

USE OF STRUCTURAL DOME FORMWORK SYSTEMS IN SUSTAINABLE TRANSPORTATION APPLICATIONS

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ABSTRACT

Transportation agencies are actively seeking new and innovative solutions to build more sustainable infrastructure, while maintaining or improving economy and durability. A structural dome formwork system is one innovative product that is currently being evaluated for use in transportation applications. This product consists of interlocking, modular, dome-shaped units, made from recycled plastic, that serve as a permanent formwork for concrete floors, sidewalks and pavements. The resulting product is a concrete slab with a system of interconnected vault-like voids below the surface.

This concept provides a number of environmental and economic benefits. One major benefit of the dome shaped system is the ability to provide structural carrying capacities equivalent to conventional slabs, but requires less concrete to do so (up to a 20% reduction in concrete consumption). A significant savings in raw materials can be achieved. The system has also many additional demonstrated benefits, including reduced reinforcing steel, granular base and hard fill requirements, protection of the concrete from excess moisture due the ventilated design, and protection of tree roots from damage in urban areas.

This paper presents a number of Canadian case studies involving the use of the structural dome formwork system in transportation applications, including roadways, sidewalks, floor slabs and urban tree root protection. For each case study, details about the design, construction, and performance are provided. Performance results to date indicate that this technology has great promise as a concrete pavement technology and in various other transportation related applications. The economic and environmental benefits are diverse, and help agencies meet their sustainability goals, while providing a good return on investment.

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INTRODUCTION

Transportation agencies are being challenged to build more sustainable infrastructure, while simultaneously maintaining or improving economy and durability. In order to do so, new and innovative solutions are necessary. Innovation is a key component in the development of the next generation of solutions for our roads and highways. Agencies are striving to design and build longer lasting, more durable infrastructure with fewer financial resources, while incorporating more marginal materials, reducing environmental impacts and minimizing construction impacts on the travelling public.

One new innovative technology that has the potential to provide these desired benefits is being evaluated for use in transportation applications. This technology consists of interlocking, dome-shaped plastic units that serve as a permanent formwork for concrete construction, as seen in Figure 1. Concrete is poured over the modular dome-shaped units to create a structural slab with a series of interconnected vault-like voids beneath the concrete surface. Nominally 560 mm by 560 mm in size, the forming units, which are made from 100% recycled polypropylene, can be obtained in a variety of different heights ranging from 50 mm to 700 mm, depending on project specific geometry and anticipated loadings.



FIGURE 1 Example of the structural dome formwork system (1).

This product, developed in Italy, has seen widespread use across the world in the construction of floor slabs in residential, commercial, industrial and institutional buildings. It was originally conceived as a solution to passively ventilate radon gas emitted and reduce vapour intrusion from the ground beneath floor slabs at United States Air Force bases in Italy (1). Over 46.4 million square metres (500 million square feet) of this product have been installed since the early 1990s worldwide.

This paper outlines the benefits of this technology, sustainability related or other, and presents a number of recent Canadian case studies involving the use of the structural dome formwork system in transportation applications, including roadways, sidewalks, industrial floor slabs and roadside tree root protection. For each case study, details about the design, construction and performance are provided.

SUMMARY OF SUSTAINABILITY AND OTHER BENEFITS

The dome-shaped formwork system provides a number of potential benefits in concrete construction. The dome shape has been used since ancient times, as can be observed in many early architectural designs. Since this type of structure primarily resolves any forces into compression, it is well suited for concrete construction, which has excellent compressive strength, but limited tensile strength. The mechanics of the dome shape allow the formwork system to provide carrying capacities equivalent to conventional flat slabs, but much less concrete material is required to do so (up to 25 percent).

The reduction in material consumption provides significant environmental benefits. Concrete is one of the most commonly used civil engineering materials. While concrete structures are durable and economic, these features do not come without a significant impact on the natural environment. Globally, approximately 1.6 billion tonnes of cement and 10 billion tonnes of aggregates are used annually (2). Portland cement production is an energy intensive process with notable impact on the physical environment. The production of one tonne of Portland cement requires about four gigajoules of energy and emits 1.25 tonnes of carbon dioxide into the atmosphere (3). In addition to the greenhouse gas contributions of cement production, aggregate production also has a scarring environmental impact. The amount of high quality readily available aggregates for construction use is declining rapidly.

In addition to concrete savings, the use of this product can also reduce the need for granular base materials or engineered fill. Laboratory research indicates that the dome shape adds appreciable stiffness to the slab, allowing constructors to reduce the amount of granular base materials required, or even eliminate the granular layer entirely and place the plastic form directly onto the subgrade (4). Not only do material savings of this magnitude provide environmental benefits, but they also translate to cost savings, making sustainable construction more affordable. In many cases, the cost of the plastic formwork units is easily offset by the savings achieved by reduction in material consumption.

In addition to material savings, the dome shape also provides other performance related benefits. The presence of the underslab void reduces the slab's contact with the underlying layers, improving below slab ventilation and drainage. Since water cannot leach up through the bottom of the slab, it protects from moisture and humidity in areas with high water tables or marginal drainage conditions. The underslab void space can be easily ventilated, either passively or actively. This activity helps effectively control humidity levels and the intrusion of undesirable naturally emitted gases such as radon and methane. Also, since the plastic

formwork does not allow moisture to enter into the concrete slab, the potential for mould and mildew growth or damage to floorings when used in building applications is eliminated (1).

The structural dome formwork system also allows for construction in areas with poor soil conditions without having to improve them through processes such as soil stabilization. As an example, in areas with expansive soils, the empty voids provides space for the swelling soil to occupy (1). As the reactive soils are not restrained, the uplift pressure will not cause the concrete to heave and crack.

Additionally, the resulting underslab void can be used in a number of beneficial applications. For one, the underslab void allows for the quick, easy and cost-effective installation and repair of buried utilities, such as cables and pipes, after construction. These utilities can be accessed without having to cut through the slab itself, which is expensive and unsightly. As another example, the structural dome formwork system can be employed in creative sustainable stormwater management solutions, by using the underslab void as a reservoir. The underslab void can be designed to hold rainwater while it naturally infiltrates back into the ground, reducing runoff from impermeable areas into sewer systems. Likewise, the void can be used for tree root protection. The placement of uncompacted soil in the voids allows the roots of trees planted in urban areas to grow more quickly and expand more evenly, which is not always possible in cramped tree pits.

These listed benefits have allowed numerous developers, designers, contractors achieve their green building goals and gain Leadership in Environmental and Energy Design (LEED) certification for their projects.

CASE STUDIES

The structural dome formwork system has seen use on a number of projects in Canada. Most applications have seen the dome-shaped formwork used in place of a conventional floor slabs (slab on grade, suspended slab) to address challenging site conditions, such as high water tables, marginal soil bearing capacity, natural noxious gases and vapour intrusion.

Some examples of Canadian projects incorporating the structural dome formwork system into their construction include:

- Mount Sinai Hospital, Toronto
- University of Toronto Scarborough
- Vaughan Mills, Pickering Town Centre & Square One shopping malls in the Greater Toronto Area (GTA)
- New BMO bank branches (as part of a LEED certification program)
- Toronto fast ferry passenger terminal
- Various residential subdivisions in the GTA

Although it has been widely used in the construction of floor slabs in residential, commercial, industrial and institutional buildings as noted above, this product had not seen much use in transportation applications until recently. Concrete pavements and sidewalks, as an example, are subjected to different conditions than most floor slabs, including frequent and heavy dynamic loads and exposure to a harsh environmental conditions year round, which pose unique design challenges.

Canadian engineers, contractors, facility owners and government agencies have been leaders in applying the structural dome-shaped formwork system in transportation applications. Four case studies from Southern Ontario are presented in greater detail:

Evergreen Brick Works Industrial Pavement / Floor Slab

The Evergreen Brick Works is an environment focused community centre situated on the site of a redeveloped brownfield site in Toronto, Ontario. The Brick Works site was home to the former Don Valley Brick Works, a large brick making operation that ran for nearly a century using locally quarried materials. The present day Brick Works, seen in Figure 2, is home to a farmers' market, historical exhibits, banquet rental space, parklands and more.



FIGURE 2 Rendering of present day redeveloped Evergreen Brick Works.

As part of the redevelopment, a number of existing buildings were refurbished, which included replacement of the dilapidated floor slabs. A strong new flooring system was needed to carry the substantial anticipated loadings in an area with marginal soils and abundant water. The

structural dome formwork system provided a solution for controlling vapour intrusion and reducing slab weight. The design consisted 50 mm to 100 mm of concrete above 300 mm high plastic domes.

Falling Weight Deflectometer (FWD) testing was completed on the dome formwork slab, shown in Figure 3. The FWD test results showed that the structure was generally structurally sound with an average normalized deflection of 114 μm . However, a considerable amount of variability was observed in this value, which can be seen from the coefficient of variation of 32%. However, the minimal concrete thickness and variations in thickness may contribute to the non-uniformity. Nevertheless, the other calculated parameters indicated, listed in Table 1, are indicative of a fairly stiff slab, even considering the presence of the large underslab void.



FIGURE 3 Dome formwork industrial pavement at Evergreen Brick Works

TABLE 1 Summary of Evergreen FWD Results

ND1 (μm)		Area (in)		E _p (MPa)		SN _{eff} (mm)	
Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
114	36	29	2	13 806	5 472	141	22

Holcim Mill Creek Pit Pavement

Holcim (Canada) Inc. partnered with Dufferin Construction Company, Pontarolo Engineering Inc. and Applied Research Associates, Inc. to evaluate the viability of the structural dome formwork system in concrete roadway pavement applications. A trial pavement section was

constructed at a sand and gravel pit in Aberfoyle, Ontario. This 100 metre long, one lane, pavement section leads away from the pit's scalehouse, carrying the exiting loaded aggregate trucks. This location is subjected to high truck traffic, which allowed for a rapid evaluation of the system's performance under heavy loads.

Three adjacent sections of varying thickness, each 30 metres in length: 75 mm, 115 mm & 150 mm of concrete above the domes were built. Gradual transitions were incorporated between the different thickness sections. Dome formwork units with a height of 260 mm were used for this project.

This section was constructed using fixed steel perimeter forms. After the perimeter forms were installed and the plastic domes were laid out, a welded wire mesh was placed on top of the plastic units prior to paving, with the expectation that the steel mesh will help hold together any cracks that form. Concrete was placed using ready mix concrete trucks, which was then consolidated using handheld vibrators and a roller screed. A bull float and a wet burlap drag was used to finish it. Late season paving necessitated the use of curing blankets, but the pavement was opened to traffic within a week. Transverse joints were uniformly sawcut at an interval of 4.75 metres. Photos of the construction activities are presented in Figure 4.



a) Formwork units laid out with wire mesh on top



b) Placement and consolidation of concrete



c) Finishing of concrete with bull float and burlap drag



d) Structural dome formwork pavement in service

FIGURE 4 Photos of construction activities at the Mill Creek Pit.

Since construction, Falling Weight Deflectometer (FWD) testing, Ground Penetrating Radar (GPR) testing, visual condition surveys and coring have been completed on this section to evaluate pavement performance. This pavement section remains in service, with the exception of the 75 mm section, which was removed after poor early performance. The 115 mm section is in fair condition, displaying moderate cracking and a few areas of surface spalling. The 150 mm section is good condition, showing only a few low severity cracks. This section has carried over 1.4 million ESALs to the end of April 2014.

The remaining pavement sections have shown very good performance after more than three and a half years of carrying heavy traffic on a daily basis. The FWD testing has indicated good structural capacity and load transfer. This trial has demonstrated that approximately 125 to 150 mm of concrete above the formwork is necessary to carry truck traffic and that there is no apparent need for dowel bars, since sufficient load transfer is being provided without their presence. However, the construction process indicated that is very desirable to construct pavements using this product using a slipform paver.

Following the construction of the first trial, two short experimental sections were constructed by Dufferin Construction using a concrete slipform paver in combination with the structural dome formwork system at their yard in Oakville, Ontario, shown in Figure 5. The results of this testing indicated dome formwork could be slipformed as long as a sufficient amount of concrete was placed on top of the formwork units closest to the paver. The weight of the concrete was necessary to hold the units in place and prevent the motion of the paver from shoving the formwork units out of position. It was also confirmed that the paver's vibrators were able to provide adequate compaction of the concrete material around the formwork, particularly in the "feet," without manual effort.



FIGURE 5 Photos from slipform paving trials

Lessons learned from the first concrete pavement trial and the slipforming trials were incorporated into the design and construction of the next project.

Holcim Milton Quarry Pavement

In order to gain a better understanding of the performance of the structural dome formwork system in pavement applications, a larger concrete pavement test section was constructed by the Holcim team at a quarry in Milton, Ontario. In cooperation with the Centre for Pavement and Transportation Technology at the University of Waterloo, the 98 meter long pavement section was instrumented with a number of sensors to measure pavement responses. This site also carries high volumes of heavily loaded trucks carrying aggregate products, and is consequently subjected to an even more aggressive accelerated loading scenario.

Two pavement designs were developed to accommodate the quarry traffic. The trial pavements were constructed on top of the existing 300 mm thick granular base. One half of the trial pavement was constructed with 150 mm of concrete above the plastic units and other half with 175 mm of concrete above the domes. Again, the 260 mm high formwork units were used for this concrete pavement section. The two pavement designs are seen in Figure 6.

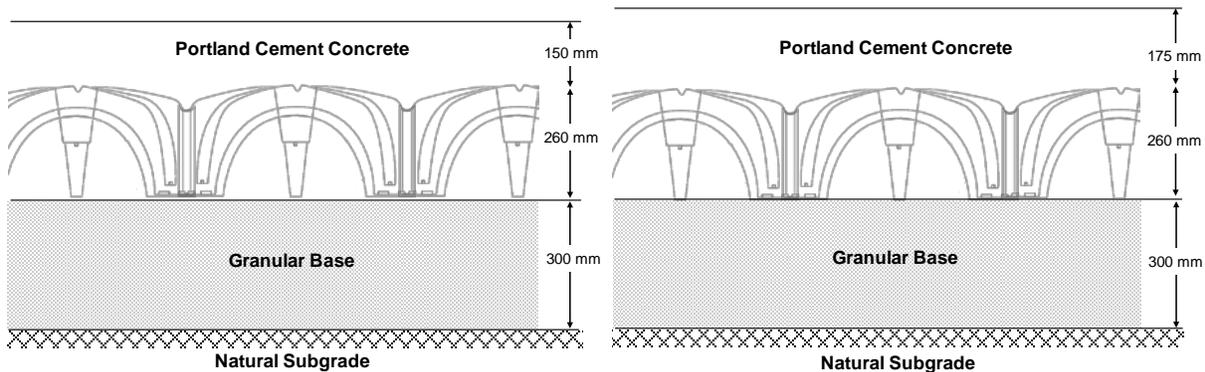


FIGURE 6 Milton Quarry pavement designs

Construction began by removing the existing asphalt and regrading the granular base. Once the base was recompact, the plastic domes were laid out. Paving followed using a slipform paver. The formwork product was found to be easily slipformed as long the plastic domes directly in front of the paver were weighed down with a sufficient head of concrete to prevent the paver from shoving them out of place. A conveyor truck was needed to place the concrete, which arrived in ready mix trucks, onto the dome units. After the concrete was consolidated and finished by the paver, the pavement surface was textured with a wet burlap drag, followed by transverse tining and the application of white pigmented curing compound. Once the concrete hardened, joints were sawcut. A continuous longitudinal sawcut was made down the centreline to divide the roadway into the two 4 m wide lanes. Transverse contraction joints were also sawed at a uniform spacing of four meters. The structural dome pavement section was opened to traffic one week after the paving day. Some of the construction activities at the Milton site are illustrated in Figure 7.



FIGURE 7 Photos of construction activities at Milton Quarry [2].

Regular monitoring has been ongoing since completion of construction. Evaluation activities have included visual condition surveys, Falling Weight Deflectometer (FWD) testing and collection and analysis of the instrumentation data. The embedded instrumentation and post-construction FWD testing have provided excellent insight into the behaviour of the structural dome formwork pavement. The sensors installed included strain gauges, pressure cells and moisture probes, as seen from left to right in Figure 8.



FIGURE 8 Instrumentation installed in the trial pavement sections.

The strain gauges have shown that the measured strains at the top of the dome are generally compressive at all times (5). The dome shape succeeds in virtually eliminating any tensile stresses in the thinnest section of concrete, even when subjected to flexure by heavy traffic loads. The infrequency and low magnitude of the tensile strains measured is a positive sign, as suggests a minimized potential for cracking.

Moreover, the pressure cells have revealed that the structural dome formwork system is able to distribute loads over a large area, despite the fact that dome-shaped slab rests on individual “feet”, each with a small bearing area of approximately 200 mm². When a wheel load of approximately 13 kN axle was applied directly over top of a “foot”, the pressure cell at that location only measured a 1.3 kPa increase (5). If tire load had traveled directly from the point of application to the base layer, an increase in pressure of approximately 40 kPa would have been expected. The results of this testing show that applied loads do not appear to become concentrated near the point of application. This ability to distribute loads over larger area minimizes concerns about high point loads being transmitted the underlying pavement layers, which may cause differential settlement and cracking.

Load transfer across joints is another key performance consideration for jointed concrete pavements. The design team discussed whether dowel bars would be needed in order to achieve acceptable load transfer levels. In the end, the Milton pavement was constructed without the use of dowel bars at the transverse joints, which simplified construction a great deal. Most current design procedures, including AASHTO 1993, recommend the use of dowel bars for concrete pavements carrying high volumes of heavy trucks (6).

Additionally, the effect of the location of the transverse joint with respect to the top of the dome was also investigated. At the top of the dome, the thickness of concrete varies from 150-175 mm and directly above the “feet”, the thickness jumps up 410-435 mm, which results in large increase in available shear area for providing load transfer through aggregate interlock. In the Milton pavement, with a uniform joint spacing of four meters, approximately 60% of the joints were located above the dome and the remainder, above the “foot”.

FWD testing revealed excellent load transfer at all joints in both lanes, as seen in Figure 9. The most recent data indicated that load transfer at all joints ranged from 82% to 100%, averaging 95% (5). These results show that the dome-shaped system is capable of carrying heavy traffic loads while providing the necessary load transfer without the need for dowel bars. Joint location also does not appear to play a significant role in load transfer efficiency measurements. Equally good load transfer was observed at joints above the dome and at the joints above the “foot”.

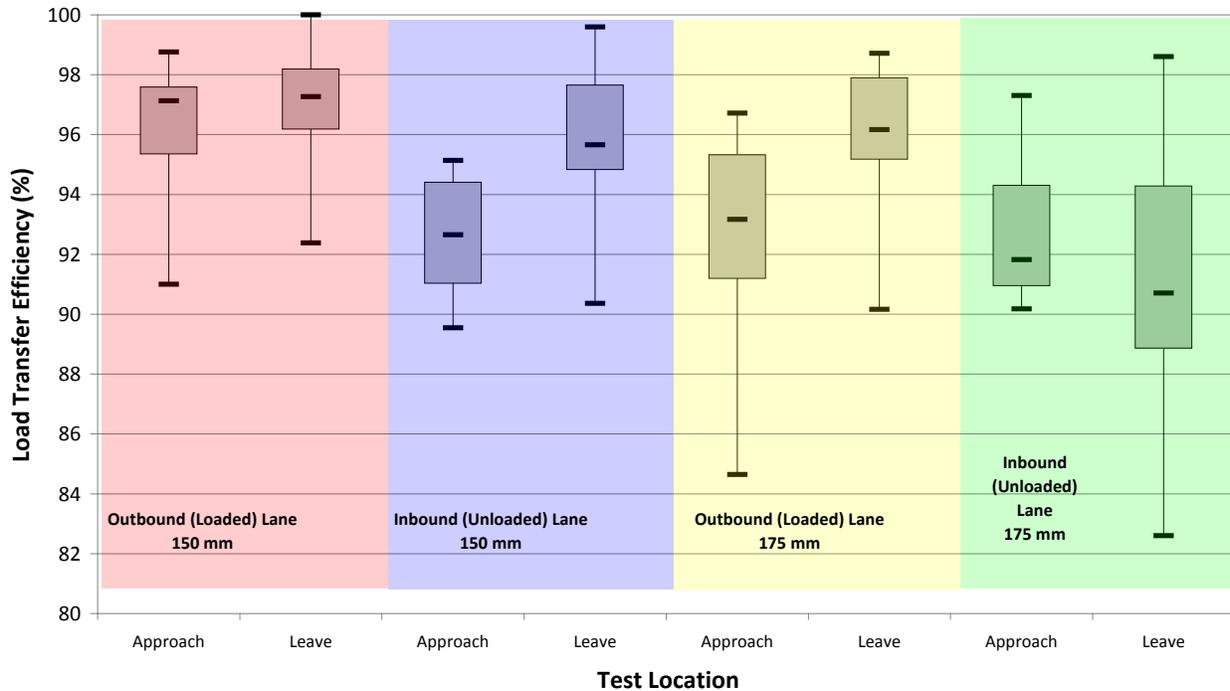


FIGURE 9 FWD load transfer efficiency results (5).

The Falling Weight Deflectometer was also used to assess the structural equivalency of the dome-shaped pavements. FWD data from Milton site was compared to FWD data from conventional concrete pavements of varying thicknesses in southern Ontario. The comparative analysis shows that a pavement with 150-175 mm of concrete over the plastic dome-shaped formwork is approximately equivalent structurally to a conventional 250 mm Jointed Plain Concrete Pavement (JPCP) (5). Accounting for the volume of concrete required to cover the dome formwork itself, the Milton pavement section required approximately 20% less concrete to construct than its structurally equivalent JPCP counterpart. Further savings was achieved by eliminating the need for steel reinforcement and steel load transfer devices. The cost savings incurred through the use of structural dome formwork system easily offset the cost of the formwork itself, resulting in a net savings. These reductions in material requirements have also boosted the sustainability of this project, through the conservation of raw materials and energy.

Visually, the Milton pavement remains in excellent condition two years post-construction. On average, 450 trucks per day travel over the test section year round. This number rises to over 750 trucks per day at the peak of the construction season. This project has demonstrated that the dome-shaped formwork can successfully be used to build concrete pavements that carry heavy arterial level traffic. Since the trial section was opened to traffic, over 2.6 million Equivalent Single Axle Loads (ESALs) have been applied, without any significant pavement degradation.

Highway 7 Sidewalk Tree Pits

In efforts to greatly improve transit services in York Region, the Regional Municipality of York has undertaken the construction of the next phase of its bus rapid transit system. This ongoing undertaking, termed "vivaNext", will feature dedicated transit rapidways along major routes throughout the Region.

As part of the bus rapidway construction, Highway 7 was widened in Markham, which necessitated the reconstruction of the sidewalks. However, the vivaNext program also has stringent landscaping provisions. One of the streetscaping improvements required the planting of trees along the boulevard. An innovative solution was required to encourage the long-term healthy growth of the urban trees.

Cramped tree pits and the overcompaction of soil surrounding tree roots in urban areas can be harmful to trees. In these circumstances, trees are not able to grow strong root systems and absorb the nutrients necessary to sustain themselves. Arborists recommend uncompacted soil around the root system, which is conducive to root growth and allows it to expand more quickly and evenly.

The structural dome formwork system provided the required solution for the vivaNext sidewalks and streetscaping. A 100 mm thick concrete slab was placed on top of 700 mm high plastic domes, as seen in Figure 10. The underslab void and dedicated tree areas were subsequently blown full of nutrient rich, uncompacted soil. The interconnected, soil-filled, underslab voids provide lots of additional space for the expansion of the roots, which improves tree stability and provides more area for nutrient absorption. The volume of available space allows prevents the roots from causing the sidewalk to heave or crack. At the same time, a sturdy sidewalk has been constructed using the dome formwork installed on solid ground. The dome-shaped forming system allows designers to incorporate the urban landscaping requirements into the sidewalk design in a holistic manner.



FIGURE 10 Sidewalks incorporating the dome-shaped formwork system.

CONCLUSIONS

While the technical evaluation of this system is ongoing, the performance data obtained to date from these case studies suggest that this technology has great potential as a sustainable technology, particularly in concrete pavement applications. Sustainability is becoming an increasingly important consideration in transportation infrastructure design and construction. New, innovative systems and products, such as the structural dome formwork system, must be considered for their technical, environmental, social and economic benefits. The possible benefits of the dome-shaped formwork have been found to be diverse, and can help agencies meet their sustainability goals in a cost-effective way. Many more possible applications for this formwork system exist and await to be uncovered.

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