Recent Advances in Concrete-Encased with Engineering Plastics

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Abstract
The interest in the engineering plastics has recently grown due to its two main functions: as formwork for fresh concrete and as encasement for hardened concrete. Due to the limited test data, the mechanical performance of these structures continues to be pursued through experimental methods. Within this frame, the goal of this study is to gather the new knowledge and highlight the most recent researches and advances on the applications of the engineering plastics for the innovative construction of civil structures. Such knowledge will help to provide the platform for further research in this field.

1. Introduction
Engineering plastics have been used in construction applications for several decades. However, there is a need to promote these new materials in civil engineering applications to protect and contain concrete elements under compression load. Based on its technological and economic advantages, the environmental performance of such tubular elements has been established previously. Recently, several studies explored the potential use of plastic tubes for structural concrete encasement which represent new trends in the search for alternative materials. Composites like a concrete-filled steel tube (CFST) have shortcomings such as high cost and corrosion. CFPT was reported as a viable alternative for conventional steel tube for structural applications provided that appropriate design methodologies are employed. This study reports on new trends and the most recent advances made within the last year concerning the use of engineering plastics for structural applications. This is achieved by reviewing recently published sixteen papers in the year 2019-2020. Several models have been proposed for the strength of concrete incorporating natural or recycled materials and encased with engineering plastics. These models are examined and the current research needs are also discussed.

1.1. Temporary and permanent formwork
As a non-metallic pour-in form for concrete [1], the plastic tube can improve column constructability and enhance its resistance to environmental influences (chemical plant, large water tanks, and undercover car parks). The engineering plastic finds practical applications in plastic-coated columns with structural or architectural finishing. Another practical application of CFPT is in residential buildings, Fig. 1, with acceptable performance.

2. Mechanical behavior of CFPT
2.1. Short CFPT
Four sizes of uPVC tube were used as confining device for concrete cylinders having an aspect ratio h/D (height/diameter) of two. The post-peak stress-strain behavior of CFPT specimens proved to be affected by the 2t/D ratio, where t is tube thickness. The absolute value of the slope decreased as the 2t/D ratio increased. The authors
reported the confinement to be noticeable for lower concrete classes and higher thickness to diameter ratios (2t/D) and proposed the following two equations for the strength and strain of CFPT [2]:

\[
\frac{f_{cc}}{f_{co}} = 1 + \frac{2.7f_{lu}}{(f_{co})^{0.394}}(\frac{2t}{D})^{0.453}
\]

(1)

\[
\frac{\varepsilon_{cc}}{\varepsilon_{co}} = \varepsilon_{co} + 0.043\left(\frac{f_{lu}}{f_{co}}\right)^{0.99}
\]

(2)

Accordingly, hoop stress \(\sigma_t\) can be calculated from the equation:

\[
\sigma_t = \frac{f_{cc} f_{ext}}{\pi D} = \sigma_y = \text{tube yield stress}
\]

(6)

Or \(\sigma_t\) can be determined from burst pressure test, Fig. 4.

Engineering plastic tubes are economical alternatives for the advanced composite tubing systems. A new type of multi-layered uPVC introduced to confine concrete in new research [3]. Coupons composite of a strong layer sandwiched between two hard layers of UPVC exhibited good performance when tested under direct tension, Fig. 2. In another study, the performance of CFPT under concentric loading was examined by testing 36 short-stub columns. The test variables were the plastic tube and coarse aggregate/cement ratio (a/c) ratio. The proportion of coarse aggregate altered in increments of 0.5 resulting in twelve mixes with a/c ratios from 3 to 8. It was reported that the aggregate characteristics were one of the influential parameters that affected the performance of short CFPT columns.

The peak strain for CFPT was higher than for unconfined specimens, and the ductility was assessed from the ratio of ultimate strain to the peak strain, since the CFPT undergoes a gradual deformation under axial load with considerable shortening and plastic deformation before failure, Fig. 3. For evaluating the ultimate strength of CFPT, the following equation was proposed:

\[
N_U = f_{cc} A_c + f_y A_P
\]

(3)

A confinement index was introduced:

\[
\xi_p = \frac{f_{pp} A_P}{f_{uc} A_c}
\]

(4)

Where \(f_{pp}\) = yield strength of plastic tube; \(A_P\) = cross-sectional area of the plastic tube; \(A_c\) = area of the concrete core. The strength enhancement ratio (\(\xi_p\)) was determined from [3]:

\[
\frac{f_{cc}}{f_{co}} = 1 + 1.98\xi_p
\]

(5)

2.2 Long CFPT columns

The behavior of slender concrete columns encased in a thin, flexible plastic pour-in from under axial load was explored in an experimental study [1]. The Stress-strain relationship of the uPVC coupons in compression was established. An increase in strength of 42% to 71% was reported for slender CFPT specimens over plain concrete columns. The elastic and total energy was computed from the axial load-rotation curves. The ultimate confining stress of CPPF was obtained as follows [1]:

\[
f_{cc} = f_{uc} + 0.5(f_1)^{-1.15}
\]

(7)

Where \(f_{cc}\) = confined concrete compressive strength; \(f_{uc}\) = unconfined concrete compressive strength and was determined from testing concrete cylinders, \(f_1\) = lateral confinement pressure; \(K_1\) = strength related confinement pressure coefficient; and \(f_{pp}\) is the nominal confinement ratio determined from:

\[
f_{pp} = \frac{2\varepsilon_{pp} E_{pp}}{f_{pp} \varepsilon_{pp}} \frac{21\varepsilon_{pp} E_{pp}}{f_{pp} \varepsilon_{pp}}
\]

(8)

here \(\varepsilon_{pp}\) = thickness of plastic pour-in form (PPF); \(E_{pp}\) = ultimate tensile strain; \(E_{pp}\) = modulus of elasticity; \(f_{pp}\) = yield strength; \(f_{pp}\) = internal diameter of PPF. The lateral confinement pressure was obtained:

\[
f_{pp} = \frac{21\varepsilon_{pp} E_{pp}}{f_{pp} \varepsilon_{pp}}
\]

(9)
In another research, PPF was used in three low-cost composite systems for concrete construction [4]. It included concrete-filled tubular plastic forms (CPFF), steel-reinforced concrete-filled tubular plastic (CPFF-SC and CPFF-Re), and welded wire fabric reinforced concrete-filled tubular plastic (CPFF-WM). It was observed that a hinge was formed and the mode of failure altered from brittle shear for RC specimens to ductile beam failure mode for CPFF columns. The three composite systems demonstrated compression softening with different rigidities that can ameliorate the axial and to less extent the radial performance of the columns. Furthermore, the strength capacity of CPFF specimens was increased by 36%, 43%, 28% and 20.5% compared with its equivalent steel-reinforced columns without PPF.

2.3 Deformations

The elastic-plastic behavior and the material ductility are the main features of the polymeric tube, usually considered to be belonging to the set of mechanical properties. Yield is a short phenomenon relative to the life span of CFPT specimens, affects the ductility and energy dissipation capacity. Therefore the post-peak deformation characteristics of concrete might change from brittle to ductile failure when the tube is used as permanent formwork.

3. Reinforced CFPT columns

3.1. Fiber-reinforced CFPT

CFPT reinforced with polypropylene fibers (PP) was tested under axial compression [5]. Ductility increased considerably with the fiber volume fraction. Unlike for PVC, The authors argued that the tensile stress-strain curve of uPVC coupons tested in tension consist of five zones. it includes: (1) the linear elastic, (2) nonlinear elastic, (3) post-peak softening, (4) flat plateau and (5) strain hardening (which was not present in PVC tensile response). A model for the prediction of ultimate strength of CFPT was proposed based on a database of 75 test points:

\[ N_0 = \frac{\eta_f f_c A_c + f_t A_t}{\eta_a} \]

From nonlinear regression the \( \eta_a \) was determined for PVC-UPVC confined concrete:

\[ \eta_a = 3.39 + \left[ -0.41 + \left( \frac{\eta_l}{\eta_a} \right)^{0.28} \left( \frac{f_c}{f_t} \right)^{0.82} \right] \left( 0.5 \frac{f_c}{f_t} \right) \]

For PVC-UPVC confined concrete reinforced with PP fiber:

\[ \eta_a = 3.39 + \left[ -0.41 + \left( \frac{\eta_l}{\eta_a} \right)^{0.28} \left( \frac{f_c}{f_t} \right)^{0.82} \right] \left( 0.5 \frac{f_c}{f_t} \right) \left( 0.13 - (F - 0.52)^2 \right) \]

Where:

\[ \eta_l = 0.905 + 10.35 \lambda^2 \] \hspace{1cm} (15)

\[ \lambda^2 = \frac{N_{pl,ck}}{E_0} \] \hspace{1cm} (16)

Where: \( N_{pl,ck} \) = plastic resistance to the compression; \( E_0 \) = Euler elastic critical normal force

4. CFPT specimens with additives

To predicate the plastic capacity of columns with different failure mechanisms (Fig. 5), CFPT tested in two modes of axial load application; composite mode, load was applied to the entire cross-section, and confining mode (load was applied to the concrete core only) Fig.6. material failure dominated in all tested specimens, with customary shear failure [7]. The authors reported that the composite mode columns showed more enhancements in strength, 2.25 to 1.56, than those of confining mode, varied from 2.07 to 1.55.

Figure. 5 Columns and their constitutes; (a) PVC tubes; (b) Concrete columns; (c) Composite mode columns; (d) Confining mode columns

The trend reversed for ductility, where confining mode columns showed more axial and lateral deformations than the corresponding composite mode specimens. The following expressions were proposed for confining mechanism:

\[ f_{ec} = 0.905f_{cu} + 10.35f_t \]

and for the composite mechanism:

\[ f_{ec} = 0.94f_{cu} + 8.02f_t \]

5. CFPT columns incorporating recycled aggregate (RA)

In a study, 250 by 560mm CFPT specimens with and without steel reinforcement were tested under compression [8]. One of the test parameters was stirrup spacing. For concrete mixing, less than 20% of the coarse aggregate was replaced by coarsely-crushed demolished concrete lumps having a size in the range 100 to 150mm. Reinforced specimens with the stirrup spacing of 90mm exhibited higher ultimate load with the least deformation. The use of steel reinforcement resulted in a 10 to 15% enhancement in CFPT strength.

Figure. 6 Two different loadings of CFPT under axial load [7].
In another research, the behavior of reinforced uPVC tubular columns filled with RA under axial compression load was explored [9]. It was reported that good confinement can improve the load capacity and ductility of RA columns. Strength equations from Euro code 4 were used to evaluate the suitability and structural use of such a system.

6. Double skins CFPT

The behavior of concrete-filled double skin CFPT tubes under concentric load was investigated [10]. Drum type was the prevalent failure mode observed for double skin CFPT specimens with lower aspect ratios, Fig.7. The internal tube of the double skin CFPT column exhibited local buckling. The following equation was proposed:

\[ f_{cc} = f_{co} + \frac{2.7 f_{cu}}{(f_{co})^{0.994} (2t/D)^{0.59}} \left( 1 - \lambda \right) \left( 1 - 0.05 \frac{d}{D} \right) \quad (19) \]

Where \( D \) = external diameter and \( d \) = internal diameter. Equation (19) was modified to consider the length effect:

\[ f_{cc} = f_{co} + \frac{2.7 f_{cu}}{(f_{co})^{0.994} (2t/D)^{0.59}} \left( 1 - \lambda \right) \left( 1 - 0.05 \frac{d}{D} \right) \quad (20) \]

It is observed that the PVCT was in a pure shear state when the shear span ratio was \( \lambda = 0 \) and the failure of the PVCT columns were characterized by typical bending failure.

In the latest research [12], the strength reduction factor \( \phi \) mandated by ACI 318-14 for a reinforced concrete column was modified to account for plastic tube confinement effect for design applications. The authors stipulated that some uncertainties associated regarding the tube material properties and the peak strength model influence the strength reduction factor. They suggested a strength reduction factor \( (\phi) \) of 0.75 instead of 0.65 mandated by ACI 318-14 when the tube used as stay-in-place formwork; alternatively, a new model was proposed to calculate the strength reduction factor and design a CFPT according to ACI 318-14. A new expression for strength reduction factor that accounts for the uncertainties associated with the design parameters (\( t, D, f_{py} \) and \( d \)) was developed to design a CFPT:

\[ \Phi = 0.65 + 3.35 (2t/D)^{1.65} \quad (22) \]

8. New Applications of CFPT

8.1 PVC-FRP confined concrete (PFCC)

The high material and labor cost limits the application of Fiber Reinforced Polymers (FRP) in new civil applications [13]. A more economical composite structure was proposed using PVC tube externally strengthened with FRP. The mechanical behavior of nine PVC-CFRP confined concrete columns with a ring beam joint (PCRCJ) and one PVC confined concrete column with a ring beam joint (PFRCJ) under axial compression was investigated [13]. The specimens designed with the concept of strong connection joint and weak column.

The failure mode changed from the cracking of PVC tube and fracture of CFRP strips for the PCRCJ to the buckling of PVC tube. Increasing the CFRP strip spacing decreased the ultimate strain of the PVC-CFRP confined concrete column. An equation was proposed for evaluating the ultimate bearing capacity of the PCRCJ under axial compression load:

\[ N = N_p + N_{ps} \left( f_{p} A_{p} + f_{c} A_{c} \right) + f_{p} A_{p} (0.212 + B_{1} \xi + C_{1} \xi^2) \quad (23) \]

8.2 Geopolymer concrete piles (GPGCPs) with PVC-FRP

A promising scheme was proposed by Zhang and Hadi [14], which consists of PVC-FRP as strengthening materials for piles, the new system is characterized by the high strength-to-weight ratio, high durability and high anti-corrosion ability of PVC-FRP resulting in geogrid-confined pervious geopolymer concrete piles (GPGCPs). The main feature of the new system was the presence of two peak axial stresses for the GPGCPs with FFCC. The first peak (the maximum axial stress) was reported to be 20% higher than the maximum axial stress of GPGCPs without FFCC.

8.3. PVC-FRP confined concrete (FFCC) incorporating recycled aggregate

Another type of structural concrete core with recycled aggregate, encased by a PVC tube and the tube further confined with a PFPR tube, was investigated [15]. Polyster FRP (PFPR) is more economical in terms of material cost to use than other FRP types, despite its lower stiffness. However, plastic PVC is much cheaper in terms of material and labor costs with large tensile and compression deformation capacity despite its much lower stiffness [15]. Among the test variables was the configuration of the tube. Design-oriented strength and strain models were proposed for the tested specimens:

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\[ f_{\text{cr}} = 1.17 - 0.0043 \left( \frac{f_l}{f_t} \right)^{2.665} \]  
\[ \varepsilon_{\text{cr}} = 1 + 63.64 \left( \frac{f_l}{f_t} \right)^{0.817} \]  

8.4 PVC-CFRP column with a ring beam

The mechanical characteristics of the PVC-CFRP confined concrete column with a ring beam joint (PCRCJ) were researched [16]. Among the tested specimens was one PVC confined concrete column with a ring beam joint (PRCJ) subjected to axial compression, which was designed with the concept of strong connection joint and weak column. The failure mode of PRCJ was due to the buckling of the PVC tube. While the failure mode of the PCRCJ was due to the cracking of the PVC tube and fracture of CFRP strips. A model for estimating the stress-strain curve of the column was proposed:

\[ \sigma_{\text{cl}} = 0.58E_{\text{c}}\varepsilon_{\text{cl}} - \frac{(E_c - E_f)^2}{12f_{\text{to}}} \varepsilon_{\text{cl}}^2 \quad 0 \leq \varepsilon_{\text{cl}} \leq \varepsilon_t \]  
\[ \sigma_t = f_{\text{cr}} + E_{\text{c}}\varepsilon_t \]  
\[ N_wzad = f_{\text{cr}} + N_c \]  
\[ f_{\text{cr}} = 24.734(\xi_{\text{sf}})^{-0.0692} \]  
\[ N_s = f_{\text{cr}} + K\varepsilon_{\text{cr}} \]  
\[ \varepsilon_{\text{cr}} = 2f_{\text{cr}}/(E_c - E_f) \]  
\[ f_{\text{cr}} = 24.734(\xi_{\text{sf}})^{-0.0692} \]  
\[ K_g = \frac{S_f}{S_f} \]  

Where: \( \sigma \) = axial stress of reinforced PFCSC; \( \varepsilon_{\text{cr}} \) = axial strain of PFCSC; \( E_c \) = slope of reinforced section; \( f_{\text{to}} \) = slope of the reinforced section, which indicates the intercept of reinforced of the reinforced section of PFCSC; \( \varepsilon_t \) = intersection of parabola and reinforced section; \( \varepsilon_{\text{cr}} \) = ultimate strain of PFCSC; \( N_wzad \) = carrying the capacity of the steel bar; \( K_g = 1.16; \) \( \xi_{\text{sf}} \) = intercept of the straight section of the reinforced concrete column without PVC-CFRP reinforcement; \( \varepsilon_{\text{cr}} \) = the axial ultimate strain of the PVC-CFRP tube concrete column without column loading.

Also, \( \xi_{\text{sf}} \) = equivalent confinement effect coefficient; \( A_c \) = CFRP strip area; \( k_g \) = constraint influence coefficient for the CFRP strip; \( s_f \) = width of CFRP strips; and \( s_f^2 \) = CFRP strip spacing were for predicting the stress-strain curve of PVC-CFRP confined concrete column with the joint, the following model was proposed:

\[ f_{\text{cr}} = \frac{N_wzad}{A_c} \]  
\[ f_{\text{cr}} = f_{\text{cr}} \left( f_{A_c} + f_{A_c} \right) + f_{A_c} A_p \frac{B_3 (1 + C_1 \xi^2 + C_2 \xi^2)}{A_c} \]  

Conclusions

This study gathered the most recent advances on the use of UPVC tube for confining concrete, along with recent models for predicting the load capacity of CFPT. The following conclusions can be drawn from the review of the recent literature:

1- Most of the proposed strength and stress-strain models are based on a limited number of experimental data.

2- There is no model for the strength of CFPT based on a comprehensive database of experimental test results.

3- Engineering plastic is a new class of construction materials which can be used in infrastructure applications such as piers and bridge columns. This innovative material offers several advent-ages such as reducing the brittleness of concrete and providing additional shear and compressive capacity.

4- With proper design methodologies, CFPT specimens can be used for structural applications with economic and technical advantages.

5- There is no available design guideline for UPVC tube confined concrete columns. More research is needed to narrow the gap between recent research and the use of CFPT in practice.

The mechanical behavior of individual components of CFPT columns needs to be further explored which could improve our understanding of CFPT based materials. Research is needed to develop design methods for large-scale structural response and their use in field applications. The long term structural behavior of CFPT columns including flexure, shear, torsion, bond, and fatigue needs to be researched for different loading and environmental conditions.

Declaration of Conflict of Interests

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References


[4.] Abdulla N A. Mechanical behavior of slender composite columns under axial compression load. KSCE Journal of Civil Engineering, 2020, 24(1), 208-218


