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EXPERIMENTAL STUDY OF CONFINED CIRCULAR CONCRETE SPECIMEN WITH HEATED SHRINK PLASTIC FILM (HSPF)

HOONG-PIN LEE[1,*], JIAN-HENG MOK[1],
HAN-SIN CHEONG[1], YI-FENG LIM[1], KENNETH LEE[1],
NURHARNIZA A. RAHMAN[1], WEN-PEI LOW[1], SK MUIZ A. RAZAK[2]

[1]Department of Civil Engineering, Faculty of Engineering and
Quantity Surveying, INTI International University, Persiaran
Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Sembilan, Malaysia
[2]Faculty of Civil Engineering Technology, Universiti Malaysia Perlis,
02600 Arau, Perlis, Malaysia
*Corresponding Author: hoongpin.lee@newinti.edu.my

Abstract

Concrete dilation plays an important role in compressive strength where it leads to concrete cracking at its ultimate due to low ductility and brittleness. Studies have reported good performance of confined concrete in enhancing such behaviour under either passive or active confinement, where passive confinement requires compression loading to activate confinement efficiency, while active confinement activates prior to loading. Active confinement necessitates skilled labour and is more expensive than formal confinement. Heat Shrink Plastic Film (HSPF) is proposed as a new and novel active confinement for concrete, with significant advantages such as low cost, easy to operate and active confinement behaviour. This paper discusses the performance of HSPF-confined concrete specimens with various layers in their longitudinal and lateral stress-strain behaviour and volumetric strain. An empirical model was proposed for compressive strength prediction purposes. Eighteen concrete specimens of G25 were prepared and wrapped in 5-25 layers of HSPF confinement. Strain gauges were installed in longitudinal and lateral directions and tested under compression tests following ASTM-C39. It is noticed that the higher the layers of HSPF confinement, the better the strength enhancement, where 5 layers of HSPF give a strength increment of 5%, while 25 layers give a 75% to control concrete. Volumetric strain behaviour evidenced that HSPF confinement with 15 layers and above shows active confinement. A prediction model was proposed and compared with several existing studies. The trend is identical at a lower volumetric ratio, and the current model shows better performance at a higher volumetric ratio. Overall, HSPF-confinement has been proven as an active confinement, which makes it a suitable option for structural retrofitting.

Keywords: Concrete confinement, concrete upgrade, heat shrink plastic film (HSPF), product innovation, resilient infrastructure.

1. Introduction

In the past decades, research has intensively proven that external confinement is effective in upgrading the strength capacity and post-peak ductility behaviour of confined concrete [1-4]. This has made it a suitable structural upgrading and retrofitting method to accommodate higher structural loads and solve concrete's brittleness upon reaching ultimate [5-8]. Such advantages make external confinements popular in structural strengthening and retrofitting. A variety of confining methods are proposed, such as fibre reinforced polymer (FRP), steel strapping tensioning technique (SSTT), reinforced concrete (RC) jacketing, and concrete filled tube (CFT). However, the execution mechanism of confinement needs special equipment, skilful labour, and a tedious process to take care of it.

FRP requires epoxy as an adhesive material, which is weak against weathering. Moreover, a skilful technical person is needed throughout the whole installation process [9]. Therefore, FRP confinement is generally classified as passive confinement which has been well documented [10]. CFT requires steel tube pre-fabrication as external confinement [11], and the infill concrete materials used to bond concrete core and tube are important, so efficiency of confinement is secured [12, 13]. SSTT confinement needs a special machine and compressor to perform confining stress. The rigidity of the connection clip is critical for sustaining dilation forces when loaded [13, 14].

RC jacketing requires highly skilled workers and a high manufacturing cost owing to the concern about corrosion on steel jackets since defective steel will devastate its effectiveness [15]. Minor mistakes in any processing stage might lead to confinement inefficiency. Moreover, the majority of the existing confinement methods mentioned above consist of passive confinement, where the confinement efficiency is doubtful when a confined structure is in service. Passive confinement needs larger lateral dilation from the concrete core under loading to mobilise the confinement effectiveness, while active confinement starts to mobilise prior to loading [16]. To achieve this, majority of confinement technique utilizes expansive concrete in generating lateral tension force onto the concrete core [15].

All research work conducted shown positive improvement in strength enhancement, but the execution technique makes the confinement work more tedious, and efficiency and consistency are the biggest challenge. Hence, it is important to propose a confinement method that is able to provide an easy confinement method yet is promising in strength and ductility enhancement.

Commonly, external confinement is subjected to a triaxial state of stress under compressive load, resulting in the strength and ductility enhancement of the confined concrete [4]. Such confinement provides passive confinement where its efficiency relies on concrete dilation, or in other words, Poisson's effect. External confining pressure is needed to achieve active confinement. Past research shows better results in axial stress, axial strain, and ductility with active confinement, where confining materials are mobilised prior to loading and work immediately upon loading [15, 17].

At a given axial strain, lateral strain, and confining pressure, actively confined concrete exhibits higher axial stress performance than concrete with passive confinement. However, in spite of these encouraging results, the active confinement method is less popular due to its practical limitations using conventional mechanical pre-stressing techniques and the needs of skilful technical personnel. Hence, a proposal is needed for a new low-cost confinement method that is able to exhibit active confinement with a simple technique.

In this paper, a new and novel confinement method is presented - Heat Shrink Plastic Film (HSPF) confinement. This technique uses the heat-shrink characteristic of plastic film to exert confinement on the concrete core. To date, there are no available resources for such confinement on concrete, and only a heat dryer is used to perform the confinement work. The main objective of the experimental research is to study the compressive strength performance of concrete with various layers of HSPF confinement. A systematic experimental study has been conducted based on uniaxial compression test result on the behaviour of HSPF-confined concrete with different volumetric ratios is presented. The behaviour of these specimens was then examined in terms of stress-strain relationships in the longitudinal deflection, transverse strain, mode of failure, and volumetric strain. Based on the comparison between the volumetric ratio of HSPF and enhance compressive strength, a strength model for HSPF confinement on concrete is proposed at the end of the paper.

2. Experimental Work

The materials preparation and the methods used to conduct the experiments are explained in the following section.

2.1. Materials, proportion, and specimen preparation

All the concrete used in this study was prepared using ready-mix concrete G25, with a water-binder ratio of 0.55 and a slump of 75 mm. Ready-mix concrete can improve the concrete's consistency and homogeneity, reducing the chances of human error during manual mixing. The mix proportion is presented in Table 1 below. All the concrete cylindrical specimens were prepared in one go. To ensure that fresh concrete could be placed in formwork without premature hardening, a retarder admixture was added to the mixture to delay the concrete's setting time.

A total of 18 cylindrical specimens of dimensions of 150 mm × 300 mm in diameter and height, respectively, were prepared. Moist curing was stopped at 28 days, and concrete specimens were wrapped with HSPF confinement with prescribed layers. As a control, three concrete specimens were left unconfined, while the remaining three concrete specimens were wrapped in 5, 10, 15, 20, and 25 layers of HSPF confinement. The method of confinement is illustrated in the next section.

Table 1. Mix proportion of concrete used in the study.

Raw Material	Mix Proportion (kg/m^3)
Ordinary Portland Cement	248
Pulverised Fly Ash	66
Coarse aggregate, crushed, 20 mm nominal	1015
Fine aggregate, natural sand	831
Retarder	0.5
Water-binder ratio	0.55

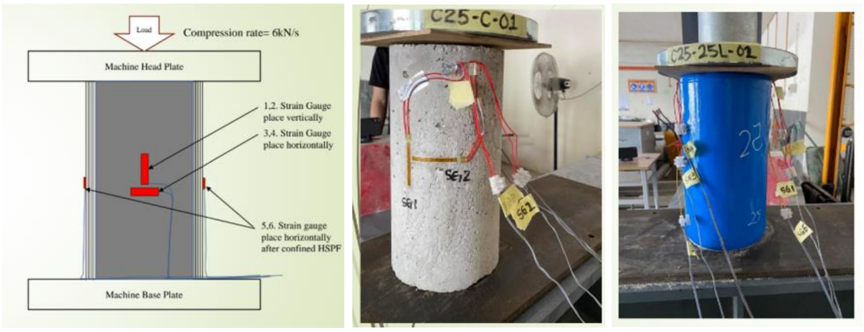
2.2. Confining Method and Experimental Setup

Heated Shrink Plastic Film is a polymer-type plastic film that shrinks when exposed to heat. For this study's use, the HSPF physical properties require a 0.07 mm thickness and a density of less than 1.33 kg/m^3. The tensile strength of HSPF under machine direction (MD) and cross direction (TD) is 60 MPa (> 500% elongation) and 200 MPa (> 40% elongation), respectively. The heat shrink property of HSPF is about 5% and 60% for both MD and TD, respectively. Film's shrinkage will tightly wrap any object it covers, as illustrated in Fig. 1.

HSPF confinement can be properly done layer by layer with a handheld heat gun and heat blow on the wrapped plastic film evenly under a heat temperature of 105 °C. As an example, for a 5-layer confined concrete specimen, it is first wrapped with the first layer of HSPF, and then the film is heat blown till it is tightened. Afterward, the same step continues until the last HSPF layer is done. During heat blow, it is to be reminded not to over-tighten the plastic film, as over-heat will break the film.

Fig. 1. Heat blow of 105 ◦C on HSPC confined concrete.

Strain gauges were installed to measure the longitudinal and lateral dilation of unconfined and confined specimens. For control concrete, 2 longitudinal and 2 lateral strain gauges were installed in diametrically locations, while for confined concrete, an additional 2 lateral strain gauges were installed on the surface of HSPF in a diametrically location. It is important to clean the concrete surface with acetone before installing the strain gauge. This is to make sure the strain data collected is perfect and without disturbances. CN glue was used to stick strain gauges on the surface of control concrete and plastic film. Strain gauges' connections were set up with a data acquisition system, and they were ready to be loaded under a uniaxial compressive strength test once they were ready. Figure 2(a) illustrates the schematic diagram for the installation location of the strain gauges, while Fig. 2(b) and 2(c) show the actual installation of strain gauges on unconfined and confined concrete specimens, respectively. All unconfined and concrete specimens were tested under uniaxial compressive strength tests at a pace of 6 kN/s until failure in compliance with ASTM C39. A 3 mm wooden plate was put at the top and bottom of the specimen during testing to avoid any inconsistency due to uneven surfaces. Failure modes of concrete specimens were observed and recorded while stress-strain readings were obtained from the data acquisition system.



(a) **(b)** **(c)**

Fig. 2. Strain gauges installation on unconfined and HSPF confined specimens: (a) schematic diagram; (b) strain gauges on control concrete; (c) strain gauges on confined concrete.

3. Experimental Results and Discussion

The following section discusses about the results examined, including mode of failure, stress-strain behaviour, and a strength model equation fits to the experiment is proposed.

3.1. Concrete specimens' failure modes

For unconfined concrete specimens, the failure mode is generally explosive with diagonal shear failure. It occurs at the ultimate point, without giving any adequate warning or sign. Figure 3 shows the failure mode of an unconfined specimen under a uniaxial compressive test. Due to page constraints, only three representative samples are shown.

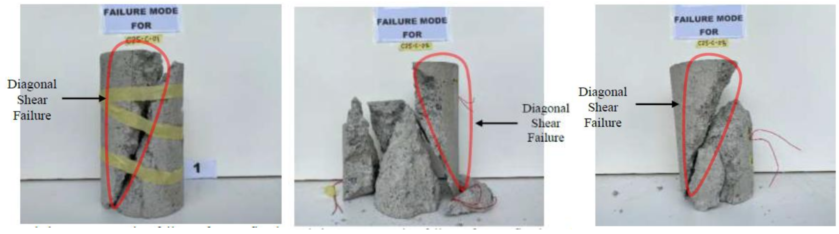


Fig. 3. Failure modes of unconfined concrete specimens.

Generally, for HSPF confined concrete specimens, cracking sounds and small explosions were heard, but no failure was observed like for unconfined specimens. This is due to the release of the stored energy in concrete when the confinement energy is not able to hold it. It can be observed with the fracture of plastic film at the top and bottom regions of confined specimens. There was no explosive failure observed, with HSPF confinement, but when the plastic film was removed, concrete was observed to bulge in the typical diagonal shear failure plane and crush along the crack line, as indicated by the circle in Fig. 4(a). However, no collapse occurred, but there was permanent displacement or bulging due to lateral dilation. Figs. 4(a) and (b) show the modes of failure for concrete with HSPF confinement and concrete after the confinement has been removed, respectively.

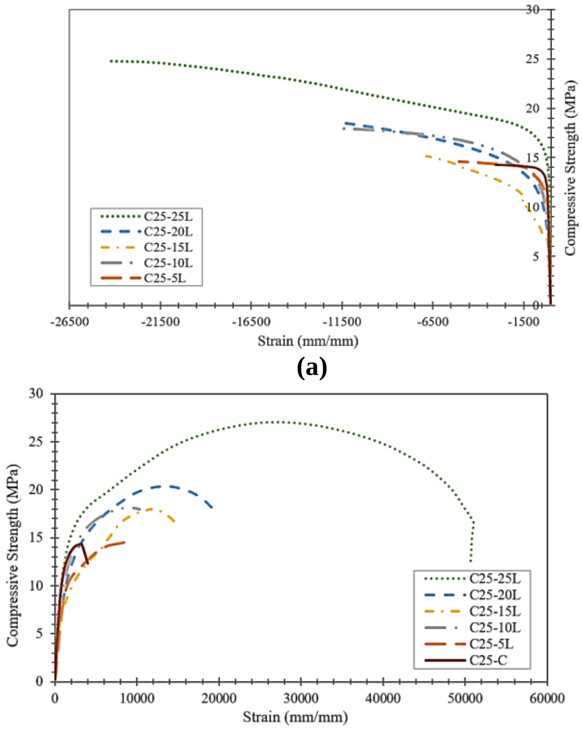
Fig. 4(a). Modes of failure of HSPF confined concrete specimens at 4 different angles.

Fig. 4(b). Modes of failure of HSPF confined concrete specimens at 4 different angles, after taking off the confined plastic film.

3.2. Stress-strain behaviour of HSPF confined concrete specimens

Figure 5 shows the stress-strain curve for unconfined and HSPF confined concrete specimens in both lateral (a) and longitudinal (b) directions. The concrete samples were named with the following annotations: C25 refers to the concrete grade, -C refers to the control concrete sample, while -5 L to 25 L refers to the layers of HSPF confinement. It was noticed that the stress-strain behaviour of 5-layer HSPF confined concrete specimens was near to similar in compressive strength to unconfined concrete, but the latter failed prior to peak strength. The ultimate compressive strength for the concrete cylinder specimen group was at about 15 MPa, while the 10-layer and 15-layer HSPF confined concrete specimens had a similar stress-strain pattern at 17 MPa of compressive strength. Due to a higher confinement ratio, 15-layer specimens were able to sustain more strain. Other than that, confined specimens with 20 layers and 25 layers were found to have 20 MPa and 28 MPa of compressive strength, respectively. Moreover, the confined specimens with a 25-layer HSPF confinement showed extremely high strain compared to others. It can be concluded that the compressive strength of a confined concrete specimen is directly proportional to the confinement ratio. The ductility of a confined specimen can also be enhanced when the confinement layers are increased. The higher the confinement layers, the more difficult it is to install. Hence, in this study, the HSPF confinement is limited to 25 layers.

Figure 6(a) shows the stress-strain curves for HSPF confined specimens in a lateral direction, installed on the external surface of the confinement. It is to check the mobility of the confinement under compressive loading. Overall, HSPF confinement did not mobilise at the beginning of the test, and it started to respond laterally at about 5 MPa of compressive strength due to concrete control's lateral dilation. HSPF confinement starts to dilate aggressively when the compressive load reaches 90% of its respective ultimate load. This phenomenon is not applicable to specimens with 25 layers of HSPF confinement, where they dilate aggressively at about 70% of their respective ultimate load. The minimum and maximum stain capture are about 15000 mm/mm (231%) for unconfined concrete specimens and 35000 mm/mm (538%) for unconfined concrete specimens, respectively. Hence, it can be concluded that concrete with HSPF confinement is able to delay the failure at higher deformation or stain and protect the concrete control from sudden failure.

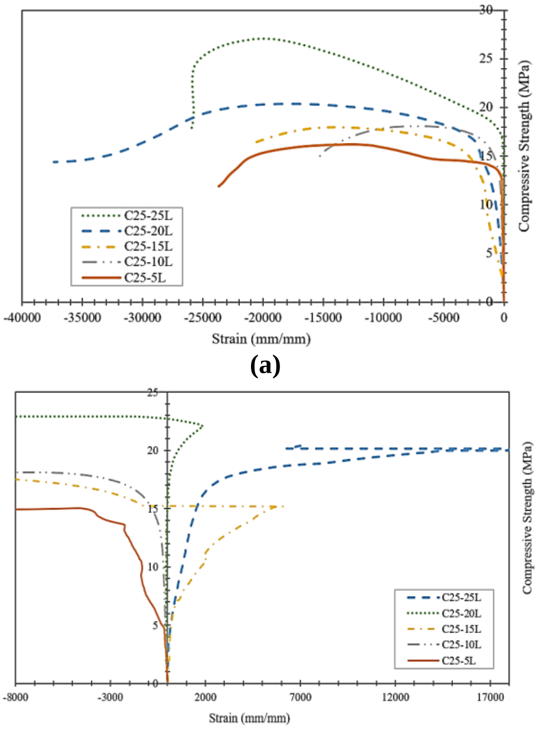


(a)

(b)

Fig. 5. (a) lateral stress-strain curves; and (b) longitudinal stress-strain curves for unconfined and HSPF confined concrete specimens.

The confinement mechanism is different for active and passive types. Hence, it is important to understand the type of confinement applied so that a proper confinement execution can be applied. In addition to stress-strain behaviour, concrete with confinement under a uniaxial compression load will exhibit volumetric changes. Before the concrete fails under the load, it exhibits a volumetric strain contraction. After all, due to the propagation of microcracking in the material microstructure, the concrete invariably undergoes a volumetric strain expansion before concrete failure occurs. The concrete's volumetric strain contraction will be more obvious when concrete is confined with a confining stress like HSPF confinement prior to loading [18, 19], where a steeper curve will be obtained. Volumetric strain, εv, is used to illustrate the dilatancy behaviour of confined concrete and can be written as: $\varepsilon v=\varepsilon c+|2\varepsilon j|$, where εc and εj are the longitudinal and transverse strain directions or hoop strains for concrete, respectively. A positive value indicates the volumetric strain contraction, while a negative value indicates the volumetric strain expansion.



(a)

(b)

Fig. 6. (a) lateral stress-strain curves; and (b) volumetric strain curves for HSPF confined concrete specimens.

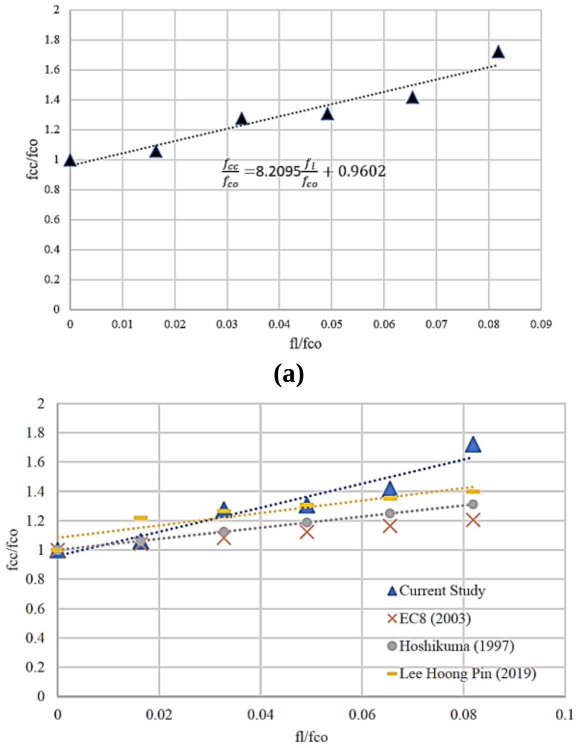
Figure 6(b) illustrates the volumetric strain behaviour for HSPF-confined concrete specimens. The unconfined concrete specimens only experienced strain expansion without any contraction. It dilates continuously from the initial stages of loading. This phenomenon occurs on confined concrete with 5 layers and 10 layers of HSPF, indicating a passive confinement type. It may be due to the low volumetric confinement of HSPF. The inability to sustain the lateral dilation forces exerted by control concrete results in no compressive strength enhancement except in ductility. For higher confinement volumetric ratios (15 layers and above), all exhibit active confinement behaviour, where they experience higher volumetric strain contractions until reaching the concrete’s ultimate capacity and gradually fail in the volumetric strain expansion region. The moving curves indicate the negative direction in the volumetric strain curves and gradually fail in the region. This occurs due to the lateral confining stress exerted by HSPF confinement, leading to a higher axial concrete strain than that of radial concrete expansion. Hence, such confinement can be considered “active confinement.”

3.3. Proposed strength model equation

Figure 7(a) presents the proposed strength model equation for HSPF confinement, while Fig. 7(b) compares the strength model proposed in this study to existing studies. The existing models consist of different types of confinement, such as reinforcement steel confinement, FRP confinement, and steel strapping confinement. Based on the average compressive strength results of each confined concrete specimen group, a strength model equation is proposed, as follows:

$$\frac{f_{cc}}{f_{co}} = 8.2095\,\frac{f_1}{f_{co}} + 0.9602 \tag{1}$$

where f_{co} and f_{cc} are the ultimate compressive strengths of unconfined and confined concrete specimens, respectively, while f_l is the volumetric ratio of confined concrete, i.e., the ratio of the confinement volume to the concrete volume. The R-square for the proposed model is 0.93, which indicates good consistency of HSPF confinement in strength enhancement to its confinement layers at a gradient of 8.21. HSPF confinement shows identical strength enhancement when the volumetric ratio is below 0.05 but surpasses the rest with better strength enhancement when the volumetric ratio is above 0.05. This shows that HSPF confinement is applicable in the construction industry, especially in structural upgrade, repair, and rehabilitation. The proposed model is limited to concrete strength below 30 MPa and with an HSPF confining ratio of below 25 layers.



(a)

(b)

Fig. 7. (a) Proposed model equation based on experimental study; (b) comparison of proposed model equation with existing studies.

4. Conclusions

This study investigated the strength of confined and unconfined concrete with various layers of HSPF. There are discussions on the stress-strain behaviour of unconfined and confined concrete specimens in both longitudinal and lateral directions. A strength model is proposed at the end of the study. Several conclusions can be drawn, as follows:

- HSPF confinement is a new method of confining concrete specimens, and it is proven in the current study on its capability to enhance the concrete's compressive strength and ductility behaviour beyond ultimate. This also demonstrates the suitability of such confinement for use as repair and rehabilitation materials in concrete structures. From the experimental study, the higher the confinement layers (volumetric ratio), the higher the strength enhancement. Compared to unconfined concrete, the strength enhancement percentage of HSPF confinement of 5 layers, 10 layers, 15 layers, 20 layers, and 25 layers is 5%, 27.5%, 30.5%, 41.6%, and 75%, respectively.
- With HSPF confinement, concrete's brittle behaviour can be enhanced. Confined concrete specimens were not explored and collapsed when compressive strength was at its ultimate. HSPF confinement safeguards and protects concrete structures even after reaching peak load.
- A strength model is proposed for HSPF confinement. It shows similar commitment to existing models at a low volumetric ratio but gives superior performance at a higher volumetric ratio. The strength model is capable of providing useful parameters in concrete confinement design.

It is to be noted that the current outcomes are based on an experimental scaled study, where the data collected was under good control conditions. Since a disparity might exist between experimental conditions and practical application, additional tests will be conducted on-site.

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Nomenclatures

f_{co}	Ultimate compressive strengths of unconfined concrete specimens, MPa
f_{cc}	Ultimate compressive strengths of confined concrete specimens, MPa
f_l	Volumetric ratio of confined concrete, i.e., the ratio of the confinement volume to the concrete volume.

Greek Symbols

ε_c	Longitudinal strain directions or hoop strains for concrete, mm/mm
ε_j	Transverse strain directions or hoop strains for concrete, mm/mm
ε_v	Volumetric strain.

Abbreviations

ASTM	American Society for Testing and Materials.
CFT	Concrete filled tube.
FRP	Fibre reinforced polymer.
HSPF	Heated shrink plastic film.
MD	Machine direction.
RC	Reinforced concrete.
SSTT	Steel strapping tensioning technique.
TD	Cross direction.

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