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Effect of Hybrid FRP Confinement on Tin Slag Polymer Concrete Compressive Strength

Muhamad Soffi Manda, Mohd Ruzaimi Mat Rejab, Shukur Abu Hassan, Mat Uzir Wahit

Abstract: ***This study investigates the strength enhancement of Tin Slag Polymer Concrete (TSPC) under hybrid GFRP and CFRP confinement in comparison with mono GFRP and CFRP confinement on TSPC circular short column samples. Hybrid FRP confinement is prepared by wrapping TSPC with GFRP followed by CFRP both 1 layer using epoxy Sikadur 330 as matrix binders with 50 mm overlap. Compression test was performed on unconfined TSPC (TSPC-UC), TSPC with GFRP confinement (TSPC-GF), TSPC with CFRP confinement (TSPC-CF) and TSPC with hybrid FRP confinement (TSPC-HB) with 1mm/ min loading rate. The test results have revealed that the ultimate strengths are 59.19 MPa (TSPC-UC), 85.54 MPa (TSPC-GF), 108.77 MPa (TSPC-CF) and 124.59 MPa (TSPC-HB). The corresponding compressive strain measured at ultimate compressive strength is 0.0300 (TSPC-UC), 0.0453 (TSPC-GF), 0.0398 (TSPC-CF) and 0.0588 (TSPC-HB). Stress versus strain curve has shown that compared to TSPC-UC, externally strengthen sample with GFRP, CFRP and Hybrid FRP have enhanced TSPC strength with slight different behavior. TSPC-GF has less strength enhancement with larger strain while TSPC-CF provide larger strength enhancement but with lower strain. However, TSPC-HB has shown the highest strength enhancement with larger strain benefit from combined GFRP and CFRP properties. Failure mode of hybrid FRP confinement on TSPC (TSPC-HB) has shown combination of both FRP components failure mode (TSPC-GF and TSPC-CF) as in rupture pattern and delamination. The results of this study has provide findings on the effect of hybrid FRP confinement on TSPC circular column sample in close expectation based on literatures.***

Keywords: ***TSPC, Hybrid FRP Confinement, Compression, Stress versus Strain, Failure Modes.***

I. INTRODUCTION

According to a recent review by [1], the application of Fiber Reinforced Polymer (FRP) material as reinforcement in concrete structure has been employ since the last three decades. The review reveals that Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) have been frequently employed in concrete structure reinforcement. In comparison among both, CFRP has provided greater strength enhancement than GFRP. One of the methods of FRP application in enhancing concrete structure performance is through hybrid FRP confinement which has been introduced to strengthen the concrete structure through external mean. The hybrid FRP confinement uses more than one strengthening materials and this method combined the properties of confinement materials to support the core material during load bearing application. Previous study has also reported that hybrid confinement has been performed on concrete structure using either FRP materials, metallic materials or both. Besides external strengthening, internal strengthening of concrete using hybrid reinforced has also been introduced. This approach is different from confinement or external strengthening because reinforcement materials are inserted in the concrete mixtures together with the concrete aggregates. A study by [2] has found that the addition of hybrid fiber improves the cyclic mechanical properties in the aspect of peak strength, peak strain, toughness, and post peak ductility of Hybrid Fiber Reinforced Concrete (HFRC) under uniaxial tension and compression. The addition of hybrid fibers by [2] is an approach of internal strengthening of concrete structures. Besides that, [3] has also performed a study on hybrid reinforcement of concrete mixture for pavements by the addition of steel fibers and polypropylene fibers in the concrete mixture. The results show that hybrid fibers have increased the compressive strength of the concrete compared to mono fibers addition. In hybrid approach for external strengthening of a concrete structure, previous studies have also reported that hybrid confinement using several FRP materials or metallic material or both combined have successfully improved the compressive strength of the concrete structure. For instances, [4] has studied steel and FRP composites as hybrid confinement on RC square column elements where the steel is employ as internal strengthening and FRP material as external strengthening. The objective of the study is to evaluate the effect of hybrid strengthening using CFRP confinement and internal steel reinforcement on the square concrete column specimen. The study shows that hybrid strengthening by metal and FRP are very efficient in improving the stiffness, strength and ductility of the column elements under both eccentric and axial compression.

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This study has revealed that combining internal strengthening and external strengthening are also one of the approaches in hybrid strengthening of a concrete structure. In another report, [5] states that by using only one type of FRP in concrete structure strengthening, the strength was enhanced but sudden rupture also increased due to decrease in ductility. Therefore, FRP materials combination in hybrid confinement must compensate both strength enhancement and hoop strain to reduce the effect of sudden rupture. The reason is to engineer the structural failure to occur with early sign before total fracture occur. Similarly, [6] also report that hybrid FRP confinement through external bonding on concrete structure should increase residual capacity with higher deformation before rupture due to an improved energy absorption capacity.

In addition, [7] has concluded that hybridization has effectively contribute to maximizing lateral strain efficiency of FRP jacketing on circular concrete column. In a study by [8], the researcher has performed hybrid confinement study of concrete by fiber-reinforced polymer sheets and fiber ropes under cyclic axial compressive loading. The confinement used in the study is by GFRP and polypropylene fiber ropes (PPFRs). The response shows a temporary load drop occurred upon initiation of the fracture of the GFRP sheet. Then the load regaining began, thus PPFRs prevented an abrupt load capacity loss and ensured further increased of concrete strain ductility and increased the supported axial loads. [9] Has performed a study on seismic behavior of seismically damaged Reinforced Concrete (RC) frame column strengthened with sprayed hybrid Basalt Fiber (BF)/CFRP confinement. The study found that, the hybrid confinement has enhances the energy dissipation and ductility. However, in term of strength enhancement, no obvious increase in the peak loads was observed. [10] Has reported a study to strengthen concrete structure using hybrid of GFRP, BFRP and CFRP confinement. In the study, confinement using each one layer of CFRP+GFRP (C1G1) and BFRP+CFRP (B1C1) has provide almost similar strength enhancement (133.89% and 135.59%) but C1G1 has resulted in bigger hoop strain. [10] Concluded that C1G1 as preferred hybrid confinement method to enhance strength of circular concrete column based on the test results.

After that, there was a study by [11] on comparison of hybrid and non-hybrid confinement. The focus of [11] study is to assess the performance of hybrid and non-hybrid confinement on corrosion damaged RC circular column under compression. The FRP materials used by [11] are GFRP and CFRP with two component epoxy binder. The tensile strength of the materials is determined using flat coupon test, ASTM D3039 and the results are as in Table 1. Both of the FRP materials are wrapped around the RC circular column using manual wet lay-up technique with 50mm overlap to produce hybrid confinement of GFRP and CFRP on the RC circular column. The result of compressive test shows that the hybrid confinement has enhanced the strength of the RC circular column specimen compared to non-hybrid mono-fiber confinement of CFRP and GFRP. However, CFRP confinement strength is close to the hybrid confinement.

Table 1: FRP material strength based on 1 layer with epoxy binder

FRP Materials	Thickness (mm)	Tensile Strength (ASTM D3039)
GFRP	0.114	3220 MPa
CFRP	0.065	4470 MPa
HYBRID	0.179	5200 MPa

Finally, according to [12], in a study to investigate the strength of FRP confinement using GFRP and CFRP on circular concrete column, the researchers has concluded that both confinement materials significantly enhanced the strength of the circular concrete column compared to plain concrete column. Similar study has also been performed by [14] and [15] but on Tin Slag Polymer Concrete (TSPC) column. According to a recent review by [16], TSPC is a newly introduced polymer concrete material which composed of 30:70 unsaturated polyester resin (UPR) and fine (<1mm) tin slag (TS) aggregates. In both studies by [14] and [15], GFRP and CFRP confinement on TSPC column has significantly increased the strength of TSPC column compared to the unconfined column. However, the effect of hybrid confinement using both GFRP and CFRP has never been investigated. As previously reported by [11], hybrid confinement of GFRP and CFRP on concrete structure has enhanced the concrete strength but the results are close to mono-fiber confinement using CFRP only. Therefore, this study investigates the strength enhancement of TSPC under hybrid GFRP and CFRP confinement. The results was discussed by comparing the effect of Hybrid FRP confinement with mono GFRP and CFRP confinement on TSPC circular column specimen.

II. MATERIALS AND TESTING

A. TSPC Preparation

Hybrid confinement has been performed to investigate the effect of combined confinement based of previous study by [14] and [15], using GFRP and CFRP confinement to TSPC circular short column specimen. The specification of TSPC specimen, GFRP and CFRP has been applied based on [13], [14] and [15]. TSPC specimen was prepared by casting the wet mixture of Unsaturated Polyester Resin (UPR) with 1 % of Methyl Ethyl Ketone Peroxide (MEKP) and fine (<1 mm) tin slag aggregates into 50 mm PVC pipe. After casting, the mixture was cured for 3 days before demould and cut into 100 mm length representing the height of the short column specimen. The standard used for TSPC specimen preparation is [18] and [17], standard specification for molds for forming concrete test cylinders vertically and concrete test specimens in laboratory.

B. Hybrid FRP Confinement

Wrapping procedure was referred to [19], guide for the design and construction of externally bonded FRP systems for strengthening concrete structures by American Concrete Institute (ACI).

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In addition, the method of wrapping application for hybrid confinement of CFRP and GFRP material has also been referred to [11] and [20]. According to [11], both GFRP and CFRP fabric was cut into rectangular size 100mm x 207mm based on TSPC specimen wrapping area together with the addition of 50mm overlap. The matrix binders for FRP and external bonding are Epoxy Sikadur 330 with 4:1 part A and B. Upon the application of Sikadur 330, GFRP material was wrapped around TSPC specimen followed by CFRP material using manual wet lay-up technique. According to [11], both GFRP and CFRP are applied on at one layer of wrapping. Then, the wet hybrid FRP application around TSPC column was wrapped with plastic laminates to create tight bond and smooth surface finish. The samples were cured at room temperature for 30 days according to Sikadur 330 manufacturer recommendation. "Fig. 1" describes the process to prepare TSPC with hybrid FRP confinement.

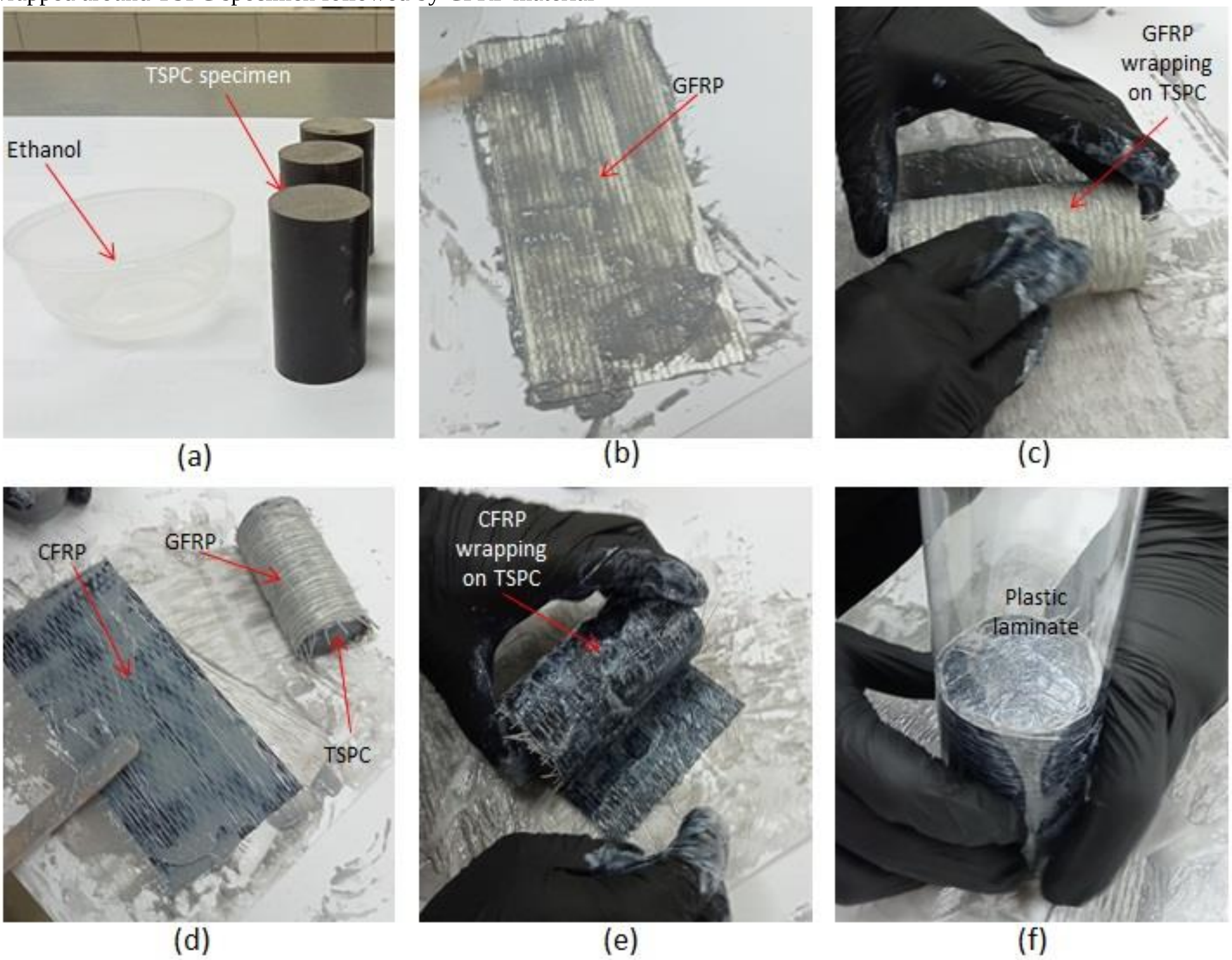

Fig. 1. (a) Cleaning and drying TSPC short column specimen using ethanol. (b) Application of Epoxy Sikadur 330 on GFRP (100 mm x 207 mm) using hand lay-out. (c) Wrapping first layer of confinement on 100 mm TSPC column specimen using GFRP. (d) Application of Epoxy Sikadur 330 on CFRP (100 mm x 207 mm) using hand lay-out. (e) Wrapping second layer of confinement on 100 mm TSPC column specimen using CFRP. (f) Wrapping the hybrid FRP confinement on TSPC column using plastic laminate for curing.

C. Mechanical Test Setup

Compression test has been performed based on [21] standard test method for polymer concrete compressive strength. In the testing program, Shimadzu 1000 kN universal tensing machine has been employed. The speed of loading is set at 1 mm/ min of the machine cross head in uniaxial direction. The specimen was placed on bottom pressure plate and uniaxial compressive load was applied by top pressure plate. The test samples designation were TSPC-UC for unconfined TSPC, TSPC-HB for TSPC with hybrid confinement composed of GFRP and CFRP materials. Data for mono GFRP (TSPC-GF) and CFRP (TSPC-CF) confinement was acquired from [14] and [15] to compare the effect of hybrid FRP and mono FRP confinement. "Fig. 2" show the compression test set up.

Fig. 2. Compression test set up. (a) Overview of testing machine. (b) Preparing the top and bottom compression plates. (c) Placement of test sample on testing machine.

III. RESULTS AND DISCUSSIONS

A. Mechanical Test Results

Table 2 presents the mechanical test results from experimental (TSPC-UC & TSPC-HB) and previous studies (TSPC-GF & TSPC-CF). From the table, highest maximum load and displacement has occur on TSPC with hybrid GFRP and CFRP confinement, TSPC-HB which indicates that hybrid confinement on TSPC column has provide more advantage in load bearing potential (244.63kN) with higher displacement (5.880 mm) compared to unconfined TSPC-UC (116.22 kN and 2.997 mm), TSPC with mono GFRP confinement, TSPC-GF (167.95 kN and 4.527 mm) and TSPC with mono CFRP confinement, TSPC-CF (213.56 kN and 3.977 mm). Then the next parameter measured, compressive modulus is a measure of the sample stiffness and it reflects the sample resistance toward deformation under linear elastic behavior. The results show that the external constraint using FRP has resulting in stiffer material from TSPC-UC (3.22 GPa), TSPC-GF (3.65 GPa), TSPC-CF (4.69 GPa) and the highest compressive modulus is TSPC-HB (5.00 GPa). Measurement on yield strength property represents the point where strength measurement and displacement start to change from linear to non-linear relationship. This point becomes a separation point between elastic and plastic behavior of the material under compressive loads. Test results have shown that yield strength of TSPC has increased with the application of GFRP, CFRP and Hybrid FRP confinement where TSPC-UC, 46.55 MPa, TSPC-GF, 51.25 MPa, TSPC-CF, 67.57 MPa, and TSPC-HB, 76.06 MPa. After achieving yield strength, each sample will continue to resist further compressive load increment until ultimate strength was reached. The test results have revealed that the ultimate strengths are 59.19 MPa (TSPC-UC), 85.54 MPa (TSPC-GF), 108.77 MPa (TSPC-CF) and 124.59 MPa (TSPC-HB). The corresponding compressive strain measured at ultimate compressive strength is 0.0300 (TSPC-UC), 0.0453 (TSPC-GF), 0.0398 (TSPC-CF) and 0.0588 (TSPC-HB).

Table 2. Summary of mechanical test results

Sample	Max Load (kN)	Max Disp. (mm)	Compressive modulus (Gpa)	Yield strength (Mpa)	Ultimate Strength (Mpa)	Compressive Strain	Strength Enhancement
TSPC-UC	116.22	2.997	3.32	46.55	59.19	0.03	0.00%
TSPC-GF	167.95	4.527	3.65	51.25	85.54	0.0453	44.50%
TSPC-CF	213.56	3.977	4.69	67.57	108.77	0.0398	83.75%
TSPC-HB	244.63	5.88	5	76.06	124.59	0.0588	110.48%

B. Load versus Deformation and Stress versus Strain Curve

Compressive load application on all variant of TSPC samples from TSPC-UC, TSPC-GF, TSPC-CF and TSPC-HB has results in axial deformation that physically shorten the samples. Then, the samples resistance towards external load per unit cross sectional area of each sample has provide the equivalent compressive stress.

Similarly, the axial deformation that shortens the height of each TSPC column sample per unit of its initial height (100 mm) has provided the compressive strain of every test samples. "Fig. 3. (a)" shows the behavior of each test samples under compressive loading. Upon the beginning of loading, TSPC-UC, TSPC-GF and TSPC-CF start to elastically deform while TSPC-HB has shown a little delay in providing the elastic deformation. This situation may be due to excessive confinement material which making first contact with top pressure plate before reaching TSPC top surface or due to uneven placement of TSPC-HB sample. During this process, all of the samples have shown load/ strength to displacement/ strain in proportional rate up to yielding which occur at different rate.

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Observation on "Fig. 3." shows that the slope of TSPC-HB is larger indicating that TSPC-HB is stiffer compared to other samples.

TSPC-UC shows the lowest slope followed by TSPC-GF and TSPC-CF. Then, TSPC-UC is first to reach yield point followed by TSPC-GF, TSPC-CF and finally TSPC-HB reaching the yield point indicating that TSPC-HB has the highest yield stress. After yielding, the test samples experiencing strain hardening where strain rate grows larger compared to proportional behavior with lower strength enhancement. At a certain point, the strength start to decrease and this point reveals the ultimate strength of each test samples. TSPC-UC has shown the lowest ultimate strength, followed by TSPC-GF, TSPC-CF and TSPC-HB. After ultimate strength, the test samples start to undergo strain softening behavior where the straining occur with strength decreased and this condition occur up to fracture. From "Fig. 3. (b)", TSPC-HB has shown the highest strength enhancement with larger strain compared to TSPC-UC, TSPC-GF and TSPC-CF. The important findings in this behavioral curve is that compared to TSPC-UC, TSPC-GF provide less strength enhancement with larger strain while TSPC-CF provide larger strength enhancement but with lower strain. This condition indicate that CFRP has higher strength but tend to cause sudden fracture but GFRP has lower strength but providing more strain compared to CFRP. Therefore, TSPC-HB combine both properties of GFRP and CFRP which results in higher strength enhancement with higher strain as shown in "Fig. 3. (b)".

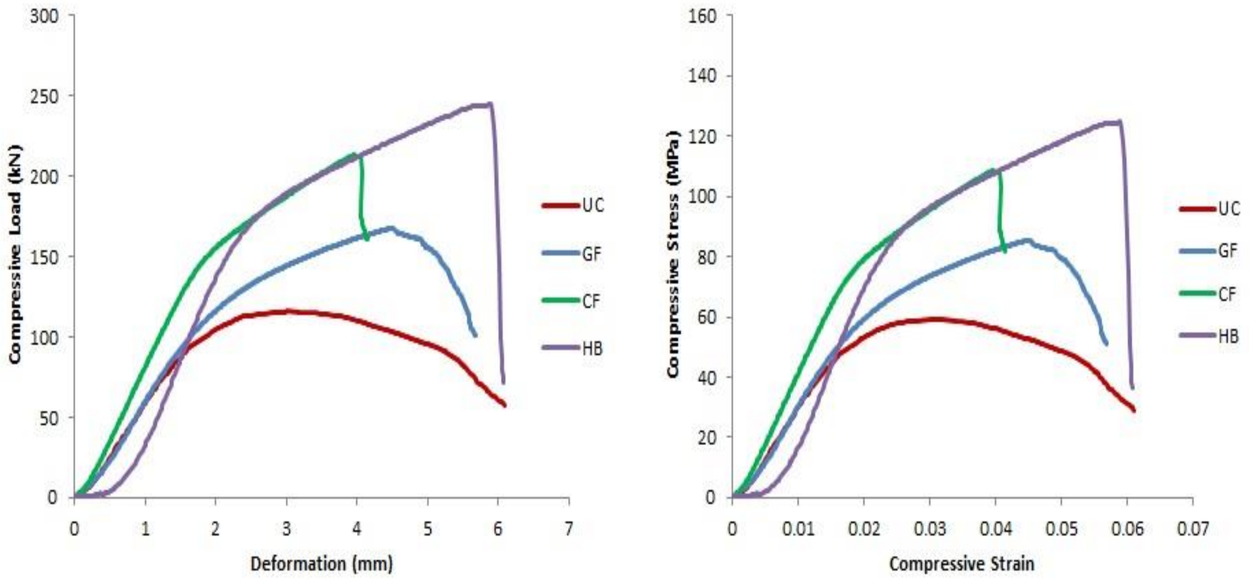

Fig. 3. (a) Compressive load versus deformation. (b) Compressive stress versus compressive strain.

C. Mechanical Properties Comparison

Yield stress value for TSPC-UC is 46.55 MPa and with the application of external bond using GFRP, CFRP and hybrid FRP on TSPC, the value increase. "Fig. 4(a)" shows that TSPC-GF has provide a little enhancement in yield stress to 51.25 MPa. However, with the application of Carbon fiber, TSPC-CF has provided large yield stress enhancement up to 67.57 MPa. TSPC-HB in comparison with TSPC-CF has provided a little increased in yield stress (76.06 MPa). After yield stress, the tests samples will achieve ultimate strength which is also represent compressive stress of the test samples.

According to "Fig. 4 (b)", TSPC-UC has 59.19 MPa of compressive stress, but with the application of GFRP, CFRP and hybrid FRP confinement on TSPC, the compressive stress was enhanced with 85.54 MPa (TSPC-GF), 108.77 MPa (TSPC-CF) and 124.59 MPa (TSPC-HB). Similarly "Fig. 4 (c)" shows that the compressive strain for TSPC-UC is 0.0300 and the value increased with 0.0453 (TSPC-GF), 0.0398 (TSPC-CF) and 0.0588 (TSPC-HB). In compressive strain value, TSPC-GF has higher strain compared to TSPC-CF, unlike their corresponding compressive strength enhancement. The reason is that CFRP has higher strength but lower strain compared to GFRP. However, the TSPC-HB values compensate both strength and strain to provide better confinement performance to strengthen TSPC column. Finally, "Fig. 4 (d)" indicate that the compressive modulus of all of the test samples variant is 3.32 GPa (TSPC-UC), 3.65 GPa (TSPC-GF), 4.69 GPa (TSPC-CF) and 5.00 GPa (TSPC-HB).

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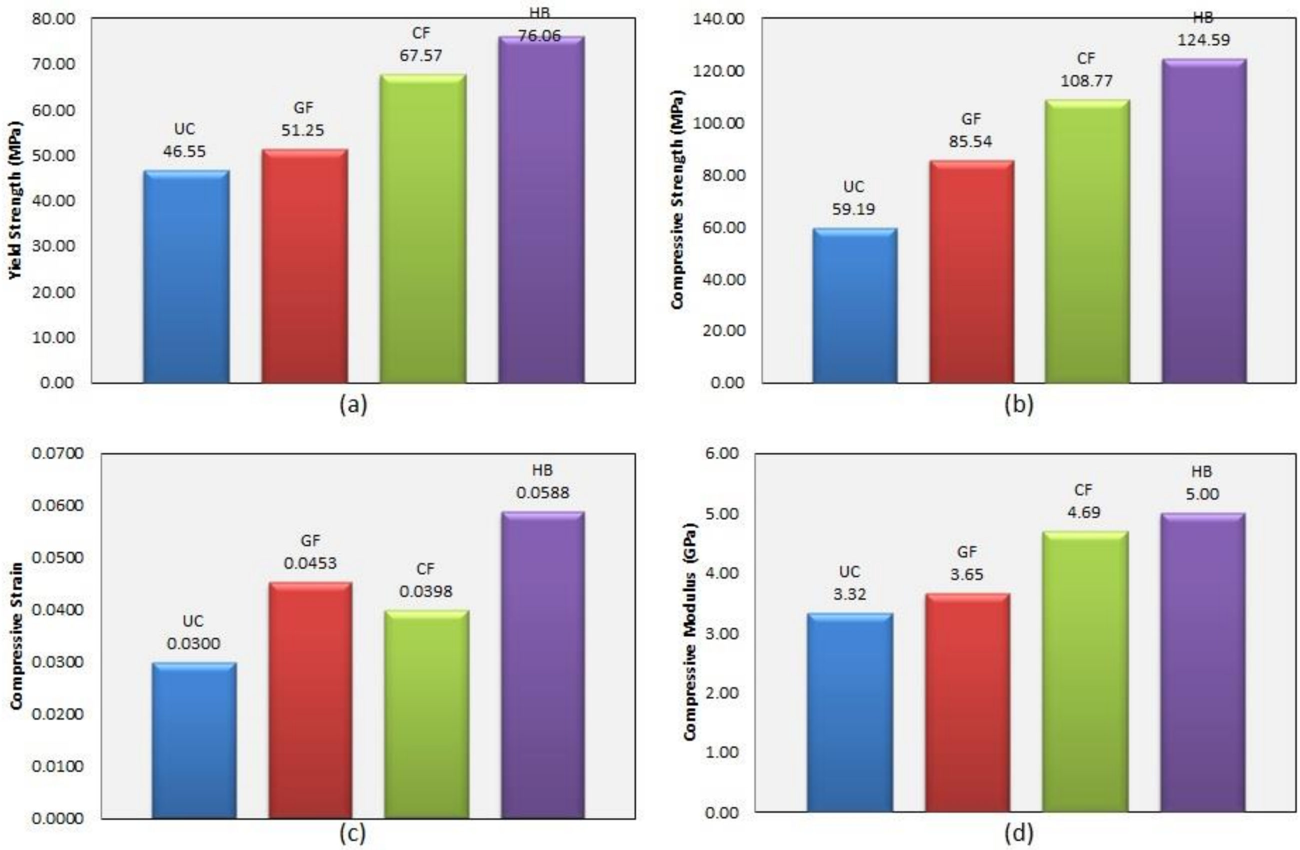

Fig. 4. Comparison of mechanical properties on TSPC-UC, TSPC-GF, TSPC-CF and TSPC-HB. (a) Yield Stress. (b) Compressive Stress. (c) Compressive Strain. (d) Compressive Modulus.

D. Strength Enhancement Pattern

TSPC strengthening through externally constraint of TSPC column by FRP materials has been proven by previous studies. [14] and [15] has presented that single layer of GFRP and CFRP confinement on TSPC circular column sample has enhanced the strength up to 44.50 % (TSPC-GF) and 83.75 % (TSPC-CF). The strength measurement for unconfined TSPC is 59.19 MPa, 85.54 MPa with GFRP confinement and 108.77 MPa with CFRP confinement. Then, with the application of both FRP materials in the strengthening process to provide hybrid FRP confinement on TSPC, the strength has enhanced up to 124.59 MPa which equivalent to 110.48 % of strength enhancement percentages. However, according to Fig. 5, the rate of strength increment decreased from TSPC-GF to TSPC-CF and TSPC-HB. The effect of combined strength from GFRP with CFRP was not multiplied and this finding is similar with previous experimental study on cement concrete column strengthening as report by [11]. This condition occur due to the fact that confinement effect only provide delay in maximum hoop strain gain during compressive loading application, thus provide a little time to also caused an increased in the strength gain. However, for efficient performance, hybrid FRP confinement has provide better strength enhancement with corresponding larger strain which preventing sudden rupture during failure.

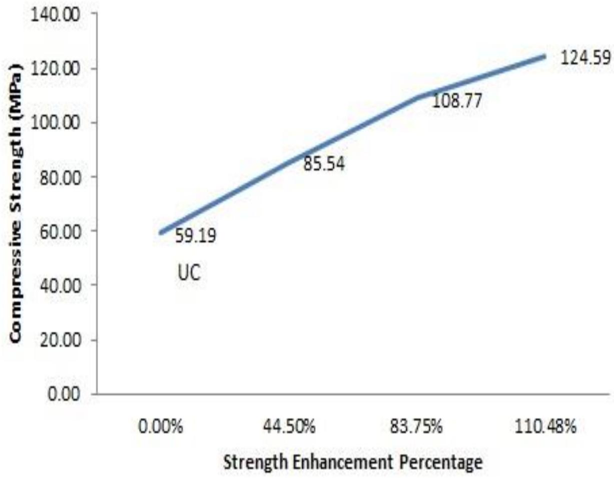

Fig. 5. Strength enhancement pattern (compressive strength and enhancement percentage comparison)

E. Failure Modes

"Fig. 6." shows the failure modes of each test sample during compression test. "Fig. 6. (a)" indicate that unconfined TSPC has failed under shear failure. This type of failure is common among most of concrete column under compression. With the application of GFRP confinement on TSPC column, "Fig. 6. (b)" shows that the GFRP rupture has occur in the middle section of the column sample.

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During barreling of TSPC core, GFRP has provided external constraint to restrain further hoop strain until exceeding the limit and fracture occur as shown by TSPC-GF. “Fig. 6. (c)” shows the failure mode of TSPC-CF where the delamination clearly occurs on CFRP at the middle section.

CFRP at top and bottom section was still in good bond with TSPC core column. This indicates that CFRP failed and rupture in sudden and rapid rate compared to GFRP failure. Then, “Fig. 6. (d)” shows the failure mode of hybrid FRP confinement on TSPC column (TSPC=HB). Compared with mono GFRP and CFRP confinement application, the rupture and delamination of hybrid FRP occur at top section and cover larger area compared to TSPC-GF and TSPC-CF. The failure location may indicate that the hoop strain was resisted by hybrid FRP up to a higher amount compared to single GFRP and CFRP confinement capacity. The barreling of TSPC core mare have expands large enough to impart the top section of hybrid FRP wrapping. The observation of rupture and delamination pattern of hybrid FRP combined both failure type of GFRP and CFRP as in TSPC-GF and TSPC-CF failure modes.

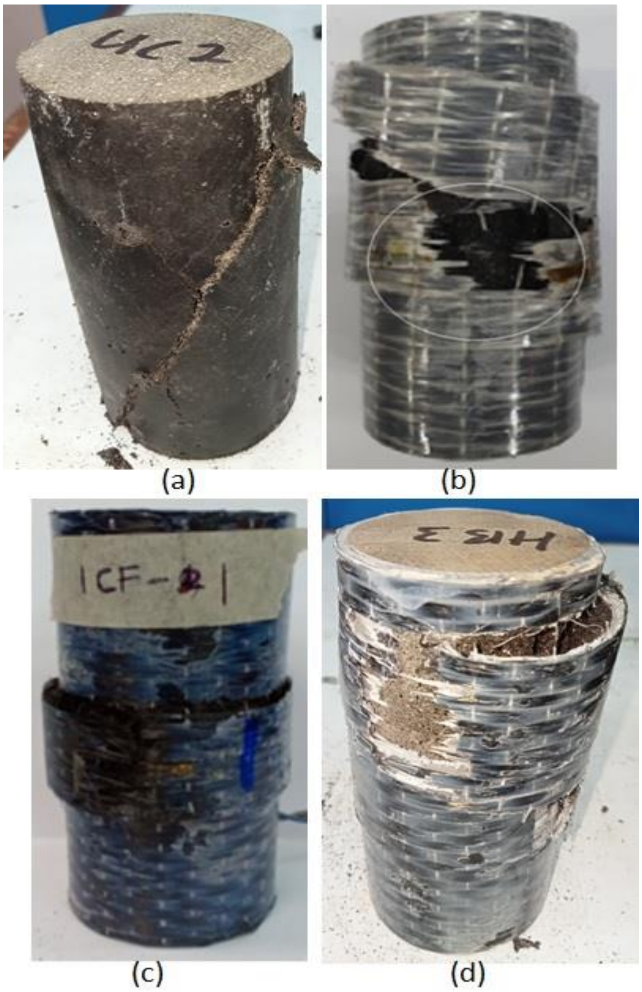

Fig. 6. Failure mode of test samples. (a) TSPC-UC. (b) TSPC-GF. (c) TSPC-CF. (d) TSPC-HB

IV. CONCLUSIONS

The results of this study has provide findings on the effect of hybrid FRP confinement on TSPC circular column sample in close expectation based on literatures. Some concluding remarks are as the following.

• Mechanical properties of TSPC-HB have shown an improved performance compared to TSPC-UC, TSPC-GF and TSPC-CF in term of yield strength, compressive strength, compressive strain and compressive modulus.

• Combination of GFRP and CFRP in hybrid FRP confinement on TSPC column has provided strength enhancement with large compressive strain compared to mono GFRP and CFRP confinement.

• Hybrid FRP confinement has enhanced the strength of TSPC column but the rate strength increment decreased from TSPC-GF, TSPC-CF and TSPC-HB based on strength enhancement pattern curve.

• Failure mode of hybrid FRP confinement on TSPC (TSPC-HB) has shown combination of both FRP components failure mode (TSPC-GF and TSPC-CF) as in rupture pattern and delamination.

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material/ Data Access Statement	Not relevant.
Authors Contributions	All authors have equal participation in this article.

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