Sustainability of the cement and concrete industries

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ABSTRACT: Sustainability is important to the well-being of our planet, continued growth of a society, and human development. Concrete is one of the most widely used construction materials in the world. However, the production of portland cement, an essential constituent of concrete, leads to the release of significant amount of CO_2, a greenhouse gas (GHG); production of one ton of portland cement produces about one ton of CO_2 and other GHGs. The environmental issues associated with GHGs, in addition to natural resources issues, will play a leading role in the sustainable development of the cement and concrete industry during this century. For example, as the supply of good-quality limestone to produce cement decreases it will become more difficult to produce adequate amounts of portland cement for construction. There is a possibility that once there is no more limestone, say in a geographical region, and thus no portland cement, all of the employment associated with the concrete industry as well as new construction projects will be terminated. Due to limited natural resources, concern over GHGs, or, both, there are regions in the world where cement production is being curtailed, or, at least, cannot be increased to keep up with the population increase. Therefore, it is necessary to look for sustainable solutions for future concrete construction. A sustainable concrete structure is constructed in order to ensure that the total environmental impact during its life cycle, including its use, will be minimal. Sustainable concrete should have a very low inherent energy requirement, be produced with little waste, be made from some of the most plentiful resources on earth, produce durable structures, have a very high thermal mass, and be made with recycled materials. Sustainable constructions have a small impact on the environment. They use "green" materials, which have low energy costs, high durability, low maintenance requirements, and contain a large proportion of recycled or recyclable materials. Green materials also use less energy and resources, and can lead to high-performance cements and concrete. Concrete must keep evolving to satisfy the increasing demands of all of its users. Designing for sustainability means accounting for the short-term and long-term environmental consequences in the design.

1 INTRODUCTION

According to the World Commission on Environment and Development of the UN, sustainability means "meeting the needs of the present without compromising the ability of the future generations to meet their own needs" [UNFCCC COP9 Report 2004]. The sustainability of the cement and concrete industries is imperative to the well-being of our planet and to human development. However, the production of portland cement, an essential constituent of concrete, leads to the release of a significant amount of CO_2 and other greenhouse gases (GHGs) [Malhotra 2004]. The environmental issues associated with CO_2 will play a leading role in the sustainable development of the cement and concrete industry during this century. One of the biggest threats to the sustainability of the cement industry is the dwindling amount of limestone in some geographical regions. Limestone is essential to the production of portland cement. As limestone becomes a limited resource, employment and construction associated with the concrete industry will decline. Therefore, those involved with these industries must develop new techniques for creating concrete with a minimal use of limestone. Concrete production is not only a valuable source of societal development, but also a significant source of employment. Concrete is the world's most consumed man-made material. It is no wonder that in the U.S.A. alone, concrete construction accounted for two million jobs in 2002 [United States House Resolution 394 2004]. About 2.7 billion m^3 of concrete was produced in 2002 worldwide. This equals to more than 0.4 m^3 of concrete produced per person annually worldwide. Therefore, to create not only sustainable societal development, but also to sustain employment, such as batch plant operators, truck drivers, ironworkers, laborers, carpenters, finishers, equipment operators, and testing technicians, as well as professional engineers, architects, surveyors, and inspectors, the concrete industry must continue to evolve with the changing needs and expectations of the world.

2 WHAT IS SUSTAINABILITY?

Limestone is used to manufacture portland cement (Fig. 1). Currently, portland cement is the most commonly used material in producing concrete.

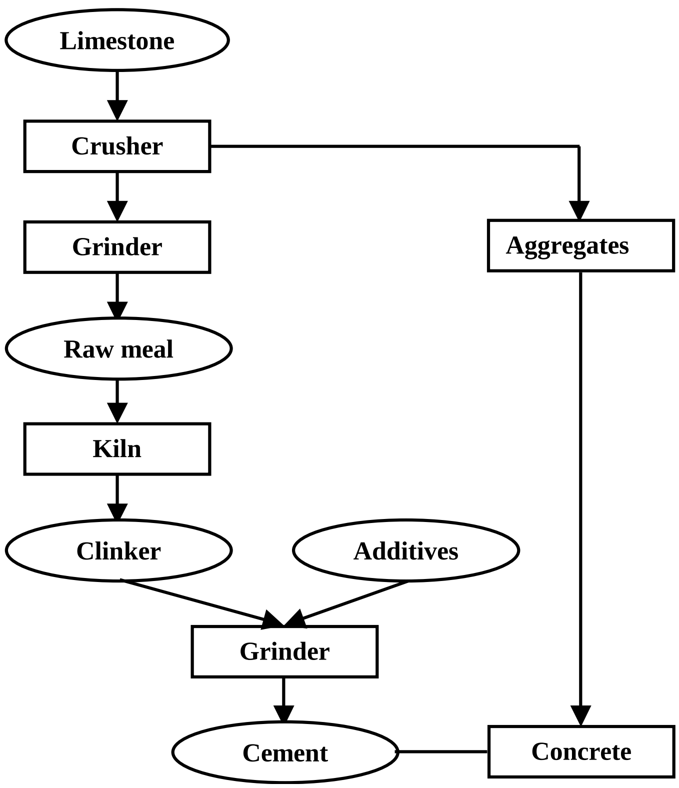

Figure 1. Limestone for cement and concrete [modified from Worrell and Galtisky 2004]

Entire geographical regions are running out of limestone resources to produce cement. And major metropolitan areas are running out of materials to use as aggregates for making concrete. Sustainability requires those in the construction industry to take the entire life-cycle, including construction, maintenance, demolition, and recycling of buildings into consideration [McDonough et al. 1992, Worrell & Galtisky 2004].

A sustainable concrete structure is one that is constructed such that the total societal impact during its entire life cycle is minimal. Designing with sustainability in mind includes accounting for the short-term and long-term consequences of the structure. In order to decrease the long-term impact of structures, the creation of durable structures is paramount.

Building in a sustainable manner and scheduling appropriate building maintenance are significant in the “new construction ideology” of this new century. In particular, to build in a sustainable manner means to focus attention on the effects on human health, energy conservation, and physical, environmental, and technological resources for new and existing buildings. It is also important to take into account the impact of construction technologies and methods when creating sustainable structures [McDonough et al. 1992]. An integrated sustainable design process can reduce project costs and operating costs of the building or the infrastructure construction.

There are many challenges associated with portland cement production. Of these, energy and resource conservation, the cost of producing portland cement, and GHG emissions are the most significant. Therefore, supplementary cementing materials such as fly ash and slag should replace larger amounts of portland cement in concrete. However, before any construction occurs, all aspects of the building materials to be used should be evaluated. In order to build structures and infrastructures that are cost efficient, environmentally friendly, and durable, the impact of the building materials on local and worldwide air conditions must be examined [McDonough et al. 1992]. CO_2 emissions are expected to rise by about 50% by 2020 from the current levels (Table 1) due to portland cement production [Malhotra 2004].

Table 1. CO_2 Emissions in 2002.

Country	Percent CO_2
U.S.A.	25
E.U.	20
Russia	17
Japan	8
China	>15
India	>10

Total CO_2 emissions worldwide: 21 billion tons [Malhotra 2004]

For each ton of portland cement clinker, 1.5 to 10 kg of NO_x is released into the atmosphere. In 2000, worldwide cement clinker production was approximately 1.5 billion tons. It means that in 2000 between 23 and 136 billion kg of NO_x was produced to make portland cement clinker [Malhotra 2004].

If the challenges associated with reducing CO_2, NO_x, and other GHGs are to be met, then the concrete industry must develop other materials to replace portland cement. Use of blended cements and organic chemical admixtures must be significantly increased for sustainability of the cement and concrete industries.

3 CONCRETE

For over 200 years, concrete has been accepted for its long-lasting and dependable nature. In addition to durability and dependability, concrete also has superior energy performance, is flexible in design, affordable, and is relatively environmentally friendly [Cement Association of Canada 2004]. It can be expected that concrete will be needed to both increase industrialization and urbanization while protecting the environment. To do this, the concrete industry should consider recycling industrial by-products such as fly ash safely and economically. When industrial by-products replace cement, even up to 70%, in concrete, the environmental impact improves along with the energy efficiency, and durability of concrete [Naik et al. 2003].

Concrete is a building material that is not only strong and durable, but can also be produced in ways that are environmentally friendly and architecturally moldable in esthetically pleasing forms [National Building Museum 2004]. With sustainable concrete structures and infrastructure, the concrete industry can develop a sustainable future for generations to come. Furthermore, buildings that are constructed to be both durable and environmentally friendly often lead to higher productivity because the buildings generally lead to better air quality and therefore, higher productivity [Coppola et al. 2004]. One example of the advantage of sustainable concrete is buildings constructed with concrete that have reduced maintenance and energy costs. Another is concrete highways, which reduce the fuel needed for heavily loaded trucks. A third example of the benefits of sustainable concrete construction is illustrated in insulating concrete homes that have energy reductions of up to 40 % [Cement Association of Canada 2004].

The cement and concrete industries can make substantial contributions to sustainable developments by creating and adopting technologies that can reduce the emissions of greenhouse gases. The cement and concrete industries could contribute to meeting the goals and objectives of the 1997 Kyoto Protocol [UNFCCC COP9 Report 2004]. Among other things, Kyoto Protocol requires to meet a target of reduction in GHGs to 1990 level. Those involved with the manufacture of portland cement would have a huge impact on the sustainable development of the concrete industry as a whole because currently cement production contributes slightly over 7% of worldwide GHGs (primarily CO_2); or, about 1.6 billion tons of GHGs. Any future taxes on GHG emission would have noticeable and noteworthy economic impact on the price of cement.

There are a number of characteristics that apply to innovative concrete products. First, they are produced with precast or cast-in-place reinforced concrete elements that are made with portland cement and pozzolanic materials that include renewable and/or recycled components. Second, innovative concrete products are constructed to enhance the performance of concrete elements, which may also contain recycled concrete as aggregates. High-performance materials are intended to reduce cross-sections and the volume of concrete produced. They are also intended to increase the durability of concrete structures to minimize the maintenance needs of the concrete construction, and limit the amount of non-renewable special repair materials that need to be used in the maintenance of the concrete [Coppola et al. 2004].

Concrete producers are creating sustainable solutions for many market sectors including agriculture and construction. In agriculture, integrated waste management solutions have been developed that convert manure into biogas, nutrient rich fertilizer, and reusable water. In construction, industrial, commercial, and institutional buildings are being constructed so that they are more energy efficient, have better air quality, and necessitate less maintenance [McDonough et al. 1992].

U.S. foundries generate over 7 million tons (8 million tons) of by-products. Wisconsin alone produces nearly 1.1 million tons (1.25 million tons) of foundry by-products, including foundry sand and slag. Most of these by-products are landfilled. Landfilling is not a desirable option because it not only causes a huge financial burden to foundries, but also liability for future environmental costs, and restrictions associated with landfilling. One of the innovative solutions appears to be high-volume uses of foundry by-products in concrete and other construction materials [Naik & Kraus 1999].

In addition, in 1996 the USA produced 136 million tons of construction and demolition (C & D) debris, about 1.5 kg per person per day. About 25 to 40% of landfill space is C & D debris [McKay 2004]. If this trend continues, the cost of landfilling will continuously increase, as will the potential health and environmental risks of landfill materials. Furthermore, the cost of landfilling is escalating due to shrinking landfill space and stricter environmental regulations. Such C & D debris (e. g., concrete as well as gypsum wallboards from C & D debris) can be recycles to make new concrete [UWM-CBU 2007].

A study was reported in 1999 whose aim was to evaluate the environmental impact of controlled low-strength materials (CLSM) incorporating cement and industrial by-products such as coal fly ash and used foundry sand [Naik and Kraus 1999]. The results demonstrated that excavatable flowable slurry incorporating fly ash and foundry sand as a replacement for up to 85% of fly ash could be produced. In general, inclusion of both clean and used foundry sand caused a reduction in the concentration of certain contaminants. The use of foundry sand in flowable CLSM slurry, therefore, provided a favorable environmental performance.

4 PORTLAND CEMENT

Portland cement is not an environmentally friendly material because its manufacture creates greenhouse gas emissions; and, it also reduces the supply of good-quality limestone and clay. As good engineers, we must reduce the use of portland cement in concrete. We must use more blended cements in order to reduce the need of portland cement clinker per ton of blended cement produced by blending with the clinker other pozzolanic materials, such as coal or wood fly ash, slag, silica fume, and/or other pozzolanic materials. As a cement production feed material, instead of clay, industrial by-products such as used foundry sand and/or coal combustion products (CCPs) such as fly ash should be used in optimum possible quantity.

The most energy intensive stage of the portland cement production is during clinker production. It accounts for all but about 10 % of the energy use and nearly all of the GHGs produced by cement production. Kiln systems evaporate inherent water from the raw meal and calcine the carbonate constituents during clinker preprocessing [Worrell & Galtisky 2004].

Sources of CO_2 and GHG emissions in the manufacturing of portland cement [Malhotra 2004] are:

– from calcinations of limestone = ± 50 – 55%;
– from fuel combustion = ± 40 – 50%; and,
– from use of electric power = ± 0 – 10%.

5 INNOVATIVE CEMENT PRODUCTS

While the embodied energy linked to concrete production is low, pozzolanic materials (PM), especially coal fly ash, have been used by the concrete industry for over 70 years. Their use can contribute to a further reduction of concrete's embodied energy. When used wisely and judiciously, PM can improve the long-term properties of concrete. Fly ash can, and does, regularly replace portland cement in concrete [Malhotra 2004, Naik et al. 2003, Mehta 2002].

One process that is even more environmentally friendly and productive is the use of blended cements. Blended cements have been used for many decades. Blended cements and are made when various amounts of clinker are blended and/or interground with one or more additives including fly ash, natural pozzolans, slag, silica fume, and other PM. Blended cements allow for a reduction in the energy used and also reduce GHG emissions [Malhotra 2004, Mehta 2002].

Most innovative concrete mixtures make use of PMs to partially replace cement. The advantages of blended cements include increased production capacity, reduced GHG emissions, reduced fuel consumption in the final cement production, and recycling of PMs [Worrell 2004, Cement Association of Canada 2004].

The manufacture of portland cement is the third most energy intensive process, after aluminum and steel. In fact, for each ton of portland cement, about six million BTU of energy is needed [Naik & Kraus 1999].

Although cement production is energy inefficient, there have been major initiatives that have reduced energy consumption [Worrell 2004]. Of these, the most significant has been the replacement of wet production facilities with dry processing plants. In addition, the cement industry has also moved away from petroleum-based fuel use.

Despite these advances, there are still some shortcomings when energy use is evaluated for the concrete industry. Dry process cement plants use pre-heaters, which increase the alkali content of cement [Worrell 2004]. Thus, cement producers need to continue to develop ways to control the alkali content without increasing the energy consumption levels of the cement [Coppola et al. 2004]. Furthermore, current innovations and energy savings are linked to the amount of energy consumption by converting wet-process to dry-process cement production and the number of pre-heaters needed to complete the process [Worrell 2004].

For each million tons of capacity, a new portland cement plant costs over 200 million dollars. The cost associated with the production of portland cement, along with the CO_2 emissions and energy issues, makes it unlikely that developing countries will be able to employ modern technology to reduce GHGs. Also, government regulations of GHGs will likely force the cement industry to create blended cements and use supplementary materials for blended cements in order to meet the societal development needs [Malhotra 2004, Worrell 2004]

To produce one ton of portland cement, 1.6 tons of raw materials are needed. These materials include good quality limestone and clay. Therefore, to manufacture the current production of 1.6 billion tons of cement annually, at least 2.5 billion tons of raw materials are needed [Wu 2000].

As good engineers, we must employ environmentally friendly materials to reduce the use of portland cement by replacing a major part of portland cement by PMs for use in concrete. In the USA, such materials - primarily fly ash, slag, silica fume, natural pozzolans, rice-husk ash, wood ash, and agricultural-products ash – are available, for up to 70% replacement [Naik et. Al 2003]. All these materials can be used to supplement the use of cement in concrete mixtures while improving product durability.

One of the important benefits of the increased use of other types of cementitious materials (such as PMs) is the reduction of GHG emissions. With a replacement of cement with other recyclable resources, worldwide CO_2 emissions would be reduced. A replacement of 50% of cement worldwide by other cementitious materials would reduce CO_2 emissions by 800 million tons. This is equivalent to removing approximately 1/4 of all automobiles in the world [Malhotra 2004]

Fly ash availability in the USA in 2005 was estimated at 120 million tons by the American Coal Ash Association [ACAA 2006]; by 2010 it is estimated to be 160 million tons. Portland cement availability in 2002 was estimated at 80 million tons; by 2010 it is estimated to be 100 million tons. The fly ash disposal challenge and the limited availability of portland cement have the same solution: replace large amounts of portland cement with fly ash to create durable and sustainable concrete.

6 THE HANNOVER PRINCIPLES - DESIGN FOR SUSTAINABILITY

In 1991, as the planning of the World's Fair was underway, the City of Hannover, Germany asked William McDonough and Michael Braungart to create sustainability principles to guide the large-scale development of EXPO 2000 in Hannover. "The Hannover Principles - Design for Sustainability" also include directives concerning the use of water. Although these guidelines were created for the World Fair, they are still a good tool to guide current and future development around the world [McDonough 1992].

Designers, planners, government officials, and all those who participate in the construction of new buildings and infrastructures should use the Hannover Principles. A new design philosophy has developed from these principles and should be included in sustainable systems and construction in the future. There are a number of examples of societies that have created sustainable and environmentally friendly communities. There is hope that the Hannover Principles will inspire development and improvements that are committed to sustainable growth with practical limits to create a sustainable and supportive future for communities and the world.

The Hannover Principles by William McDonough [McDonough 1992]: Insist on rights of humanity and nature to co-exist; recognize interdependence; respect relationships between spirit and matter; accept responsibility for consequences of design; create safe objects of long-term value; eliminate the concept of waste; rely on natural energy flows; understand the limitations of design; and, seek constant improvement by the sharing of knowledge.

The Hannover Principles are not "cast-in-concrete". They were devised to provide a tangible document that could evolve and be adapted as our understanding of our interdependence with nature becomes more important over time.

For sustainability, consider your actions on the following [McDonough 1992]: materials—use indigenous materials; land use—protect and create rich soil; urban context—preserve open spaces; water—use rainwater and gray-water (shower, sink, bath and laundry excess); wastes—recycle, air—create clean air; energy—use solar and wind energy, recycle waste energy; responsibility to nature—create silence; and, maintenance—minimize or eliminate for future generations.

Materials are critical to creating sustainable and responsible concrete designs. In order to ensure that the most effective and environmentally friendly materials are being used, the entire life-cycle of the structure should be taken into consideration. Material choice should include anticipation of the extraction, processing, transport, construction, operation, disposal, re-use, recycling, off-gassing and volatile organic compounds (VOC) associated with the material [McDonough 1992]. According to McDonough, constructions should be flexible to serve a variety of different needs (e.g., today's storage building can be tomorrow's school). Adapt materials that are sustainable in their process of extraction, manufacture, transformation, and degradation, as well as recyclability. Consider toxicity, off-gassing, finish, and maintenance. Recycling is essential. Make allowance for disassembly and reuse. Plan for reuse of the entire structure in the future. Minimize use of hazardous chemicals. Eliminate waste that cannot be part of a naturally sustainable cycle. Any solid wastes remaining must be dealt with in a non-toxic manner. Life-cycle costs must be studied, analyzed, and incorporated in planning and construction of a building or infrastructure. Life-cycle cost analysis process must evaluate energy use and environmental impact during the life of the product, process, and/or activity. This process must include extraction and processing of raw materials, manufacturing, transportation, maintenance, recycling, and returning to the environment. Costs and benefits must be evaluated and understood in both the short-term and long-term. Demolished concrete must be recycled. It can be readily used in new concrete for aggregates.

For the sustainability of the cement and concrete industries, use less water and portland cement in concrete production; and use more blended cements and tailor-made organic chemical admixtures. The devastation of air is a global problem, regardless of the locality in which the pollution is created [McDonough 1992]. The overall design of concrete structures must not contribute to atmospheric degradation. Those involved in the cement and concrete industries must evaluate ozone depletion and global warming throughout the construction and planning process. A major contribution to this effort is the use of more blended portland cement to minimize global climate change.

Water resources are being depleted by various uses [Bourg 2004]. Therefore, potable water should be conserved to serve life-sustaining needs rather than infrastructural needs. Rainwater and surface run-off water can be used as a water conservation method by recycling these water resources in construction instead of using potable water. Gray water should be recycled and used for grass, shrubs, plants, trees, and gardens; as well as for concrete production [McDonough 1992]. Furthermore, mixtures with less water should be developed with new technologies to create mortar and concrete containing a minimal amount of water.

Benjamin Franklin said over 200 years ago in Poor Richard's Almanac, "When the well's dry, we know the worth of water." Many facilities may have requirements that can be completed with non-potable water. By using non-potable water, a significant amount of money can be saved by avoiding or reducing potable water purchases and sewerage costs. To be as effective as possible, non-potable water for construction and building uses should be identified early in the planning and designing process to be most cost-effective. Four ways to utilize and recycle water are to reuse water on site for repeated cycles of the same task, treat and reuse water on site for multiple purposes, use gray water after solids have been eliminated, and collect non-potable water from sources such as rainwater, lakes, rivers and ponds for use in construction [Bourg 2004].

Energy efficiency, providing the same (or more) services for less energy, helps to protect the environment. When less energy is used, less energy is generated by power plants, thus reducing energy consumption and production. This in turn reduces GHGs and improves the quality of the air. Energy efficiency also helps the economy by saving costs for consumers and businesses. According to McDonough [1992]: (a) use buildings' thermal inertia (e.g., concrete building's mass allows it to retain heat); (b) use day lighting and natural ventilation; (c) use wind power and solar power; (d) recycle waste energy; (e) judiciously use color materials on surfaces; (f) reduce heat-islands in buildings; and, (g) manage and moderate micro-climates of buildings.

7 WASTE MATERIALS

Engineers, architects, planners, and builders should reuse industrial by-products and post-consumer wastes in concrete and other cement-based construction materials. Post-consumer wastes that should be considered for use in concrete include glass, plastics, tires, and demolished concrete, and clay bricks. To do this successfully, designers must watch for harmful hydration reactions of portland cement and changes in volume of concrete. The recycling of industrial by-products has been well established in the cement and concrete industries over the past couple of decades [UWM-CBU 2007]. The use of coal fly ash in concrete began in the 1930s, but volcanic ash has been used in mortar and primitive concrete for several millenniums in Egypt, Italy, Mexico, and India. The use of by-products such as rice-husk ash, wood ash, silica fume and other pozzolanic materials, in addition to coal fly ash, can help to reduce the need for portland cement in addition to creating more durable concrete and reducing greenhouse gas emissions [Malhotra 2004, Mehta 2002, ACI 2004]. This will also contribute to the improvement of air quality, reduction of solid wastes, and sustainability of the cement and concrete industry [Mehta 2002].

In summary, for sustainability of the cement and concrete industries: use less portland cement; use less water; use application-specific high-quality, durable aggregates; and, use organic chemical admixtures.

Fundamental laws of nature state that we cannot create or destroy matter; we can only affect how it is organized, transformed, and used. To manage natural resources, humanity must obey the rules of nature: use only what you need and never use a resource faster than nature can replenish it.

Resources are extracted from the earth by 20% more than the earth produces. Therefore, what is consumed in 12 months will take 14.4 months to be replenished. The use of sustainable development procedures will reduce that rate [Time Magazine 2002]. "The issue is not environment vs. development or ecology vs. economy; the two can be (and must be) integrated" [Ricoh Company 2004].

8 CONCLUSIONS

As Kofi Annan, U.N. Secretary General, said in 2002, "We have the human and material resources needed to achieve sustainable developments, not as an abstract concept but as concrete reality" [Time Magazine 2002]. Professionals involved in the cement and concrete industries have the responsibility to generate lasting innovations to protect both the industries' future viability and the health of our environment. Large volumes of by-product materials are generally disposed in landfills. Due to stricter environmental regulations, the disposal costs for by-products are rapidly escalating. Recycling and creating sustainable construction designs not only contributes to reduced disposal costs, but also aids in the conservation of natural resources. This conservation provides technical and economical benefits. It is necessary for those involved in the cement and concrete industries to eliminate waste and take responsibility for the life cycle of their creations. In order to be responsible engineers, it is necessary to think about the ecology, equity, and economy of our design [McDonough 1992].

Engineers must apply forethought into direct and meaningful action throughout our development practices. Sustainable designs must be used as an alternative and better approach to traditional designs. The impacts of every design choice on the natural and cultural resources of the local, regional, and global environments must be recognized in the new design approaches developed and utilized by the cement and concrete industries.

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