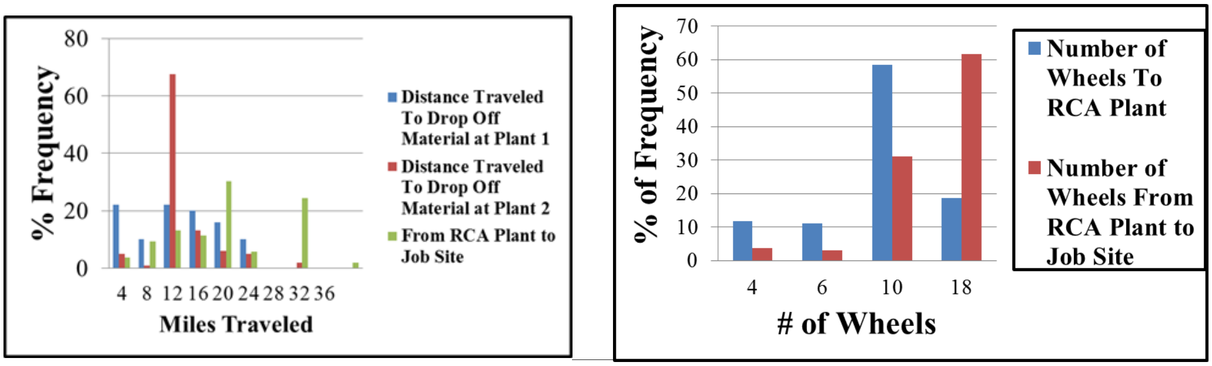


Figure 3. Movement of Material for RCA producers vs. Natural Aggregate Producers

Recycled Concrete Aggregate. Figure 4a shows transportation data recorded during the RCA plant site visits. It includes information reported by truck drivers both dropping off material to be recycled and picking up RCA. The first two entries in the bar graph can be used to estimate distance C in Figure 3, the third to estimate distance D. The figure illustrates that the most frequently traveled distance to the RCA plant to pick up or drop off material was 12 miles, which was close to the average distance of 12.5 miles. The figure illustrates that the most frequently traveled distance from the RCA plant back to a job site was 20 miles, while the average was 19 miles. Figure 4b represents the truck type of customers at the first location of RCA plants. The number of wheels for each truck provides a tool to approximate the engine type each truck possessed, thus allowing for the fuel consumption rate to be known. The combined information allows for CO2 emission estimates that take into account distance and engine type. The number of wheels for each vehicle was determined by two different methods depending on if the truck was dropping off material or purchasing material. For trucks dropping off material, a survey of vehicle types was recorded by researchers.



a) Miles Traveled To RCA Plant & Distance From RCA Plant to Job Site

b) Truck Type Based on Number of Wheels

Figure 4. Miles Traveled To RCA & Distance from RCA Plants to Job Site

For vehicles purchasing material, scale data that was recorded for vehicles' leaving the RCA plant after a purchase happened was utilized. Scale data included initial weight of the vehicle as well as the addition of the material purchased. In each case (and for the data of Figure 4), the frequency presented herein represents a compilation of hundreds of individual data points. Using the average initial weights of the various types of trucks surveyed at the RCA plant, the truck type (number of wheels) could be estimated.

Natural Aggregate. Table 5 provides the travel distances that customers travel to buy material from a plant owned by one of the largest aggregate producers in the country. The information was given for the purpose of research with the understanding the producer would not be identified. The information provided data on customers, material to each, and the total amount of purchases by each company. An important note is that this only includes transportation distances for customers buying the material. It does not include the transportation distance by the primary producer, who has to transport the material from the quarry to the processing plant, and finally from the processing plant to the distribution yards. Estimates for these values are presented later.

Table 5. Natural Aggregate customer Travel Distance (Plant 1)

Natural Aggregate Producer	Miles Traveled To Obtain Material (Plant 1)	Natural Aggregate Producer	Miles Traveled To Obtain Material (Plant 2)
Customer 1-A	9	Customer 2-A	26.6
Customer 1-B	4.3	Customer 2-B	42.4
Customer 1-C	32.2	Customer 2-C	25.4
Customer 1-D	10.2	Customer 2-D	34
Customer 1-E	25.6	Customer 2-E	136
Customer 1-F	34.9	Customer 2-F	94.9
Customer 1-G	32.8	Customer 2-G	27.9
Customer 1-E	99.9		
Average	**31**	**Average**	**55**

The average of the transportation distances for the two NA plants is 43 miles. This estimate is representative of Distance D in Figure 3.

Table 6. NA Transportation Distances from Quarry to NA Plants

Natural Aggregate Producer Quarry	Distance to Plant 1 (Miles)	Distance to Plant 2 (Miles)
Quarry 1	18.6	15.8
Quarry 2	3.1	60.5
Quarry 3	78.1	94.6
Quarry 4	46.6	76.4
Quarry 5	67.4	72
Quarry 6	68.6	80.4
Average	**47**	**67**

Table 6 was generated by finding the distances between each quarry owned by the natural aggregate company and the two plants that customer data was provided for. It’s assumed that each plant could be receiving material from any of the quarries owned by the company depending on the supply and demand, so the average for each plant was used for distance C in Figure 3.

Table 7. Summary Table of Total Distance Traveled for RCA and NA Operations

Producer Type	Distance Customer Travels to Plant	Distance from Material Source To Plant	Total Miles Traveled
RCA	12	20	32
NA	57	43	100

As expected, the transportation distances associated with natural aggregate producers were higher than that of RCA producers with the difference between the two 68 miles. The implications of this are evident in the carbon dioxide emission estimates in the following section.

CO2 ESTIMATIONS

Using the RCA facility scale data, an estimate of the quantity hauled by each vehicle type was made. Combining this information with the mileage data of Table 7 and fuel efficiency figures allows the total yearly fuel consumption of this RCA plant can be estimated. Fuel economy was assumed as follows: 4-wheels at 29 mpg, 6-wheels at 14.2 mpg, 10-wheels at 6.2 mpg, and 18-wheels at 5.9 mpg.
The fuel economy for the various truck types used to estimate CO2 emissions due to transportation distances. All four classes of trucks were assumed to be using diesel fuel. The fuel economy was found using various sources such as RamTruck's.com (2016), TruckingInfo.com (2013), and equipmentworld.com(2010).

Table 8 illustrates an estimate the amount of CO2 emitted during one year by this RCA operation due to transportation of concrete and RCA to and from the plant. The production of the RCA plant was 1,022,000 tons of aggregate. The truck distribution shown in Figure 4b and the miles traveled shown in Table 7 was used along with the total RCA plant production to estimate the quantities of RCA transported to and from the plant by each vehicle type. The yearly trips were estimated using the amount of material each vehicle type was transporting to the plant as well as the average amount of material each type of vehicle was recorded carrying at the scale of the RCA facility. It was assumed that the same amount of material that was purchased from the plant was brought to the plant to be recycled. The total amount of CO2 produced by transportation distances for the RCA plant was 4,690 tons. Using the total production for the RCA producer, it took 8.4 lbs of CO2 emissions to produce one ton of RCA. Energy from the total fuel consumed was calculated using the factor of 146 MJ/Gallon, and it has been estimated to require 55.5 MJ to use one ton of RCA for a new job.

Table 8. CO2 Emissions due to Transportation Distances at RCA Plants

# of Wheels	Tons/Veh	Yearly Trips To	Tmiles To	Tgal. Used	Tons of CO2	Yearly Trips (from)	Tmiles From	Tgal. Used	Tons of CO2	Energy Used GJ
4	1	82,900	994	34.3	377	27,600	552	19	209	7,788
6	2	61,100	733	51.6	568	16,700	333	23.5	258	10,965
10	15	19,100	474	76.5	841	21,100	422	68.1	749	21,115
18	22	8,830	106	18	197	28,800	576	97.6	1,073	16,876
				Total	**1,983**			**Total**	**2,289**	**56,743**

For NA, the production from the three locations noted in Table 1 was used with the trip distance data in Table 7 to perform similar calculations. The vehicles were assumed to be 100% 18-wheelers for all trips. Although the truck mix may be somewhat different, in many cases NA is transported via other modes such as by ship or rail, so the 18-wheeler assumption (which is the most efficient) should partially offset this. Performing the same analysis, CO2 that was emitted during one year by an NA operation due to transportation distance to and from the plant was 16,900 tons per year. The average production of the three natural aggregate producers was 1,995,667 tons per year which means that it took 16.9 lbs of CO2 and 112 MJ of energy to produce and use one ton of natural aggregate.

CONCLUSION

Table 9 shows a summary comparison of the key variables evaluated in this study. It shows that, across every measure, RCA use has a lower environmental impact than NA use. The land and water figures are good proxies for discussing the natural riverbed and forest ecology benefits to RCA use and the CO2 and energy data show the impact of RCA use in key climate inputs. Note that these figures don't include the negative impacts of simply landfilling waste concrete-they implicitly assume that all concrete waste becomes RCA. By applying weighting valuations to these and other (such as cement use in RCA vs. NA mixes, or energy required to crush RCA vs. NA) categories, future work could use this information as inputs to create an overall environmental index for RCA use.

Table 9. Summary Comparison of Key Variables

	Land(ft2)/Ton	Water(Gallons)/Ton	Transportation CO2(lb)/Ton	Transportation Energy(MJ)/Ton
NA	11.3	155	16.9	112
RCA	1.13	24.5	8.4	55.5
NA/RCA	10	6.32	2.01	2.01

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