Materials Today: Proceedings 65 (2022) 895–900

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

The mechanical and blast resistance properties of polyvinyl chloride/calcium carbonate (PVC/$CaCO_3$) nanocomposites

Sary A. Malak [a,*], Salam Kazma [b], Christ El Achkar [a]

[a] Notre Dame University, Department of Civil and Environmental Engineering, Zouk Michael, Zouk Mosbeh, P.O. Box 72, Lebanon
[b] NOVAFLOOR, Courtimmo, 62231 Coquelles, France

ARTICLE INFO

Article history:
Available online 12 April 2022

Keywords:
Ductility
Blast resistance
Toughness
Plastics
Flexural strength
Cementitious composite

ABSTRACT

This paper discusses the advantages of the use of a novel construction nanocomposite material such as polyvinyl chloride/calcium carbonate (PVC/$CaCO_3$) used for the structural retrofit of building structures. The research herein compares its mechanical (tension and flexure) and blast resistance properties to typical cementitious composites and polymer composites commonly used in the industry. Typical cementitious composites include high performance fiber reinforced concrete (HPFRC) while polymer composites include fiber reinforced polymers (FRP). This material is produced by mixing powdered recyclable polyvinyl chloride (PVC) plastic resins with calcium carbonate fillers. It is thermo-formable, recyclable, fire/water proof resistant, durable and maintenance free. It is easier to handle than other composites and has no major construction-related shortcomings. The material tensile strengths ranging between 27 MPa and 14 MPa are lower than that of fiber reinforced polymers (FRP) and close to that of cementitious composites while the tensile rupture strains between 0.01 and 0.02 are higher than other composites. Its flexural strength reached values up to 100 MPa which is close to that of FRP and higher than cementitious composites. Expected damages due to blast are lower than other composites due to its high flexural stresses and flexural modulus with low fundamental frequencies at 3.76 Hz. Thus this material might have great potential in structural repair, retrofit, and new construction that requires ductility and ease of applicability in the field.

1. Introduction

The retrofit of existing structures to resist structural loads including blast has been most commonly achieved using cementitious composites such as high performance fiber reinforced concrete (HPFRC) and polymer composites such as fiber reinforced polymers (FRP). Cementitious composites included ultra-high performance fiber reinforced concrete (UHPFRC) [1,2], slurry infiltrated fiber concrete (SIFCON) [3,4] and slurry infiltrated mat concrete (SIMCON) [4,5]. All cementitious composites consisted of steel fibers either intermixed or infiltrated with high performance cementitious composite based slurry consisting of cement, fine sand, silica fume, superplasticizers and water. The tensile modulus of elasticity ranged between 4000 MPa and 20000 MPa, the tensile strengths between 8.5 MPa and 16 MPa, rupture strains at 0.024, and toughness values ranging between 0.128 MPa and 0.29 MPa respectively. The tests results noted values for the flexural modulus of elasticity ranging between 4320 MPa and 6870 MPa and flexural ultimate stresses between 36 MPa and 45 MPa.

While the presence of fibers in cementitious materials have increased the tensile capacity of the composite, it has been reported that the addition of nanomaterials also significantly improve the mechanical properties of concrete. A study [6] has shown that the concrete containing optimal dosages of nanomaterials including nano-titanium dioxide (TiO_2), iron-oxide (Fe_2O_3), nano-clay/metakaolin, and nano-calcium carbonate ($CaCO_3$), improve the ductility and mechanical properties of fresh concrete. However higher dosages might adversely affect workability and mechanical strength. Based on this study the optimal dosages were between 1 and 4% for TiO_2, 13% for Fe_2O_3, 5–7.5% for nano-clay/metakaolin, and 0.5–2% for nano-$CaCO_3$. Additional studies [7] have shown that increasing the quantity of $CaCO_3$ from 5% to 15% in concrete mixtures, cured for 28 days, decreases the

* Corresponding author.
E-mail address: smalak@ndu.edu.lb (S.A. Malak).

https://doi.org/10.1016/j.matpr.2022.03.521
2214-7853/

compressive strength by 10% to 20% while adding gypsum will increase the strength by 10% to 20%irrespective whether sodium chloride (NaCl) solutions are present in the mixing or curing water. Low percentages of CaCO3 in powdered concrete ranging between 0.75 % and 1% showed increase in the compressive strength, splitting tensile strength and flexural strength by 30%, 30% and 12% respectively. However a further increase in content of $CaCO_3$ up to 1.5 % resulted in a decrease in the mechanical properties of powdered concrete [8]. Studies focused on evaluating the effects of lithium carbonate (Li_2CO_3) and nano-calcium carbonate ($CaCO_3$) on the mechanical properties of ultra high-performance concrete (UHPC). The results indicated that the 1-day comprehensive strength of the UHPC increased significantly with the addition of Li_2CO_3 and $CaCO_3$. Likewise, the addition of $CaCO_3$ mitigated the loss of the 28-day compressive strength. For the materials evaluated, the 1-day compressive and flexural strengths reached peak values of 72.1 MPa and 13.9 MPa, respectively, for optimum dosages of 0.075–0.1% Li_2CO_3 and 3–4% $CaCO_3$, respectively [9].

FRP has been the most commonly used retrofit technique. Its advantages include improved strength, ductility, and ease of application. Such composites have been widely adopted into codes. Many researchers reported improved structural performance of retrofitted structures with FRP than with HPFRC. However, HPFRC are more suited for bridge deck infills, rebar anchorages and column joint retrofits against seismic loadings. Glass and carbon fiber reinforced polymers (GFRP and CFRP) consist of carbon or glass fabric reinforced with epoxy resin with properties based on typical manufacturer specifications [10]. The modulus of elasticity ranged between 20000 MPa and 82000 MPa, the tensile strength between 400 MPa and 800 MPa, the rupture strains at 0.0083 and the toughness at 3 MPa. The flexural strength of FRP ranged between 104.8 MPa and 123.4 MPa with flexural moduli of elasticity ranging between 2650 MPa and 3120 MPa.

The research herein provides an alternative material solution to conventional cementitious composites and polymer composites to be used for the retrofit of existing structures. The composite consists of PVC plastics intermixed at high temperatures with high percentages of nano-$CaCO_3$ fillers to increase rigidity of the composite. The use of PVC/$CaCO_3$ nanocomposite construction materials have only recently been developed. Its properties are favorable in terms of durability, sustainability, and constructability in the field. It has been used for architectural purposes but no information exists on its structural response as a retrofit material thus, requiring investigation of its mechanical and blast properties including its tensile and flexural behavior.

PVC/$CaCO_3$ nanocomposites are manufactured by mixing 67 percent of powdered PVC recyclable plastics with 33 percent of calcium carbonates by weight through a heated extruded/calendered (rotating cylinder) concept. Its advantages include: (a) improved strength, ductility and toughness, (b) thermo-formable and easy to construct on the field by cutting, bending and welding (gluing) through a heating process, (c) adaptable to producing different shapes and sizes as required for structural use, (d) maintenance free, (e) fire, water and chemical resistant, and (f) durable and 100 percent recyclable.

Very limited research has been provided with regards to its mechanical and blast properties. In order to understand the structural response of a material a full investigation of its mechanical properties is warranted. Literature review for the mechanical properties of some of the similar plastic/filler composites is presented in the following section. Such nanocomposites include plastics more flexible than PVC such as polypropylene (PP) and high density polyethylene (HDPE) with different amounts and types of fillers, and polyvinyl chloride (PVC) with low quantities of calcium carbonate fillers. The composite discussed in this research has a more rigid plastic such as PVC with higher filler quantities resulting in more rigidity than other nanocomposites which is suitable for gravity and flexural load resistance as well as retrofit construction applications.

Based on a recent study by the same author herein for the tensile response of the composite [11], the tensile modulus of elasticity showed values ranging between 23078 MPa and 2139 MPa for thicknesses ranging between 1 mm and 12 mm respectively. The modulus of elasticity of PP/$CaCO_3$ composites with filler quantities of 15 wt% (percent by weight of composite) showed values in the range of 1500 MPa [12]. For PP/$CaCO_3$ with micro fillers at 50 wt % [13] the modulus of elasticity was in the range of 7000 MPa while for polyamide (PA6) with 20 wt% of $CaCO_3$ filler [14], the values were in the range of 3500 MPa.

The tensile strength of the composite decreased from 27.4 MPa to 14.03 MPa with an increase in thickness from 1 mm to 12 mm [11]. For PP/$CaCO_3$ composites [15], the ultimate stresses were at 16 MPa. HDPE/$CaCO_3$ composites with high quantity of fillers [16] showed ultimate stresses at 24 MPa. The tensile strengths of similar PVC/$CaCO_3$ composites [17–21] with finer and lower quantity of fillers presented higher values due to the presence of lower percent of fillers ranging between 35 MPa and 55 MPa.

Tensile rupture strains of the composite ranged between 0.01 and 0.02 and remained constant at 0.02 for thicker sections [11]. For composites such as PVC/$CaCO_3$ [17–21] with lower filler percentage, PP/ $CaCO_3$ [12,15,22], rubber/$CaCO_3$ [23–25], and polypropylene/silicon dioxide (PP/SiO_2) [26] rupture strains were ranging in values between 1 and 7. Other literature for flexible HDPE/$CaCO_3$ [16] composites presented values at 0.1.

The tensile toughness of the composite ranged between 0.23 MPa and 0.13 MPa [11]. PP/$CaCO_3$ and HDPE/ $CaCO_3$ [15,16] have toughness values of 1.9 MPa and 1.1 MPa respectively. Other studies for PP/$CaCO_3$ and PP/SiO_2 composites [22,26] presented results with higher toughness values at 4.5 MPa and 20 MPa.

The flexural modulus of elasticity for PP/$CaCO_3$ with 16 percent amount of filler by weight was at 1500 MPa and flexural strength of 39 MPa for 5 percent calcium carbonate [15]. Other studies [27] for HDPE/$CaCO_3$ composites noted that the modulus of elasticity in flexure was measured at 1000 MPa and the flexural stresses at 26 MPa. Studies for PVC/$CaCO_3$ composites with filler content up to 20 parts per hundred resin (pphr) [28] showed modulus of flexure in the range of 3500 MPa with flexural strengths in the range of 70 MPa. Some studies [29] showed flexural moduli of elasticity of 3000 MPa for PVC/blendex blend with nano-CaCO3 fillers and 4500 MPa for typical PVC/$CaCO_3$ fillers up to 25 pphr.

Composites consisting of PVC, low cost olive pits flour (OPF) and precipitated bio-calcium carbonate (PBCC) have shown a decrease in tensile strength, tensile rupture strains and flexural strength compared to typical PVC when 60% of PVC is replaced with lower content of OPF ranging between 30% and 60% and higher content of PBCC ranging between 10% and 60% [30]. Similarly higher contents of talc powder fillers ranging between 10% and 30% in polypropylene (PP) lower the tensile strength, flexural strength and the corresponding flexural strains [31]. Studies on homopolymer polypropylene filled with calcium carbonate [32] showed that increase in quantities of fillers between 0% and 50% resulted in tensile strengths ranging between 32 MPa and 20 MPa, values of modulus of elasticity between 1.54 GPa and 2.99 GPA, rupture strains between 0.11 and 0.03, flexural strengths between 50 MPa and 5.67 MPa and flexural modulus of elasticity between 1.5 GPa and 3.26 GPa. Studies [33] have shown that the use of nano fillers (size less than 0.01 μm) in PVC/$CaCO_3$ composites improves the tensile strength, modulus of elasticity and strains at rupture compared to the use of micro fillers (size between 0.7 and 100 μm). Numerical models were developed for the compressive properties of PVC/CaCO3 composites showing that the elastic modulus increases while the compressive strength and rupture strains decrease with an increase in filler content [34].

The developed mechanical properties of $PVC/CaCO_3$ nanocomposites will be used for the design of structural elements retrofitted with such material in order to predict the overall structural response due to in particular blast loads. This type of material is considered as an alternative solution to typical materials used in the industry.

The use of $PVC/CaCO_3$ nanocomposite for retrofitting does not necessarily eliminate the need for other conventional retrofits. Each type of retrofit has a specific application for which it is best suited.

Different types of cementitious and polymer fibrous composites have been used in the industry to mitigate and retrofit structures against conventional and unconventional loadings. These composites included FRC, UHPFRC and FRP. Other research focused on different types of plastics with the same quantity of fillers such as $PP/CaCO_3$ and $HDPE/CaCO_3$ or same types of plastics with lower quantities of fillers such as $PVC/CaCO_3$ however in either case such composites are more flexible which restricts its use in the construction industry. PP and HDPE are more flexible plastics than PVC while the addition of fillers in the composite provide rigidity.

Since this material has only recently been developed, information on its behavior as a retrofit material is very limited or nonexistent. Thus the objective of this study is to provide preliminary investigation on its tensile and flexural response and compare its mechanical and blast resistance properties to the other cementitious composites and polymer composites used in the construction industry. The developed mechanical properties are used to determine the strength in the different modes of failure required to assess the structural behavior and response of the retrofitted structure. The tensile, flexural and column confinement response of retrofitted structural elements with this composite is part of an ongoing funded research.

2. Mechanical properties

The mechanical properties included the tensile modulus of elasticity E, ultimate tensile stress σ_u, tensile rupture strain ε_r, tensile toughness TO, ultimate flexural strength f_m, and flexural modulus E_m.

2.1. Experimental investigation-tension

Six rough textured samples for each of the two different thicknesses of 1 mm and 10 mm have been tested. The specimen width was at 50 mm and length of 480 mm. Tests in tension, as shown in Fig. 1, were according to ASTM D638 at a stroke control rate of 2 mm/min. Fig. 2 shows one sample stress strain curve representation of a 1 mm and 10 mm thick $PVC/CaCO_3$ nanocomposite compared to cementitious composites.

2.1.1. Results-tension

Table 1 summarizes the tensile material properties as compared to other composites. The following is noted:

- It is noted that the strength and modulus of elasticity decreases with an increase in thickness from 27.4 MPa to 16 MPa and from 23708 MPa to 2434 MPa with an increase in rupture strains from 0.01 to 0.02.
- When comparing to other composites, the elastic modulus of elasticity for thin sections is higher than the other composites but lower than carbon fiber reinforced polymers (CFRP) at 82000 MPa. For thick sections, the elastic modulus of elasticity is less than that for cementitious composites and polymer composites.

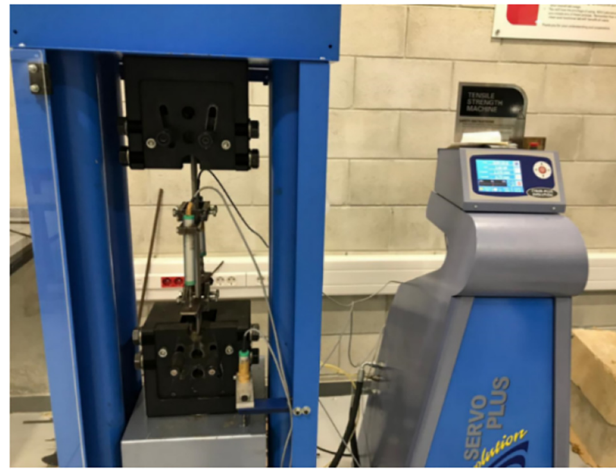

Fig. 1. Test in tension [11].

- The ultimate stress for thin sections is higher than cementitious composites but lower than FRP with high tensile strengths reaching 834 MPa. The ultimate tensile strength for thick sections are close to cementitious composites.
- Rupture strains for thin sections are lower than cementitious composites but close to that of FRP with values ranging between 0.0085 and 0.0176. For thick sections rupture strains are higher than FRP but closer to cementitious composites.
- Toughness for thin and thick sections are close to cementitious composites but lower than that of FRP with values ranging between 3 and 4.
- The overall stress strain curve for thick sections compared to the other composites shows the occurrence of a delayed peak stress reaching its value at strains of 0.02 as shown in Fig. 2.

2.2. Experimental investigation-flexure

In preparation for the flexural tests, 5 samples of 6 mm panels with width of 650 mm and length of 1450 mm were tested in bending as per ASTM E2322. Additional flexural tests, with and against the direction of grain, were done for a total of 18 samples of 10 mm thick × 50 mm wide × 240 mm long panels.

2.2.1. Results-flexure

Table 2 summarizes the flexural material properties as obtained from load deflection curves and compared to other composites. The following is noted:

- The flexural modulus of elasticity at 3600 MPa and flexural strength at 100 MPa does not vary with thickness or grain orientation.
- The ultimate flexural resistance at 100 MPa is slightly lower than GFRP composites at 123 MPa but higher than cementitious composites ranging between 36 MPa and 45 MPa. The flexural modulus of elasticity of 3740 MPa is slightly higher than that of FRP and lower than cementitious composites.

2.3. Analytical investigation-blast

A non-linear dynamic analysis [35,36] was performed on typical $PVC/CaCO_3$ panels used as a facade for a building structure situated 1 km away east from the epicenter of the explosion located at the seaport of the capital city Beirut, Lebanon. Fig. 3 shows the front elevation of the structure facing the explosion with minimal

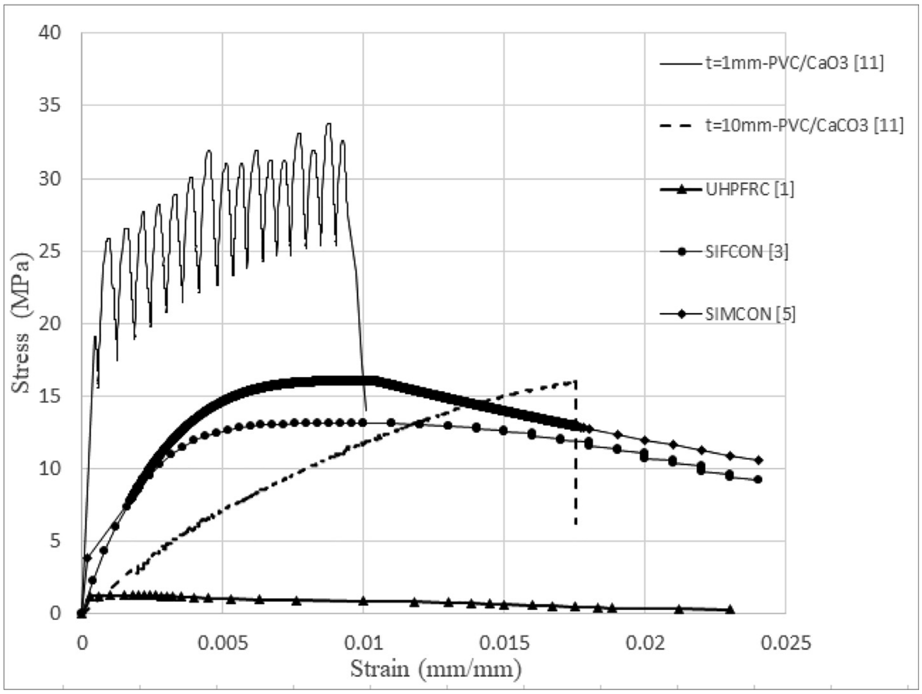

Fig. 2. Tensile stress strains curves of PVC/$CaCO_3$ nanocomposites and cementitious composites.

Table 1
Tensile results of PVC/$CaCO_3$ nanocomposites and cementitious composites/polymer composites.

Composite	E MPa	σ_uMPa	ε_r	TO MPa
PVC/CaCO3 [11] t = 1 mm	23,078	27.4	0.0103	0.2263
PVC/CaCO3 [11] t = 10 mm	2434	16.1	0.018	0.16
UHPFRC [1]	4000	8.53	0.024	0.128
SIFCON [3]	13,540	13.1	0.024	0.255
SIMCON [5]	20,653	16.1	0.024	0.29
GFRP [10]	20,900	460	0.0176	4.04
CFRP [10]	82,000	834	0.0085	3.54

Table 2
Flexural results of PVC/$CaCO_3$ nanocomposites and cementitious composites/polymer composites.

Composite	E_mMPa	f_mMPa
PVC/$CaCO_3$ t = 6 mm-Longitudinal	3740	98
PVC/$CaCO_3$ t = 10 mm-Longitudinal	3620	100
PVC/$CaCO_3$ t = 10 mm-Transverse	3460	90
UHPFRC [2]	6875	45
SIFCON [4]	4320	43
SIMCON [4]	4320	36
GFRP [10]	3120	123.4
CFRP [10]	2650	104.8

damage to the PVC/$CaCO_3$ paneling after the event. The panel dimensions are 900 mm wide × 1200 mm long × 5 mm thick. The panels are considered as a simple supported beam subjected to a triangular transient load representing the blast pressure. A similar analysis of cementitious composites and polymer composite panels with the same dimensions was also performed for comparison purposes.

Fig. 3. Front elevation of a structure (1 Km east of the seaport of the city of Beirut, Lebanon) cladded with PVC/$CaCO_3$ nanocomposite panels.

2.3.1. Results-blast

The analysis was based on a threat size of 920 Tons of Ammonium Nitrate equivalent to 400 Tons of equivalent TNT. Table 3 shows the results where γ is the density of the material. $P_r, P_i, t_r, t_i, \theta_r, \theta_i, \mu_r, \mu_i$ are the pressures, time durations, rotations at the ends of the panel, and dynamic load factors (ratio of plastic deformation to elastic deformation) for reflected and incident blast waves respectively. The dynamic load factors and rotations are a representation of the extent of damage exhibited by the component [37,38]. R_m is the flexural resistance of the panel obtained from the ultimate flexural strength f_m from Table 2, T is the period of the panel system.

As noted in the results summarized in Table 3, PVC/$CaCO_3$ panels exhibited insignificant damage for reflected and incident pressures with dynamic load factors of 10 and dynamic rotations of 18 degrees. The FRP panels also exhibited insignificant damage for reflected and incident pressures with dynamic load factors ranging

Table 3
Blast results of PVC/$CaCO_3$ nanocomposites and cementitious composites/polymer composites.

Composite	γN/mm^3	P_rMPa	t_r (sec)	P_i MPa	t_i (sec)	R_m MPa	T (sec)	μ_r*	μ_i*	θ_r* Deg.	θ_i* Deg.	Damage Extent
PVC/CaCO3 t = 5 mm	16×10^{-6}	0.013	0.19	0.006	0.55	0.004	0.266	10	10	18	18	Survival
UHPFRC t = 5 mm	24×10^{-6}	0.013	0.19	0.006	0.55	0.0018	0.24	>100	>100	>50	>50	No Survival
SIFCON t = 5 mm	24×10^{-6}	0.013	0.19	0.006	0.55	0.0017	0.303	100	>100	75	>75	No Survival
SIMCON t = 5 mm	24×10^{-6}	0.013	0.19	0.006	0.55	0.0015	0.3	100	>100	75	>75	No Survival
GFRP t = 5 mm	1.6×10^{-5}	0.013	0.19	0.006	0.55	0.005	0.288	9	6	26	18	Survival
CFRP t = 5 mm	1.6×10^{-5}	0.013	0.19	0.006	0.55	0.0043	0.315	10	8	30	24	Survival

* *Note:* dynamic load factor: >100 (failure), dynamic rotation: >50, 75, 90 (failure).

between 6 and 10 and higher dynamic rotations ranging between 18 and 30 degrees. Dynamic load factors and dynamic rotations for both materials are comparable since they have the same periods at 0.3 sec, flexural resistance at 0.004 MPa, and flexural stiffness around 3700 MPa. However, cementitious composites exhibited flexural and rotational failure since the ultimate resistances for the same period of 0.3 sec are lower in the range of 0.0015 MPa while their flexural stiffness is higher at 4320 MPa. This concludes that PVC/$CaCO_3$ and FRP panels could have great potential for retrofitting and protecting building structures against blast loads.

3. Conclusions

PVC/$CaCO_3$ composite is a novel material that exhibits improved benefits in terms of ductility and strength. It has great potential for the retrofitting and new construction of building structures exposed to conventional and blast loads. The following conclusions are drawn based on the preliminary findings presented:

- The composite is thermo-formable by bending and welding through heating which provides ease of installation in the field and has great applicability as a reusable and durable formwork for curved concrete structures. Other advantages include it being recyclable, fire/water proof, durable, and maintenance free.
- With an increase in thickness from 1 mm to 10 mm, the tensile strength decreased from 27.4 MPa to 17.1 MPa, modulus of elasticity decreased from 23078 MPa to 1701 MPa, rupture strains increased from 0.01 to 0.02, and toughness decreased from 0.23 MPa to 0.16 MPa.
- Its tensile strength is close to other cementitious composites and much less than FRP. However the composite can sustain higher strengths at higher rupture strains at failure (ductility) resulting in a delayed peak stress occurrence. The tensile stiffness for thick material is lower than other composites which is beneficial for seismic and blast resistance. Its tensile mechanical properties compare well with HDPE/$CaCO_3$ and PP/$CaCO_3$ composites of similar filler quantity and fineness however the stains at rupture are higher since the plastics PP and HDPE are more flexible than PVC. Such composites might not be suitable for the construction industry due to the lack of rigidity.
- The flexural modulus at 3620 MPa and flexural strength at 100 MPa do not vary with thickness or grain orientation. The flexural properties of PVC/$CaCO_3$ and polymer composites are similar while their flexural strength is higher and flexural modulus lower than cementitious composites.
- PVC/$CaCO_3$ and FRP panels experienced minimal damage from blast loads compared to cementitious composites due to their higher flexural strengths. A slight improvement of nanocomposites compared to polymer composites was noted due to the slight increase in flexural moduli of elasticity. However, the fabrication of thick FRP panels are hard to fabricate and deform into different shapes for retrofit applications.
- From preliminary research herein, the tensile and flexural strength of the composite has shown some improvement compared to other composites resulting in beneficial use for the retrofit of building structures that will sustain different types of loads including in particular blast loads. In addition the developed rigidity of the composite compared to other plastics with fillers is an additional advantage for retrofit.
- Based on investigation herein, it can be concluded that PVC/$CaCO_3$ composite might have great potential for using as a retrofit or new construction. The composite may be suited for retrofitting existing concrete beams, slabs or columns as additional flexural and shear reinforcement. It may be used at retaining walls as formwork, tension reinforcement and water proofing. The planks can be glued to existing damaged concrete surfaces after surface preparation or can be used for new construction as formwork that will support the concrete and remain as a permanent structure that requires no painting or plastering. The material may act as a lateral confinement to increase axial column capacity by continuously wrapping around existing columns or to be used as a permanent formwork and finished enclosure for new columns. However, further investigation is warranted to identify its structural response when used for new construction and retrofitting of existing structural members.

CRediT authorship contribution statement

Sary A. Malak: Methodology, Investigation, Formal analysis, Writing – review & editing, Writing – original draft, Supervision. **Salam Kazma:** Validation. **Christ El Achkar:** Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors would like to thank NOVAFLOOR Company for the supply and manufacturing of materials and many thanks to NDU staff, students and lab technicians who contributed with the experimental testing.

References

[1] Zhidong Zhou, Pizhong Qiao, Direct tension test for characterization of tensile behavior of Ultra High Performance Concrete, J. Testing Evaluat. ASTM, July 2020.

[2] R. Christ, et al., Study of mechanical behavior of ultra-high performance concrete (UHPC) reinforced with hybrid fibers and with reduced cement consumption, Revista Ingenieria de construccion, Vol. 34 No.2 Santiago August 2019.

[3] Antoine E. Naaman, Joseph R. Homrich, Tensile stress-strain properties of SIFCON, ACI Mater. J. 1989, 244–251.

[4] E. Hackman Lloyd, B. Farrell Mark, O. Dunham Orville, Slurry Infiltrated mat concrete (SIMCON), Concrete International, Dec. 1992, pp. 53 to 56

[5] N. Krstulovic-Opara, S. Malak, Tensile behavior of slurry infiltrated mat concrete (SIMCON), ACI Mater. J. (1997) 39–46.

[6] J.A. Abdalla, B.S. Thomas, R.A. Hawileh, J. Yang, B.B. Jindal, E. Ariyachandra, Influence of nano-TiO_2, nano-Fe_2O_3, nanoclay, nano-$CaCO_3$, on the properties of cement/geopolymer concrete, Cleaner Mater. (2022), https://doi.org/10.1016/j.clema.2022.100061.

[7] Jianzheng Wang, Shilin Song, Yu Zhang, Tao Xing, Ying Ma, Haiyan Qian, Hydration and mechanical properties of calcium sulphoaluminate cement containing calcium carbonate and gypsum under NaCl solutions, Materials 15 (2022) 816. 10.3390/ma15030816

[8] Zahraa F. Muhsin, Nada Mahdi Fawzi, Effect of nano calcium carbonate on some properties of reactive powder concrete, IOP Conf. Series: Earth and Environmental Science 856 (2021) 012026 doi:10.1088/1755-1315/856/1/0120262

[9] T. Wang, J. Gong, B.o. Chen, X. Gong, W. Guo, Y. Zhang, F. Li, K.H. Mo, Mechanical properties and shrinkage of ultrahigh-performance concrete containing lithium carbonate and nano-calcium carbonate, Adv. Civ. Eng. 2021 (2021) 1–15.

[10] Fyfe Co. LLC, Fyfe Europe S.A., 2020 info@fyfe.com, www.fyfeco.com.

[11] S.A. Malak, Tensile stress strain model of polyvinyl chloride/calcium carbonate ($PVC/CaCO_3$) nanocomposite plank, Results Mater. 10 (2021) 100193, https://doi.org/10.1016/j.rinma.2021.100193.

[12] M.Y.A. Fuad, H. Hanim, R. Zarina, Z.A. Mohd, A.H. Ishak, Polypropylene/calcium carbonate nanocomposites-effects of processing techniques and maleated polypropylene compatibilisr, eXPRESS Polym. Lett. 4 (10) (2010) 611–620.

[13] L. Jilken, G. Malhammar, R. Selden, The effect of mineral fillers on impact and tensile properties of polypropylene, Polym. Testing 10 (1991) 329–344.

[14] Baltus Cornelius Bonse, Lucian Mendes Molina, Effect of calcium carbonate particle size and content on polyamide 6 processing and properties, Polym. Process. Soc. PPS, 1779, 030019-1-030019-5.

[15] Y.W. Leong, M.B. Abu Bakar, Z.A.M. Ishak, A. Ariffin, B. Pukanszky, Comparison of the mechanical properties and interfacial interactions between talc, kaolin, and calcium carbonate filled polypropylene composites, J. Appl. Polym. Sci. 91 (5) (2004) 3315–3326.

[16] Z. Bartczak, A.S. Argon, R.E. Cohen, M. Weinberg, Toughness mechanism in semi-crystalline polymer blends: II. High-density polyethylene toughened with calcium carbonate filler particles, Polymer 40 (1999) 2347–2365.

[17] Xiao-Lin Xie, Qing-Xi Liu, Robert Kwok-Yiu Li, Xing-Ping Zhou, Qing-Xin Zhang, Zhong-Zhen Yu, Yiu-Wing Mai, Rheological and mechanical properties of PVC/$CaCO_3$ nanocomposites prepared by in situ polymerization, Polymer 45 (2004) 6665–6673.

[18] Chuansheng Liu, Chengbao Wu, Lieshu Lin, A study on the Interfacial Adhesion Strength of Different types of Calcium Carbonate Filled Poly (vinyl chloride) Composites, Advances in Engineering Research, Volume 104, 7th International Conference on Mechatronics, Control and Materials (ICMCM 2016).

[19] Xuehua Chen, Chunzhong Li, Shoufang Xu, Ling Zhang, Wei Shao, an H.L. Du, Interfacial adhesion and mechanical properties of PMMA-coated CaCO3 nanoparticles reinforced PVC composites, China Particuol. 4, No. 25-30, 2006.

[20] Irene Bonadies, Maurizio Avella, Roberto Avolio, Cosimo Carfagna, Maria Manuela Errico, Gennaro Gentile, Poly (vinyl chloride)/CaCO3 nanocomposites: influence of surface treatment on the properties, J. Appl. Polym. Sci. 122 (2011) 3590–3598.

[21] A.A. Robaidi, A. Mousa, S. Massadeh, I.A. Rawabdeh, N. Anagreh, The Potential of Silane coated calcium carbonate on mechanical properties of rigid PVC composites for pipe manufacturing, Mater. Sci. Appl. 02 (05) (2011) 481–485.

[22] D. Eiras, L.A. Pessan, Mechanical properties of polypropylene/calcium carbonate nanocomposites, Mat. Res. 12 (4) (2009) 517–522.

[23] S. Manroshan, A. Baharin, The effect of calcium carbonate on the mechanical properties and morphology of natural rubber latex films, 13th Scientific Conference & 14th Annual General Meeting, Electron Microscopy Society of Malaysia, 13-15 December 2004.

[24] N. Phuhiangpa, S. Phonghanphanee, W. Smitthipong, Study of rubber/calcium carbonate composites, in: The international Conference on Materials Research and Innovation (ICMARI), Materials Science and Engineering, 773 (2020) 012013.

[25] M.M. Al-Mosawi, Ali, J.H. Mohmmed, Experimental approach to mechanical properties of natural rubber mixing with Calcium carbonate powder, Int. J. Phys. Sci. 7(49), pp. 6280–8282, 30 December 2012.

[26] Chun Lei Wu, Ming Qiu Zhang, Min Zhi Rong, Klaus Friedrich, Tensile performance improvement of low nanoparticles filled-polypropylene composites, Compos. Sci. Technol. 62 (2002) 1327–1340.

[27] Yung Ngothai, Handoko, Putra, Togay Ozbakkaloglu, Rudolf Seracino, Effect of $CaCo_3$ size on the mechanical properties of recycled HDPE, Thermoplastic Polyolefin Blends, J. Vinyl, January 2009.

[28] Aznizam Abu Bakar, Nurul Nazihah Mohmed Rosli, Effect of nano-precipitated calcium carbonate on mechanical properties of PVC-U and PVC-U/acrylic blend, Jurnal Teknalogi 45(F) Dis. 2006: 83-93.

[29] Ning Chen, Chaoying Wan, Yong Zhang, Yinxi Zhang, Effect of nano-$CaCO_3$ on mechanical properties of PVC and PVC/Blendex blend, Polym. Testing 23 (2004) 169–174.

[30] Salah F. Abdellah Ali, Ibrahim O. Althobaiti, E. El-Rafey, Ehab S. Gad, Wooden polymer composites of poly(vinyl chloride), olive pits flour, and precipitated bio-calcium carbonate, ACS Omega 6 (2021) 23924−23933.

[31] Pham Thi Hong Nga, Van-Thuc Nguyen, Experimental study on mechanical behavior of polypropylene- based blends with talc fillers, Adv. Sci., Technol. Eng. Syst. J. 5(6) (2020) 571–576, https://dx.doi.org/10.25046/aj050669.

[32] Y. Peng, M. Musah, Brian Via, Xueqi Wang, Calcium carbonate particles filled homopolymer polypropylene at different loading levels: mechanical properties characterization and materials failure analysis, J. Compos. Sci. 5 (2021) 302, https://doi.org/10.3390/jcs5110302.

[33] Kardo Khalid Abdullah, Kálmán Marossy, Kinga Tamási, Comparison of different Poly vinyl chloride (PVC) /Calcium Carbonate (CaCO3) blends and their properties, Int. J. Eng. Res. Sci. (IJOER) ISSN: [2395-6992] [Vol-7, Issue-9, September - 2021].

[34] L. Shijun, Pan Sining, Numerical study on the effect of CaCO3 ratio on the mechanical properties of CaCO3/PVC composites, J. Phys.: Conference Series 1820 (2021), https://doi.org/10.1088/1742- 6596/1820/1/012140 012140.

[35] M. Biggs John, Introduction to Structural Dynamics, McGraw-Hill Publishing Company, Published 1964-06-01, 1964.

[36] S. Malak, N. Krstulovic-Opara, Modeling material response of fiber composites used for the retrofit of existing concrete structures under blast loadings, "ACI Technical Publication", Dennis Mertz Symposium on Design and Evaluation of Concrete Bridges, SP-340-7, April 2020, pp. 114-136.

[37] E.J. Conrath, K. Ted, K.A. Marchand, F. Mlakar Paul, Structural design for physical security state of practice, ASCE, SEI (1999).

[38] PDC-TR 06-08, US Army Corps of Engineers Protective Design Center Technical Report, Single Degree of Freedom Structural Response Limits for Antiterrorism Design, 7 January 2008.