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Research Article

Eco-Friendly Prefabricated Vertical Drains from PBS/NRC Blends: Tensile Properties and Biodegradation

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ABSTRACT

This study investigates the tensile properties and biodegradation of bio-based prefabricated vertical drains (PVDs) for ground improvement applications. The potential of using a blended polymer composed of poly(butylene succinate) (PBS) and natural rubber compound (NRC) at ratios of 0%, 10%, and 20% by weight was assessed. Tensile tests were investigated, and a 12-month biodegradation analysis of PBS/NRC blends was conducted in soft clay, potting soil, and seawater environments. The results showed that the tensile strength and Young's modulus of PBS decreased marginally as the NRC content increased. In contrast, the elongation at break of the PBS/NRC blend increased by 2.70% when NRC was substituted at 10% by weight, then declined as the NRC content increased. In addition, biodegradation was observed in all PBS/NRC blends, as evidenced by visual changes such as breakage, surface roughness, and weight loss. Moreover, the PBS/NRC blends in potting soil showed the highest percentage of weight loss, up to 6.48%. This study highlights the potential of these biomaterials as preliminary candidates for PVD applications, providing a basis for further development toward replacing conventional polypropylene (PP) materials.

1. Introduction

Plastic is a popular material used in the food, medical, agricultural, and construction industries due to its advantageous properties, including being lightweight, low cost, high strength, flexible, and resistant to chemicals [1, 2]. The global production volume each year is in the hundreds of millions of tons [3]. However, there are concerns that the use of large quantities of plastic could cause environmental problems as a result. This has been a major problem and has been difficult to solve from the past to the present. Furthermore, it has been found that the

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consumption of plastic has increased since the COVID-19 pandemic [4, 5], causing the problem of plastic disposal. For this reason, there are many solutions to plastic waste management, such as reducing, reusing, recycling, or finding alternative materials, and developing biodegradable materials to replace plastics has received a lot of attention.

One of the major applications of geosynthetics in geotechnical engineering is the use of prefabricated vertical drains (PVDs). PVDs are used to improve the ground in soft clay soil. They act as a drainage path to take more water out of soft, compressible soil, so it consolidates faster. Normally, PVDs are made from synthetic polymers, with polypropylene (PP) as a core and polyethylene terephthalate (PET) as a filter. Many research groups have studied PVDs; for example, a soft ground improvement technique using PVDs on a railway track in Bangladesh was described by Hore et al. [6]. However, commercial PVDs are produced from synthetic plastics, which are non-biodegradable. As a result, millions of meters of PVDs installed in various construction projects remain permanently in the soil layer after the end of their service life, which not only leaves pollution in the soil but can also affect the hydrological properties of the soil in the long term. Recent studies have also highlighted that conventional plastics in soil can degrade into microplastics over time, contributing to long-term environmental contamination. Qi et al. [7] reported that soil is an important sink for microplastics originating from plastic use and waste, which may have widespread impacts on agriculture and soil ecosystems. Recently, biodegradable prefabricated vertical drains (BPVDs) have been attracting attention due to concerns about pollution around the world [8]. An example of BPVDs is one made from natural fibers, with coconut fibers as a core and jute as a filter [8, 9]. These researchers focused on the natural fibers for use as PVDs.

Poly(butylene succinate), or PBS, is a biodegradable polymer synthesized from the condensation between 1,4-butanediol and succinic acid monomers [10]. PBS is used in many applications, such as agricultural film packaging [10], surgical sutures [11], drug delivery systems [12], compostable garbage bags [13], and disposable cups and cutlery [14], due to its favorable mechanical properties and biodegradability [15, 16]. However, its cost remains high compared to conventional plastics. PBS's main limitation is its stiffness, which may lead to limited ductility under certain conditions and reduced resistance to tensile and flexural stresses [10]. Therefore, adding fillers is a common strategy used to reduce costs and improve mechanical properties. Many studies have explored the addition of both organic and inorganic fillers [17, 18]. For example, Singsang et al. [18] reported a study on the mechanical and electrical properties of PBS filled with activated carbon from coffee waste. Mtibe et al. [19] studied the addition of lignin and zinc nanoparticles to a PBS/PBAT (polybutylene adipate-co-terephthalate) blend to improve the properties of PBS. Moreover, the addition of rapeseed press cake to PBS was conducted by Tschichold et al. [20].

Natural rubber (NR) is a bio-based elastomer with high elasticity and is an important renewable resource. Several reports suggest that the toughness of polymers can be improved by adding natural rubber [21-22]. For example, Laksana et al. [22] studied the effect of talc and epoxidized natural rubber (ENR) on the thermal, rheological, and mechanical properties of PBS for material extrusion 3D printing. They discovered that the incorporation of talc and ENR could enhance the ductility and dimensional stability of PBS, with an elongation at break of up to 43.1%, while also improving extrusion stability and shape retention during printing. In addition, Prasoetsopha et al. [21] found that the PBS/NRC blend demonstrated superior mechanical properties, particularly elongation at break and impact strength, which increased with an increase in NRC content. Although PBS/NR blends have been studied for other applications, which have many advantages such as being environmentally friendly and having good mechanical properties, there is still a lack of evaluation of mechanical properties and degradation under environmental conditions that directly simulate their use as PVDs.

The purpose of this research was to evaluate the mechanical properties, morphology, and biodegradability of PBS/NRC blends under three simulated conditions: soft clay, potting soil, and seawater, to build foundational knowledge and confirm the potential for the development of next-generation PVDs that are truly environmentally friendly.

2. Materials and Methods

2.1. Materials

In this research, poly(butylene succinate) (PBS), commercial name BioPBS™ FZ71PM grade (MFR = 24.2 g/10 min), was procured from PTT MCC Biochem Company Limited. The natural rubber (STR 5L) and chemical reagents used for rubber compounding, including stearic acid, zinc oxide (ZnO), tetramethylthiuram disulfide (TMTD), n-cyclohexyl-2-benzothiazole sulfenamide (CBS), and sulfur (S), were purchased from Chareon Tut Co., Ltd. All chemicals were used as received.

2.2. Sample Preparation

The preparation of PBS/NRC blends can be divided into two processes, as illustrated in Fig. 1. First, the preparation of the natural rubber compound (NRC) is illustrated in Fig. 1a, where the natural rubber and chemical reagents were used as received. NRC was prepared on a two-roll mill mixer (ML-D6L12-INV, Chareon Tut Co., Ltd., Samut Prakan, Thailand) with a roller speed ratio of 1:1.4 between the front and back rolls for 30 minutes, and a gap distance of 5 mm and room temperature were used. In the process, natural rubber was masticated for 5 minutes. Then, the order of chemical reagents was mixed every 5 minutes according to the list in Table 1. After being well mixed, the NRC was kept at room temperature for 16 hours before use to allow for improved dispersion and stabilization of the compound.

The second process is the blending of PBS/NRC (shown in Fig. 1b); before use, PBS was dried in an oven at 50°C for 24 hours and kept in a desiccator to minimize moisture uptake. The PBS and NRC were melted and mixed in an internal mixer (MX500–D75L90, Chareon Tut Co., Ltd., Thailand) with a rotor speed of 50 rpm at 145°C for 20 minutes. The total weight of each batch was 300 grams. After complete mixing, the blends were cooled and ground with a plastic grinder. In the compression process, the ground samples were pressed into film sheets with a mold thickness of 0.3 mm via hot compression molding at 145°C with 1500 psi pressure. The compression process involved three steps: preheating, pressing, and cooling for 5, 3, and 3 minutes, respectively. The PBS/NRC ratios were 100/0, 90/10, and 80/20 by weight, and each ratio was denoted as PBS, PBS90/NRC10, and PBS80/NRC20, respectively. Polypropylene (PP) was used as a reference material to compare the mechanical properties and biodegradation of the blends. Polypropylene was also mixed with an internal mixer and pressed by hot-compression molding under the same conditions, but the temperature was 180°C due to its higher melting temperature.

2.3. Tensile Testing

The universal testing machine (LS Plus Series, Lloyd) was used to determine the tensile properties. Rectangular-shaped samples were prepared according to the ASTM D882-02 standard. The method used a crosshead speed of 30 mm/min, a gauge length of 30 mm, and a load cell of 10 kN at an ambient temperature. At least five samples were examined to calculate the average and standard deviation values. Polypropylene (PP) was included as the reference material since commercial PVDs are typically manufactured from PP. Statistical analysis was performed using one-way ANOVA with a significance level of $p < 0.05$.

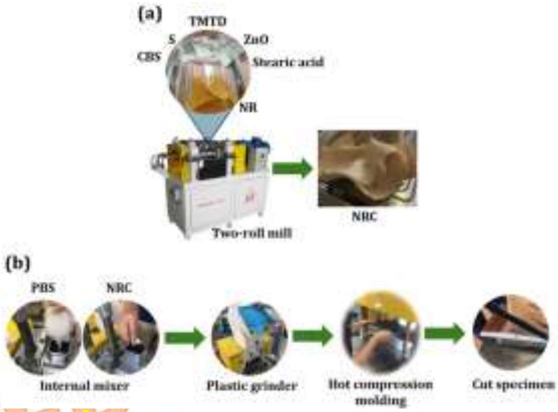


Fig. 1. Preparation of (a) NRC and (b) PBS/NRC blends

Table 1. Natural rubber compound formula

Order	Chemical reagent	Amount (phr)
1	Natural rubber (NR, C_5H_8)$_n$	100
2	Stearic acid ($C_{18}H_{36}O_2$)	2
3	Zinc oxide (ZnO)	4
4	Tetramethyl thiuram disulfide) (TMTD, $C_6H_{12}N_2S_4$)	3.5
5	Sulfur (S, S_8)	0.75
6	N-cyclohexyl-2-benzothiazolesulfenamide (CBS, $C_6H_{12}N_2S_4$)	1

2.4. Biodegradation Testing

For the biodegradation test, samples with dimensions of 10 mm × 10 mm × 0.3 mm were used. Before the test, all samples were dried in an oven at 50°C for 24 hours. The dried samples were weighed and recorded as W_0. After that, samples were studied for degradation in potting soil, soft clay, and seawater for 12 months under natural environmental conditions in Nakhon Ratchasima Province, Thailand, from June 2021 to May 2022.

Soft clay was collected from a depth of 5–8 m in Khlong Toei District, Bangkok, with a relative humidity of approximately 55–57%. Potting soil was purchased from a local plant shop in Nakhon Ratchasima Province, with a pH of 6.0–7.6 and relative humidity of approximately 80–90%. Both soft clay and potting soil were placed in plastic containers with a height of approximately 20 cm, and the samples were buried at a depth of about 5 cm from the surface. The containers were kept at room temperature. Seawater was collected from Chao Samran Beach (13°00′21.5″N, 100°03′58.5″E), with a pH of 6.0–6.8, salinity of 27–34‰, and specific gravity of

1.025–1.026. The samples were immersed in seawater and kept in containers at room temperature.

The samples were investigated in the biodegradation test at intervals of 2, 6, and 12 months. At each interval, the samples were photographed using a mobile phone to document their visual appearance. Subsequently, they were cleaned with deionized water and dried in an oven at 50°C for 24 hours. Then, they were weighed and recorded as W_f to determine weight loss. The percentage of weight loss was calculated using Eq. (1). At least three samples were averaged for each condition. In addition, the surface morphology was specifically examined using an optical microscope (OM, DM4 M, Leica, Germany) only at the 2- and 6-month intervals. PP was also tested under the same conditions to serve as the reference for comparison.

$$\text{Weight loss (\%)} = \frac{W_o - W_f}{W_o} \times 100 \qquad (1)$$

3. Results and Discussion

3.1. Mechanical Properties of PBS/NRC Blends

Figure 2 shows the average tensile strength of all samples (PP, PBS, PBS90/NRC10, and PBS80/NRC20). The tensile strengths of PP, PBS, PBS90/NRC10, and PBS80/NRC20 samples were 33.7 ± 1.3, 34.6 ± 1.7, 28.2 ± 0.8, and 19.7 ± 0.7 MPa, respectively. This result showed that the tensile strength of the PBS sample was slightly higher than that of the PP sample. Statistical analysis (one-way ANOVA) indicated a significant difference among the groups ($p < 0.0001$). Hence, this suggests that PBS possesses comparable tensile strength, indicating its potential as a candidate material for PVD applications. For comparison, the tensile strength of commercial PVDs is usually expressed as force per unit width (kN/m), with reported minimum values of about 10 kN/m [23]. Considering the specimen thickness used in this study (0.3 mm), this value is roughly equivalent to an engineering stress of 33.3 MPa, assuming a uniform cross-sectional area. In contrast, the tensile strengths measured in this work (19.7-34.6 MPa) are substantially higher than the typical requirements for commercial PVDs.

After substituting NRC, the tensile strength of the polymer blends decreased, which is consistent with previous reports [21]. This decrease was statistically significant with increasing NRC content ($p < 0.0001$). This decrease might have been due to the lower tensile strength of rubber, as the tensile strength of natural rubber is not more than approximately 20 MPa [24]. However, it is shown that the tensile strength of the PBS90/NRC10 composite (28.2 ± 0.8 MPa) remains significantly higher than that of other biocomposites, such as the biocomposite of PBS and PBAT reinforced with lignin and zinc, which exhibits a tensile strength below 26.99 MPa [19], and the biocomposite of PBS and PBAT reinforced with rapeseed press cake, which exhibits a tensile strength below 20.68 MPa [20].

The average percentage elongation of all samples is illustrated in Fig. 2. It can be seen that the average percentage elongation values of the PBS, PBS90/NRC10, and PBS80/NRC20 samples were higher than those of the PP sample. Statistical analysis confirmed that elongation at break differed significantly among the samples ($p < 0.05$). The maximum average percentage elongation value was observed in the PBS90/NRC10 sample. This value showed the same trend as the addition of NR in PLA [25]. For PBS80/NRC20 samples, the elongation of PBS was slightly lower than that of the PBS90/NRC10 sample. This was due to the discontinuity of the PBS matrix resulting from the dispersion and particle size of NRC, which becomes more pronounced at higher NRC content due to possible phase separation and reduced interfacial adhesion between PBS and NR. In addition, the NR phase may form elongated (elliptical) domains under shear during processing, which can lead to stress concentration and reduced elongation at break [18, 25].

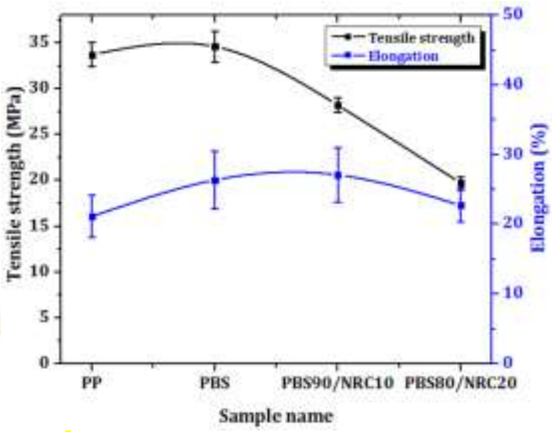


Fig. 2. Tensile strength and elongation at break of PP, PBS, and PBS/NRC blends. Statistical analysis (one-way ANOVA) showed significant differences among all groups for tensile strength ($p < 0.0001$) and elongation at break ($p < 0.05$)

Figure 3 indicates the Young's modulus of all samples. It could be seen that the Young's modulus of PBS was lower than that of PP. The addition of NRC decreased the Young's modulus of PBS due to the elasticity of rubber. Moreover, the addition of tougher polymers resulted in a reduction in Young's modulus [22]. The differences in Young's modulus among the samples were also found to be statistically significant ($p < 0.0001$). The results were consistent with the study of Singsang et al. [26], which found that the Young's modulus of poly(butylene succinate) blended with natural rubber compound decreased when the amount of natural rubber compound increased.

The mechanical properties test shows that PBS has slightly higher tensile strength than PP, suggesting that PBS is strong enough for PVD applications. Furthermore, PBS and PBS/NRC blends have higher percentage elongation than PP, especially PBS90/NRC10, which has the highest elongation, indicating great toughness, flexibility, and the ability to withstand deformation during installation and soil consolidation. Meanwhile, the Young's modulus of PBS and PBS/NRC blends is lower than that of PP, reflecting increased flexibility due to the addition of natural rubber, resulting in the material having more ability to accommodate soil deformation.

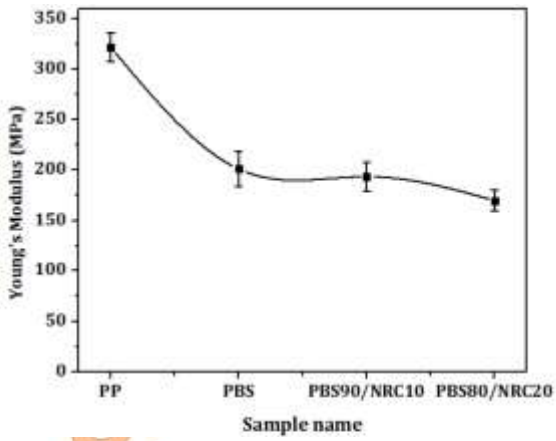


Fig. 3. Young's modulus of PP, PBS, and PBS/NRC blends. Statistical analysis (one-way ANOVA) showed a significant difference among all groups ($p < 0.0001$)

3.2. Degradation of PBS/NRC Blends

The percentage of weight loss for PP, PBS, PBS90/NRC10, and PBS80/NRC20 is shown in Fig. 4. All samples were degraded under soft clay, seawater, and potting soil for 12 months. It could be seen that all samples exhibited increased degradation over time and a slow decomposition rate in the initial months, consistent with the findings of Nelson et al. [27], who reported that weight loss of pure PBS was minimal in the initial months, a characteristic of its degradation behavior. Moreover, the degradation in soft clay was slightly lower than that in seawater. The degradation of the samples was attributed to hydrolysis of the amorphous regions of the polymer matrix due to microorganisms in the environment [28].

The degradation in potting soil for 12 months showed the highest weight loss of all samples, which were 0.14 ± 0.01%, 3.23 ± 0.71%, 4.23 ± 1.42%, and 6.48 ± 1.62% for PP, PBS, PBS90/NRC10, and PBS80/NRC20, respectively. Moreover, adding NRC could enhance the degradation of PBS. This indicated that NRC could accelerate the degradation of PBS, an effect also observed in other studies where natural fillers created pathways for microbial attack in the PBS matrix [17, 26].

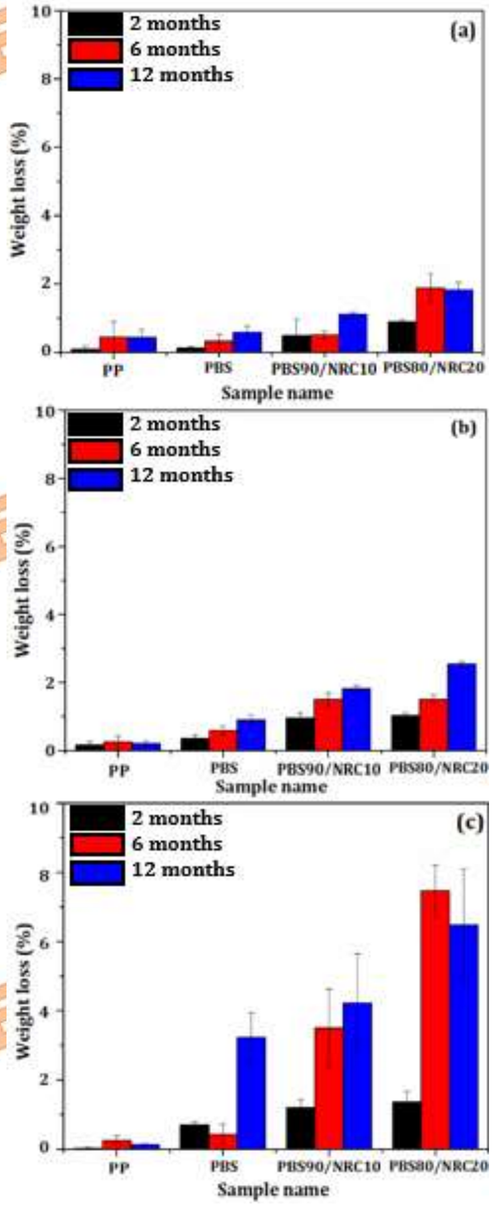


Fig. 4. Weight loss of PP, PBS, and PBS/NRC blends during biodegradation in different media: (a) soft clay, (b) seawater, and (c) potting soil

Figure 5 shows the images of degraded samples tested for 0, 2, 6, and 12 months in soft clay, seawater, and potting soil. The samples after 2 months of degradation were similar to the original samples. This result was consistent with the minimal change in the percentage of weight loss. In contrast, the images of samples degraded for 6 and 12 months in the potting soil exhibited obvious changes in the PBS/NRC blends, including visible cracks and fragmentation corresponding to the percentage of weight loss. These findings are in line with previous studies that found that PBS filled with silkworm cocoons exhibited cracks and surface erosion more than pure PBS in soil environments due to the fillers creating pathways for microbial attack, accelerating the degradation of PBS-based composites [17]. As expected, the PP sample did not show any major changes during the degradation test, consistent with reports that PP is highly resistant to biodegradation under similar conditions [29]. No apparent differences were observed in the images of degraded samples in soft clay and seawater, consistent with their lower degradation rates compared to potting soil.

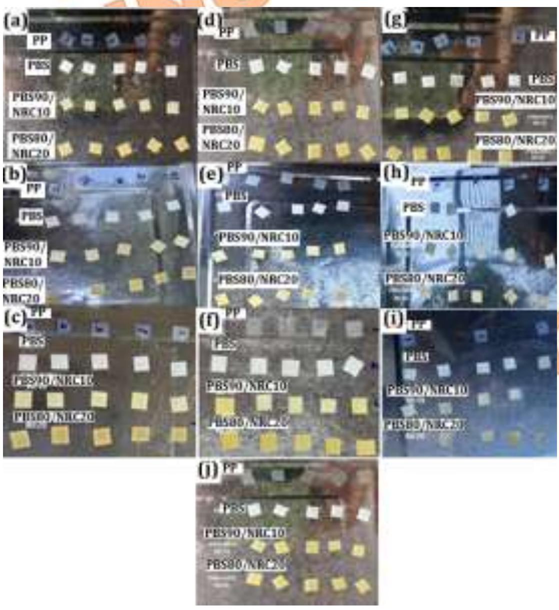


Fig. 5. Photographs of PP, PBS, and PBS/NRC blends samples taken with a mobile phone during biodegradation: in soft clay; (a) 2 months; (b) 6 months; (c) 12 months: in seawater; (d) 2 months; (e) 6 months; (f) 12 months: in potting soil; (g) 2 months; (h) 6 months; (i) 12 months and (j) before degradation

3.3. Morphology of PBS/NRC Blends

The optical micrographs of the surfaces of PP, PBS, PBS90/NRC10, and PBS80/NRC20 are shown in Tables 2 and 3. The results show that all samples exhibited a smooth surface with some scratches (indicated by the blue arrow) before the biodegradation test. After 2 months of degradation, the surfaces had no significant changes, as shown in Table 2. On the other hand, after 6 months of degradation, the surfaces of PBS/NRC blends were rough with some holes (indicated by the red arrow), as shown in Table 3,

Table 2. The optical micrographs of PBS/NRC blends and PP after a 2-month interval

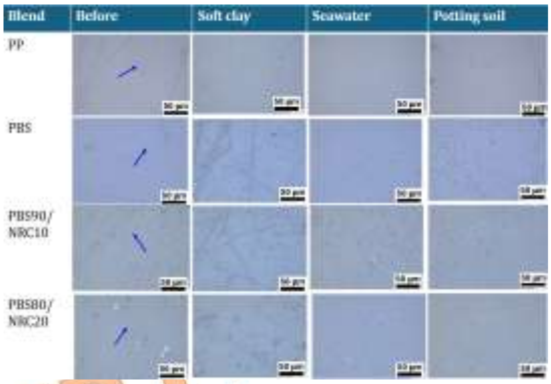
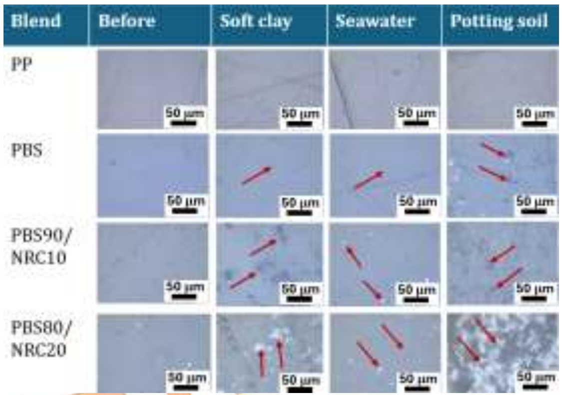


Table 3. Optical micrographs of PBS/NRC blends and PP after a 6–month interval



except for the PP sample. This might be due to the absorption of water and microorganisms in the sample, as reported previously [28]. The sample degraded in potting soil exhibited the most significant signs of degradation, followed by the samples degraded in soft clay, while the samples degraded in seawater had the lowest degradation. Moreover, increasing NRC content resulted in more surface degradation in potting soil and soft clay but not in seawater. These observations are consistent with previous studies reporting that biocomposites accelerate surface roughening and hole formation in soil burial degradation [30].

The surface roughness of the samples was inspected using an optical profilometer. The 3D images of the surface topography of the sample after a 6-month biodegradation period are shown in Fig. 6. In the images, green indicates areas at the reference level (0), red represents elevations above the reference level, and blue represents depressions or regions below the reference level. The PP samples showed almost no surface change in all tested environments, including soft clay, seawater, and potting soil, reflecting their resistance to biodegradation. In contrast, PBS samples began to show some trenches or raised areas, indicating the beginning of degradation. PBS composites, such as PBS90/NRC10 and PBS80/NRC20, showed clear changes in surface texture, with both high (red) and low (blue) areas. Depending on the environment, seawater and potting soil appeared to accelerate the formation of trenches and surface irregularities more than soft clay, which corresponds to the results of the percentage of weight loss and the optical micrographs of the surfaces mentioned above.

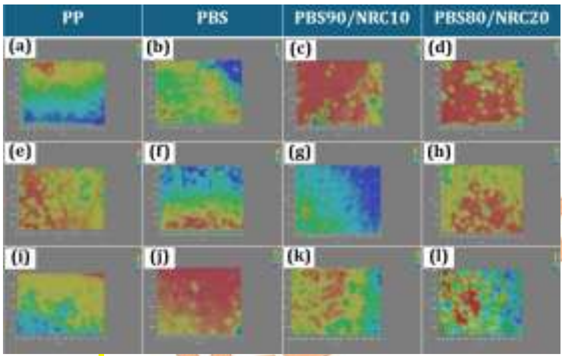


Fig. 6. Topography of the samples after 6 months of biodegradation in different media: (a)-(d) soft clay, (e)-(h) seawater, and (i)-(l) potting soil

4. Conclusions

The addition of NRC into PBS increased the elongation at break and percentage of weight loss but decreased the tensile strength and Young's modulus. The PBS90/NRC10 sample shows potential as a candidate material for biodegradable PVDs in ground improvement. The degradation of PBS/NRC blends followed the order of potting soil > soft clay > seawater. The highest weight loss was observed in potting soil (up to 6.48% over 12 months), whereas soft clay from Bangkok showed a lower but noticeable 2% weight loss. These results demonstrate the potential of PBS/NRC blends, especially with 10% NRC, as environmentally friendly candidate materials for PVD applications, although further studies on large-scale manufacturing, field installation feasibility, and long-term soil–structure interaction are required to confirm scalability and practical implementation. Future work should also investigate extended degradation periods and mechanical performance under real field conditions.

Nomenclature

PBS	Poly(butylene succinate)
NRC	Natural rubber compound
PP	Polypropylene
PVDs	prefabricated vertical drains
g	Gram
phr	Parts per hundred resin
m	Meter
cm	Centimeter
mm	Millimeter
µm	Micrometre
MPa	Mega Pascal
°	Degree
s	Second
min	minute
˚C	Degree celsius
STR	Standard Thai Rubber
ZnO	Zinc oxide
TMTD	Tetramethylthiuram disulfide
S	Sulfur
CBS	n-Cyclohexyl-2-benzothiazole sulfenamide
%	Percent

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Conflicts of Interest

The authors declare no competing interests.

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