

## SHORT TERM DURABILITY OF STEEL-STRAP CONFINED CONCRETE

Hoong-Pin Lee<sup>a,b\*</sup>, Abdullah Zawawi Awang<sup>b\*</sup>, Wahid Omar<sup>b</sup>

<sup>a</sup>Department of Civil Engineering, Faculty of Engineering and QS, INTI International University, 71800 Nilai, Negeri Sembilan, Malaysia

<sup>b</sup>Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

### Article history

Received

12 November 2015

Received in revised form

27 March 2016

Accepted

15 June 2016

\*Corresponding author  
hoongpin.lee@newinti.edu.my

### Graphical abstract



### Abstract

Steel strapping tensioning technique (SSTS) confinement has been proven as a type of external confinement to retrofit and upgrade concrete structures. Their remarkable enhancement to concrete mechanical properties, practicing active lateral confinement, low cost, easy to operate, time saving and no structure interruption during application have brought this technique as of the most affordable technique for column confinement, especially for high strength concrete (HSC) which naturally behaves insufficient in ductility. Although a great number of previous studies have demonstrated the performance of SSTS confinement, there are several anxieties related to the long term behaviour of SSTS confined columns which have yet been implemented especially in real hostile condition. Environmental effects, such as ultraviolet radiation exposure and saline solution (sea water) may affect the confining material properties, and therefore decrease the performance of the confined columns. In this study a total of twenty HSC specimens with dimension of 100 mm and 200 mm in diameter and height respectively were prepared, volumetric-identically pre-tensioned with steel strap and exposed to three conditions: indoor, outdoor and saline water for three months. The exposed specimens were monotonically tested and their performance was studied through the stress-strain relationship, mode of failure and degree of corrosion. The results show that none of the forenamed environmental conditions have exaggerating influence on the performance of the SSTS confined concrete specimens even some material has been severely corroded. It is then parallel compared with existing FRP confinement studies and the result proves that SSTS confinement able to possess the highest strength performance under similar environmental exposure.

**Keywords:** High strength concrete, steel strapping tensioning technique, lateral confinement, durability performance, environmental exposure test

### Abstrak

Teknik lilitan sisi keluli (SSTS) telah terbukti sebagai salah satu jenis lilitan sisi luaran yang boleh digunakan untuk membaikpulih dan menaik-taraf struktur konkrit. Peningkatannya yang ketara terutama terhadap sifat mekanikal konkrit, menjana tegasan sisi aktif, bahan dan teknik yang kos rendah, mudah dipasang, menjimatkan masa dan tidak mengganggu penggunaan struktur semasa kerja pemasangan dilakukan telah menjadikan ia satu teknik yang boleh diguna dalam industri, terutamanya bagi konkrit berkekuatan tinggi (HSC) yang berkemuluran rendah secara semula jadi. Walaupun banyak kajian telah menunjukkan prestasi SSTS yang baik, namun masih terdapat beberapa kebimbangan terhadap kegunaannya pada jangka masa yang lebih panjang, terutamanya pendedahannya dalam keadaan persekitaran sebenar. Kesan alam sekitar, contohnya pendedahan kepada sinaran ultraungu dan air laut boleh memberi kesan kepada bahan lilitan, dan oleh yang demikian, mengurangkan prestasi

struktur berlilitan sisi tersebut. Dalam kajian ini, sebanyak 20 spesimen HSC yang berdiameter 100 mm dan 200 mm tinggi telah disediakan dan dipra-tegangkan dengan bilangan lilitan sisi keluli yang sama. Spesimen tersebut kemudiannya didedahkan kepada 3 keadaan persekitaran, iaitu dalam bilik tertutup, di luar bilik dan dalam air masin selama 3 bulan. Spesimen yang didedahkan telah diuji dengan beban mampatan paksi *monotonic* dan prestasi spesimen dikaji melalui hubungan tegasan-terikan, mod kegagalan dan tahap kakisan pada permukaan lilitan sisi keluli. Keputusan kajian menunjukkan bahawa keadaan persekitaran tidak mempunyai pengaruh ke atas prestasi SSTT walaupun terdapat beberapa lilitan keluli telah berkarat dengan gred yang tinggi. Keputusan tersebut kemudiannya dibanding setara dengan kajian lilitan FRP yang sedia ada. Keputusan perbandingan menunjukkan bahawa SSTT memiliki prestasi yang paling tinggi di bawah pendedahan alam sekitar berbanding dengan keadaan pendedahan yang lain.

**Kata kunci:** Konkrit berkekuatan tinggi, teknik lilitan sisi keluli, lilitan sisi membujur, prestasi ketahananlasakan, ujian dedahan persekitaran

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## 1.0 INTRODUCTION

The use of SSTT as new lateral confinement method for concrete members in structural repairing and rehabilitation industry has been proven by researchers with its remarkable benefits such as low in material cost, easy confinement method, short operation time, no structural interruption during application and less depending on experienced worker [1]–[10]. Before it has been named as SSTT, pre-tensioning of steel straps around concrete specimens with notches on the clips connection have been done by fully utilizing the technique from packaging industry [1]–[6]. Later, with modification on the connection clips, Awang, *et al.* succeed to secure the pre-tensioning stress without applying notches on the clips; by emphasizing the multi-layer confining effect, SSTT has been proven able to improve the compressive capacity and ductility of concrete members, especially for HSC which naturally behaves brittle and low in ductility [7]–[10].

Although several experimental studies have demonstrated the effectiveness of SSTT as lateral confinement for structural members, important questions related to durability behaviour have not been addressed yet. Proposed design guidelines for such confinement were purely based on instant laboratory testing. Corrosion on steel strap might reduce the efficiency of SSTT confinement in a longer term as the confining material is made of steel. The confining material may undergo different service condition and corrosion rate when expose to different hostile conditions, for instance outdoor exposure, indoor exposure and sea water exposure.

This paper presents the result of an experimental study on the short term durability performance of a series of volumetric-identically confined HSC using SSTT. The testing specimens consist of uncoated and externally coated steel strap with special paint; were exposed under three important environmental conditions in Malaysia: indoor exposure, outdoor exposure and saline water exposure. The performance of these exposed confined specimens was then studied through their stress-strain relationship upon the

longitudinal deflection, mode of failure, and level of corrosion. Test setup and results obtained are presented and examined in section 2.0 and 3.0 respectively.

## 2.0 EXPERIMENTAL PROGRAM

### 2.1 Specimens Preparation

In order to have an equitable comparison based on the effect of exposing environments to the confined specimens, concrete mix proportion and dimension, confining material's lateral pre-tensioning stress, and confining ratio were set to be consistence. Therefore, a set of twenty HSC cylinder column specimens with standard dimension of 100 mm and 200 mm in diameter and height respectively were prepared in line with the mix proportions given in Table 1 and underwent wet curing for 28 days. Each of the specimens were not reinforced with reinforcing bar. The average concrete compressive strength,  $f'_c$ , at 28 days was about 60 MPa.

After 28 days of curing, the specimens were pre-tensioned laterally with same amount of volumetric ratio (i.e. a single layer of steel strap) as presented in Table 2, by using tensioner. Pre-tensioning work should be stopped once the steel strappings were tightened and the surplus steel strapping was bended to lock the pre-tensioning stress. The steel strapping used in this study as confining material was "blue tempered waxed coated steel strapping" with average width and thickness of 15.85 mm and 0.55 mm respectively. The average ultimate tensile stress of the steel strapping used in this study was about 828 N/mm<sup>2</sup> based on standard test BS EN 10002-1:1990 [11]. The spacing between straps was fixed at 10 mm along the middle section and about 7.5 mm at the two end regions (to have an equivalent volumetric ratio of 0.1 in compliance with EC8 [12]) to provide sufficient confinement and reduce the possibility of premature failure at the two end regions of the specimens during testing (refer to Figure 1(a)).

While for external coated steel strapping, before applying the coating to the assigned specimens, it is important to make sure the surface of concrete and steel strapping were clean, dry and free from contamination. This is to make sure a good bonding between the specimen and coating. As recommended by the product manual, two layers of

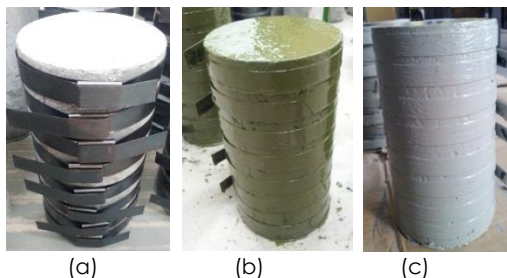
full coverage coating, including the exposed concrete surface and connection clips were painted without specifically coating thickness control. The freshly coated specimens (Figure 1) were left to dry for two days in room temperature before proceed to exposing environments.

**Table 1** Concrete mix proportion for High-Strength Concrete

MATERIALS	TYPE	QUANTITY
Cement	Type I OPC	550 kg/m <sup>3</sup>
Fine Aggregate	River Sand	885 kg/m <sup>3</sup>
Coarse Aggregate	Maximum Size of 12mm	957 kg/m <sup>3</sup>
Superplasticizer	Glenium ACE 388(RM)	0.75% of 100kg cement
Water	Fresh Water	190
Water / Cement Ratio	-	0.35

**Table 2** Testing program for durability of SSTT confined specimens

Exposure Category	Number of specimen	SSTT Confinement Status	External Coating Status	Period of Exposure (months)
Indoor Exposure (under controlled temperature 23±2°C)	2	Unconfined	Uncoated	0
	2	Confined	Uncoated	0
	2	Unconfined	Uncoated	3
	2	Confined	Uncoated	3
Outdoor Exposure (under sun and rain, outside the laboratory)	2	Unconfined	Uncoated	3
	2	Confined	Uncoated	3
	2	Confined	ZC	3
Saline Water Exposure (5% of NaCl with controlled temperature 23±2°C)	2	Unconfined	Uncoated	3
	2	Confined	Uncoated	3
	2	Confined	MP	3
<b>Total</b>	<b>20</b>			



**Figure 1** Externally coated specimens; (a) uncoated specimen; (b) ZC coating; (c) MP coating

## 2.2 Environmental Exposure

The main objective of this study is to investigate the durability performance of SSTT confined HSC columns exposed in 3 different environmental conditions for 3 months period. A total of 20 HSC column specimens were prepared, pre-tensioned with a single layer of steel strapping and assigned into particular exposure category as shown in Table 2. A series of specimens were coated with alkyd-based rust inhibitive (zinc chromate - ZC) primer or high solids epoxy-based primer (marine paint - MP) respectively to study the efficiency of external coating to corrosion in different

exposing condition. The durability performance of the confined column specimens were determined by evaluating its uniaxial compressive capacity after prescribed period of exposure. Details of the environmental conditions along with the test result are presented in next section.

### 2.2.1 Indoor Exposure

Eight specimens were kept in controlled room as control specimens for specific period of exposure, i.e. 0 month and 3 months. For each age of exposure, two specimens were pre-tensioned with a single layer of steel strapping whereas two were left unconfined as shows in Figure 2(a). The temperature of the controlled room was fixed at  $23 \pm 2^\circ\text{C}$  all along the testing period. Two humidifiers were used to control the humidity of the control room at a dry condition.

### 2.2.2 Outdoor Exposure

Six specimens were exposed to outdoor environment outside the laboratory. Two specimens were pre-tensioned with a single layer of steel strapping, followed by two specimens without any confinement

and the other two specimens with confined single layer steel strapping were coated with ZC coat for corrosion protection. The specimens in this category were directly exposed to tropical climate in Malaysia for a period of 3 months. The atmospheric exposure test was conducted as suggested in ASTM G50-10 [13], where an adjustable exposure rack was fabricated and fixed on an exposure angle of 30° from the horizontal, the rack was facing south, and the lowest specimens were at least 760mm above the ground to obtain the maximum exposure to the environment as shown in Figure 2(b). The tropical climate conditions of Malaysia during the exposure period (month of Jun to August 2012) in Malaysia are presented in Table 3.

### 2.2.3 Saline Water Exposure

This exposure involved submerging of six specimens into saline water (5% of NaCl solution), whereby two specimens were unconfined as control, two specimens were confined with a single layer of steel strapping and the other two were confined with a single layer of steel strapping and externally coated with MP coat. The exposure was carried out in control room with controlled temperature at  $23 \pm 2^\circ\text{C}$  for three months period as shown in Figure 2(c). Effects of environmental condition and corrosion on steel strapping for unconfined, confined and marine paint coated confined specimens under this exposure were studied through stress-strain relationship under uniaxial compression load test.



**Figure 2** Concrete specimens for (a) indoor exposure, (b) Outdoor exposure, (c) saline water exposure

**Table 3** Average Johor Bahru, Malaysia monthly temperature and relative humidity around the year

Month	Average Temperature °C (Min)	Average Temperature °C (Max)	Relative humidity %
June 2014	26.0	31.8	85%
July 2014	25.7	31.2	85%
August 2014	25.7	31.2	85%

### 2.3 Test Setup

The unconfined and confined specimens were tested under compression load after the designed exposing period (i.e. zero and three months) to evaluate the short-term durability performance of SSTT-confinement. The compression load tests were conducted using TINUS OLSEN Super “L” Universal Testing Machine which has the capacity of 3 MN in Universiti Teknologi Malaysia. The rate of compressive loading was programmed based on displacement-controlled loading strategy with a slow constant loading rate of 0.0067 mm/s until more than 50 percent of strength decay or abnormal stress-strain values was observed, indicating the failure of specimens.

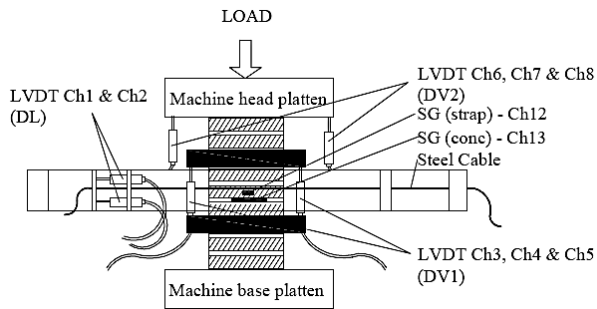
A total of eight linear variable differential transducers (LVDTs) and four strain gauges were used to measure the longitudinal and lateral strains of the confined specimens as illustrated in Figure 3. The

overall longitudinal strains (DV2 in Figure 3) of the specimens were obtained using three LVDTs mounted at the surface of the machine head platen, while another three LVDTs were installed in Longitudinal LVDT holder rig (DV1) which attached to specimen by bolts to measure the relative strains over the middle 0.5 height of the specimens. The lateral circumferential strains of the specimens were measured using two LVDTs installed in the Lateral LVDT holder rig (DL) placed at the center, by circumferentially tied a flexible steel cable around the specimens.

Two sets of strain gauges for concrete and steel strapping were attached at the center of specimens in diametrically opposite direction to measure the lateral strains of concrete and steel strapping during the load test. All strain measuring instrumentations were connected to a data acquisition system to record the values of stress and strain values obtained. During testing, any apparent cracking pattern,



buckling, deformation, steel strapping fracture, etc., were recorded. The uniaxial compression strength of cylinder column specimens were tested in compliance with ASTM C39/C39M-11 [14].



**Figure 3** Diagram for strain measuring equipment and the loading device (TINIUS OLSEN Super "L" Universal Testing Machine)

### 3.0 RESULT AND DISCUSSION

#### 3.1 Evaluation Degree of Rusting After Exposure

Right after all the specimens were exposed to respective exposure environments for three months, all activities were terminated and the degree of rusting on the surface of steel strappings was visually evaluated according to ASTM D610-08 [15]. A rust grade of range 0 to 10 was rated by referring to the percentage of surface area rusting and visual examples given in guideline, where rust grade 0 delegates the severe surface corrosion and vice-versa. Figure 4 shows the rusting condition of uncoated confined specimens for three different exposure environments. After three months exposed in laboratory under controlled temperature (indoor exposure), there was no significant surface rusting on the steel strapping for the uncoated confined specimens (given rust grade 10). Adversely, for uncoated confined specimens underwent outdoor exposure under field condition, the surface of steel strapping was entirely rusted, rated with rust grade of 0. While for those specimens exposed under saline water exposure, a moderate surface rusting with rust grade 3 was observed. Besides, for coated confined specimens, the steel strapping was ideally shielded by both coating materials, regardless of exposing

environments as shown in Figure 5. All specimens were surface-dried under open air before proceed to compression load test.

#### 3.2 Effect of Environmental Exposures to Confined Specimens

Table 4 shows the average compressive strength result of control specimen and confined specimens underwent different exposures for three months. A series of unconfined specimens (control) without undergo any environmental exposure were compressively tested its immediate characteristic strength, and averagely results 66.13 MPa. While for unconfined specimens exposed under indoor and outdoor environment, there were no major disparities for its compressive strength ratio (see Table 4). However, there was about 53 % of compressive strength decrement for the unconfined specimens exposed in saline water. This decrement may due to the transportation of chlorine onto the concrete and then deteriorates the microstructure of the concrete. The average compressive strength for control specimens were used as the datum for comparison in next section.

Figure 6 and Figure 7 show the full longitudinal stress-strain relationship for SSTT-confined specimens which have been exposed to different environment for three months. It is noted that the curve for all tested specimens are not plotted for every group of specimens but representation of average curve is shown. This is to prevent messy presentation for the test result. By comparing the compressive strength of control and SSTT confined specimen (uncoated and unexposed), the results clearly show that there is about 40% increment in compressive strength as a result of a single layer steel strapping confinement. Besides, the results also show significant ductility enhancement in the post peak region. After the post peak region, the compressive strength of confined specimens remained constant at about 30 MPa, indicating the stabilization of the specimen and this should be noted that, the confined specimens in this stage were not collapsed suddenly as unconfined specimens does. However, current study investigates the exposures performance of a series of HSC specimens with fixed confinement ratio, strength gain may had reached the maximum value and may not be so high.

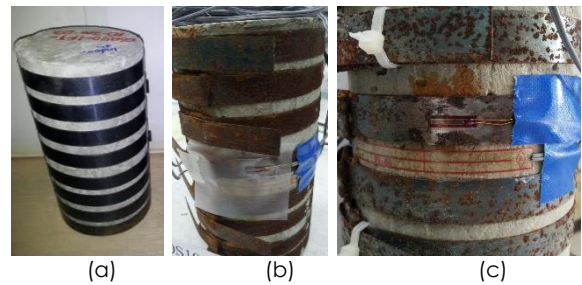
In order to visualise the effect of exposure condition on the durability of confined SSTT specimens, the performance results for outdoor, indoor and saline water exposures of these confined specimens without any coating were presented in Figure 6 as well. It is clearly reveal that the outdoor exposure (hot-wet tropical climate) did not cause any noticeable deterioration (with time for three months) to the SSTT confined specimens. Similar behaviour was obtained for those confined specimens exposed in saline water. But, about 15% of strength deterioration was observed for confined specimens exposed in indoor condition, with

controlled temperature and humidity. This decrement may due to the irregular confining pressure manually exerted by tensioner, and may not fully reprove to the exposure effect. Moreover, it is noted that for indoor exposure, there was no any defection or corrosion in the steel strapping, indicating the deterioration was not relied on exposure effect.

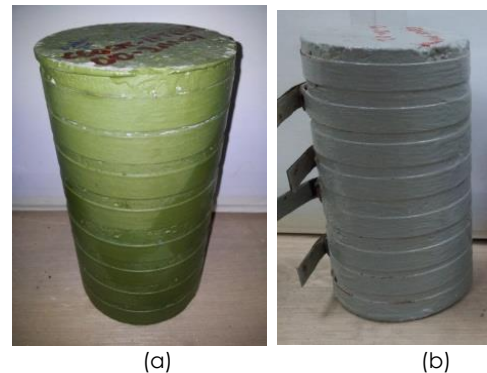
Furthermore, the strength performance for the confined specimens exposed to outdoor and saline water condition, with and without coating as prescribed in previous section for 3 months are presented in Figure 7. The results show that the strength performance for the specimens exposed to outdoor and saline water condition with and without coating (ZC and MP) are almost the same. In this study, it is noticed that the corrosion on steel strapping in different exposure conditions for a short exposing period do not attribute to strength deterioration but strength increment by about 25% comparing to the indoor exposed confined specimens. Since SSTT confinement relying on steel as the main confining material, it should not be denied that the strength deterioration may happen severely if the SSTT confined specimens are exposed to such exposure condition for a long time (e.g. number of years). Hence, further studies should be conducted to investigate performance of such confinement for a longer period of exposure.

Figure 8 illustrate the comparison graphs of current and existing studies of the strength performance versus exposure months for two similar exposure conditions (outdoor and saline water condition, without coating). As there is no existing study on the durability performance of SSTT confinement, existing study on FRP-type confinements are used. It is merit

to be mentioned that majority of existing works of different type of FRP-materials showed deterioration but strength increment for SSTT confinement.



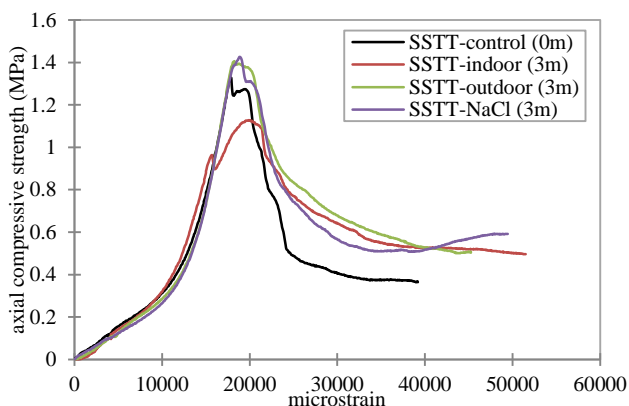
**Figure 4** Steel strapping surface rusting for uncoated confined specimens under (a) indoor exposure, (b) outdoor exposure, and (c) saline water exposure



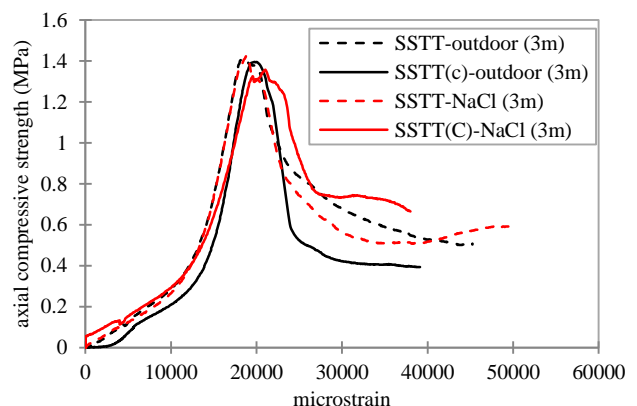
**Figure 5** Steel strapping surface rusting for (a) ZC coated confined specimen under outdoor exposure and (b) MP coated confined specimen under saline water exposure

**Table 4** Average test result of unconfined and confined concrete columns exposed under different environmental conditions

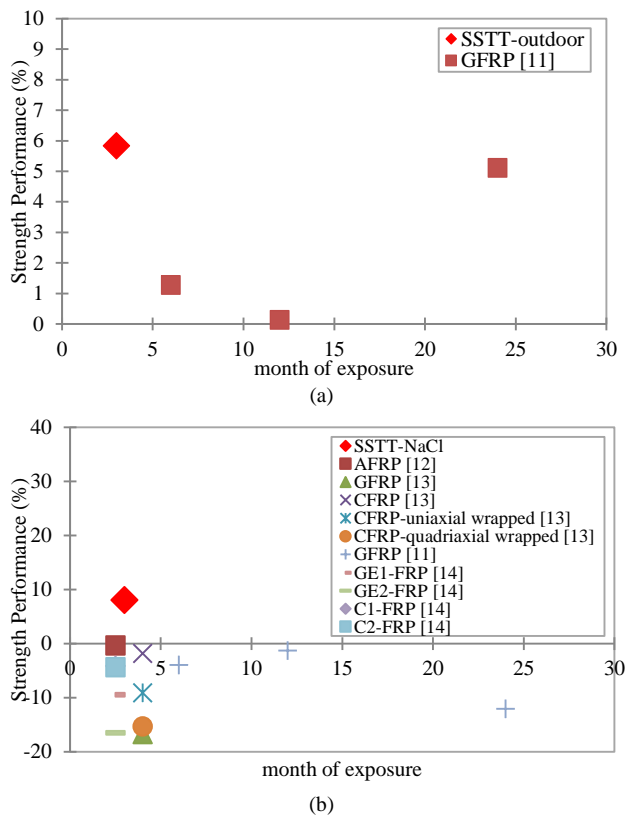
Unconfined specimen	Average compressive strength (MPa)	Compressive strength ratio
Unc – 0m (control)	66.13	1.00
Unc – ID – 3m	63.48	0.96
Unc – OD – 3m	73.07	1.10
Unc – SW – 3m	37.76	0.57



**Figure 6** Stress-strain relationship for uncoated confined specimens under different exposure environments



**Figure 7** Stress-strain relationship for coated confined specimens under outdoor and saline water exposures



**Figure 8** Comparison graphs of current and existing studies of the strength performance versus exposure months for two similar exposure conditions, (a) outdoor exposure, without coating, (b) Saline water exposure, without coating

Under the same environmental condition and exposing period of time, SSTS confinement shows better strength enhancement comparing to those FRP type confinement, especially for saline water exposure. For FRP-type confinement, none of the saline water exposed specimens able to retain positive strength performance but SSTS confinement able to holds the strength performance at +8%. This shows that SSTS confinement is more appropriate to be used in saline water condition as the epoxy used in FRP-type confinement is having reverse effect with the saline water environment. Further research endeavour is still needed to justify its reliability.

## 4.0 CONCLUSIONS

This paper deals with the strength performance of volumetric-identically confined SSTS confinement specimens exposed to different environment conditions, i.e. indoor, outdoor and saline water condition. Results from experimental testing have been presented and discussed in the form of stress-strain relationship. The experimental test results also have been compared with several existing studies to compare the strength performance of SSTS confinement. Therefore, the following conclusions may be drawn from the current study:

1. It was observed that SSTS confinement (without coating) exposed to different environmental conditions (i.e. indoor, outdoor and saline water exposure) for a period of 3 months shows no significant strength degradation. The exposed confined specimens still able to slow down the strength loss beyond the peak compression strength, providing a slow and safer concrete failure. An enhancement of about 40% in compressive strength has been obtained for the single layer SSTS confinement.
2. For coated SSTS confinement exposed with outdoor and saline water condition, the performance after the exposure also shows no strength deterioration compared to uncoated confined specimens. It is noted that with coating material, it can reduce and slow down the corrosion effect on steel strapping.

By comparing the current experimental result and existing studies, SSTS confinement possess the highest positive strength performance comparing to those FRP-type confinement. This indicates that SSTS confinement is suitable to be used in outdoor and under saline water for a short period of exposure.

## Acknowledgement

This research study is funded by the INTI International University's Seeding Grant (INT-FOSTEM-02-01-2015) and GUP Grant (Tier 2) of the Universiti Teknologi Malaysia (Project Vote No.: QJ130000.2522.09H34). Besides, the authors also would like to acknowledge the Ministry of Higher Education of Malaysia for sponsoring the research study through the MyPhd scholarship.

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