Development of Alkaline-Resistant Polyester via PVA-Based Coating for Geosynthetic Applications

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Abstract

Polyester-based geosynthetics are widely employed in civil engineering applications owing to their high mechanical performance and cost-effectiveness. However, exposure to aggressive alkaline environments, such as high-pH soils and groundwater, significantly reduces their long-term durability. In this study, polyvinyl alcohol (PVA) was employed as a coating material for polyester yarns due to its intrinsic alkaline resistance and water solubility, reducing the need for organic solvents and enhancing environmental sustainability. To improve water resistance and mechanical stability, PVA was crosslinked using crosslinkers,. The crosslinked coating was applied to polyester yarns via a padding mangle machine and dried under controlled conditions. The resulting materials demonstrated excellent alkali resistance up to pH 12.5 at 50°C, with negligible physical changes after prolonged exposure. Gravimetric analyses, including GSM determination, confirmed uniform coating deposition and mechanical reinforcement. This work provides a cost-effective, scalable, and environmentally sustainable strategy to extend the functional lifespan of polyester geosynthetics in harsh environments.

Key words:

Alkaline resistant Polyester, Crosslinking, Geosynthetics, Polyvinyl alcohol, and Tensile strength

Citation

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1. Introduction:

Polyester-based geosynthetics are extensively utilized in civil engineering owing to their outstanding mechanical strength and cost efficiency. However, their vulnerability to alkaline hydrolysis in harsh environments, such as soils and groundwater with high pH greatly restricts their long-term durability. In this study, a surface coating approach is explored to enhance the alkaline resistance of polyester materials. Coating with alkaline-resistant polymers was identified as a practical and scalable technique that effectively improves chemical stability without requiring extensive energy input or complex processing steps. This method offers a cost-efficient and industrially adaptable solution for improving the long-term durability of polyester-based materials exposed to harsh alkaline environments.

Polyvinyl alcohol (PVA) selected as the coating material due to its inherent alkaline resistance and water solubility, which minimizes the need for organic solvents and promotes environmental sustainability. PVA is a versatile synthetic polymer with a carbon–carbon (C–C) backbone and multiple hydroxyl (-OH) groups attached as side chains. These hydroxyl groups impart distinctive characteristics, including water solubility [1]. Owing to its solubility property PVA has found increasing use in packaging and other industries [2]. In addition, PVA offers advantages like excellent film-forming capability, strong adhesion, and high thermal stability [3]. PVA appears as a white, odorless, tasteless powder known for its superior film-forming properties. It is used across diverse sectors, including paper, textiles, adhesives, coatings, films and packaging, pharmaceuticals, construction, and cosmetics [4]. While PVA is water-soluble and exhibits a high degree of crystallinity, this property can limit its performance in humid conditions or in applications requiring water resistance. To overcome this limitation, several crosslinking agents such as cyanuric acid, citric acid, formaldehyde, glutaraldehyde, glyoxal, acetic acid, and Maleic acid are commonly used. However, without adequate modification or plasticization, crosslinked PVA films may become brittle, highlighting the need for optimization, particularly in coating applications.

To address this, a novel method has been developed that achieves effective crosslinking within few minutes. This innovation enhances process efficiency and broadens the applicability of PVA across industries that demand rapid

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processing. The newly developed coating technique optimizes reaction conditions to achieve rapid crosslinking while preserving or enhancing PVA's mechanical strength and stability. This advancement offers a promising, sustainable, and efficient solution for industries utilizing PVA-based coatings.

2. Materials and Methods

2.1 Materials

PVA (Molecular weight = Approx. 1,15,000, Hydrolysis degree = 98 - 99%), Calcium Hydroxide 94 %, Sodium Hydroxide pellets 98%, Sulphuric Acid (AR) 98%, Sodium Sulphate Anhydrous 99%, 40% Crosslinker -1(CL-1), 37% Crosslinker -2 (CL-2), were buy from Loba Chemie Pvt Ltd, 07, Wodehouse Rd, near Bank of India, Cuffe Parade, Mumbai, Maharashtra, India, 400005. Crosslinker -3 (CL-3), purchased from Tokyo Chemical Industry Co. Ltd, 6-15-9 Toshima, Kiti-Ku, Tokyo, Japan. Shanghai Lingfeng chemical reagents co. LTD (Shanghai, China),

2.2 Methods

2.2.1 Preparation of crosslinked films PVA / Crosslinker -1, Crosslinker -2, and Crosslinker -3

This two-step process ensures efficient crosslinking of the polymer. In the first stage, the polymer solution was prepared, and thin films were fabricated using the solution-casting method. In the second stage, the fabricated films were subjected to crosslinking in an acid bath prepared by dissolving sulfuric acid and sodium sulfate in distilled water. The preparation of crosslinked films of PVA/(CL-1), PVA/(CL-2), and PVA/(CL-3) is outlined below.

Initially, PVA (5% w/v) was dissolved in distilled water by heating the solution to 85°C under continuous magnetic stirring at 800 rpm for 30 minutes to achieve complete dissolution. The solution was then cooled to 30°C (ambient temperature), and crosslinking agents were added in the desired ratios, as specified in Table 1. The mixture was stirred for an additional 10 minutes to ensure homogeneity. The resulting solution was poured into Petri dishes to form thin films, which were dried in an oven at 70°C until complete drying. Once dried, the films were carefully peeled off for subsequent crosslinking. In the second stage, the dried films were immersed in a crosslinking bath containing sulfuric acid (5% v/v) and sodium sulfate (20% w/v) for 5 minutes at 50°C. After crosslinking, the films were thoroughly rinsed with distilled water to remove residual acid and then dried in an oven at 70°C for 10 minutes.

CL-1/PVA	CL-2/PVA	CL-3/PVA
1.0	1.0	1.0
0.8	0.8	0.8
0.6	0.6	0.6
0.4	0.4	0.4
0.2	0.2	0.2

Table1 composition ratio of crosslinking agents and PVA

2.2.2 Water-swelling degree

The water swelling degree was determined by immersing a 3 × 5 cm film sample (Figure 3c) in distilled water for 72 hours. After swelling, the dimensions (ls) and weight of the swollen film were recorded. The film was then placed in a desiccator at room temperature for three days to dry completely, after which the dried film dimensions (ld) were measured. The water swelling degree was calculated using the following equation:

$$DS = [(ls - ld)/ld] \times 100$$

2.2.3 Degree of Cross

The degree of crosslinking was evaluated based on the weight loss of the films before and after immersion in water. All prepared films were initially dried to a constant weight and recorded as m0. After immersion in water for 72 hours, the films were assumed to have reached solubility equilibrium. The remaining insoluble portions were then dried in an oven at 85°C until a constant weight was achieved and recorded as md. The degree of crosslinking was calculated using the following equation:

$$DC = \mathrm{m0}/\mathrm{md} \times 100$$

2.2.4 Evaluation of Alkaline Resistance property of PVA-coated Polyester

The alkaline resistance of the coated polyester samples was evaluated in accordance with DIN EN 14030:2003, "Screening test method for determining the resistance to acid and alkaline solutions- Geotextiles and geotextile-related products." This standard specifies a procedure for assessing the chemical stability of geosynthetics under aggressive alkaline conditions. According to the standard, the test specimens are completely immersed in solution of pH-12.5, maintained at a temperature of 60 °C for a period of three days (72 hours). Upon completion of the exposure period, the samples are removed, thoroughly rinsed with distilled water to eliminate residual alkali, and then dried under controlled conditions prior to further evaluation.

3. Result and Discussion

3.1 Water-swelling degree

Since PVA is inherently water soluble, the evaluation of water solubility after crosslinking served as a key indicator of crosslinking effectiveness. The solubility and swelling tests were therefore used to assess both the degree of swelling and the extent of crosslinking achieved. PVA was crosslinked at progressively higher crosslinker-to-PVA ratios of 0.2, 0.4, 0.6, 0.8, and 1.0, under consistent conditions summarized in Table 2. Each experiment was performed in triplicate, and the resulting film thicknesses were approximately 100 µm. Figure 1, illustrates the relationship between the swelling degree (%) and the crosslinkers/PVA ratio, with corresponding data presented in Table 2. Among the crosslinking agents tested, CL-3 exhibited the most pronounced influence on the swelling behavior of PVA films. At a CL-3/PVA ratio of 0.2, the swelling degree was 18% (±4%). As the CL-3/PVA ratio increased, the swelling degree decreased to approximately 9%, 7%, and 6% (±4%) at ratios of 0.6, 0.8, and 1.0, respectively. This reduction occurs because higher CL-3 concentrations promote reactions at both ends of the CL-3 molecule, thereby increasing the crosslinking density and reducing the free volume within the polymer matrix. Consequently, the water resistance of the film improves significantly with increasing CL-3 content [5].

Table 2: Water swelling degree.

Crosslinker / PVA ratio	CL-1	CL-2	CL-3
1.0	Gel formation	20	6
0.8	Gel formation	18	7
0.6	Gel formation	15	9
0.4	265	26	15
0.2	300	40	18

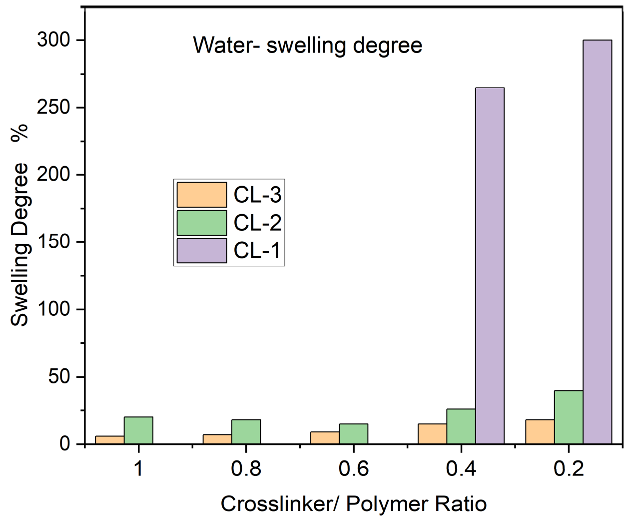

Figure 1 : Water swelling degree

3.2 Degree of Cross-Linking

Figure 2, presents the relationship between the degree of crosslinking and the crosslinker/PVA ratio, with corresponding data summarized in Table 3. The degree of crosslinking was determined using the weight loss method after immersion in water. Among the crosslinker tested, CL-3 exhibited a consistently high crosslinking degree, ranging from 96% to 99% across CL-3 /PVA ratios of 0.2 to 1.0. CL-2 showed a crosslinking degree of 93% at a 0.2 CL-2/PVA ratio, reaching a maximum of 97% at a 0.8 ratio. In contrast, CL-1 achieved a crosslinking degree of 90.2% at the lowest CL-1/PVA ratio, which decreased progressively with increasing concentration. This inverse trend may be attributed to the availability of reactive hydroxyl groups in PVA: at lower CL-1 concentrations, more active sites are accessible for crosslinking, whereas higher concentrations may hinder effective molecular interactions, reducing crosslinking efficiency. These results emphasize the necessity of optimizing crosslinker concentration to balance reactivity and performance in PVA-based systems. The observed variations could also be related to insufficient activation energy for effective reaction initiation at the relatively low experimental temperature [6].

Table 3 : Degree of Cross- linking

Crosslinker / PVA ratio	CL-1	CL-2	CL-3
1.0	64.4	96	98
0.8	66.5	97	99
0.6	68.2	94	99
0.4	76.9	94	97
0.2	90.2	93	96

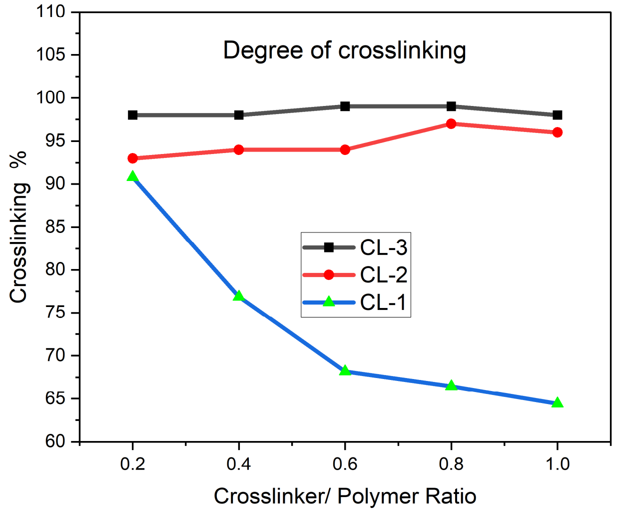

Figure 2 : Degree of cross - linking

3.3 Coating of Polyester Yarn, geotextile, and geogrid with Crosslinked PVA

Initially, a PVA-based emulsion was prepared by dissolving PVA in distilled water under constant stirring and heating to achieve a homogeneous solution. Selected additives and crosslinking agents were subsequently incorporated into the formulation to enhance coating adhesion, flexibility, and alkaline resistance. The resulting emulsion exhibited suitable viscosity and stability for application through the padding process. The prepared PVA emulsion was then applied to the polyester yarn, geotextile, and geogrid using the padding mangle unit operated at a nip pressure of 2 bars and a roller speed of 120 rpm. These parameters were optimized to ensure consistent pick-up and adequate penetration of the coating into the yarn structure without causing fiber distortion or excessive squeeze-out. After coating, the treated yarns were dried in a hot-air oven at 150°C for 4 minutes to facilitate solvent evaporation and initiate the crosslinking reaction between PVA and the crosslinker. This process yielded a thin, uniform, and adherent crosslinked PVA coating on the polyester yarn surface. The controlled drying conditions promoted the formation of a stable, three-dimensional polymer network, enhancing the chemical resistance and mechanical durability of the yarn. The coated yarns were subsequently conditioned under standard atmospheric conditions (65 ± 2% RH and 25 ± 2 °C) prior to further characterization and performance evaluation.

3.4 Evaluation of Alkaline Resistance property of coated Polyester

The Grams per Square Meter (GSM) of each specimen of virgin polyester textile, coated polyester textile, virgin polyester geogrid, and coated polyester geogrid, before and after alkaline exposure was measured to evaluate the effect of the PVA coating process on material mass and surface coverage. Each specimen was prepared with a fixed size of 20 cm × 20 cm (400 cm²), and the corresponding weights were recorded using a precision balance. GSM values were calculated using the standard relation: The calculated GSM provides a normalized value independent of sample size, allowing direct comparison between coated and uncoated materials.

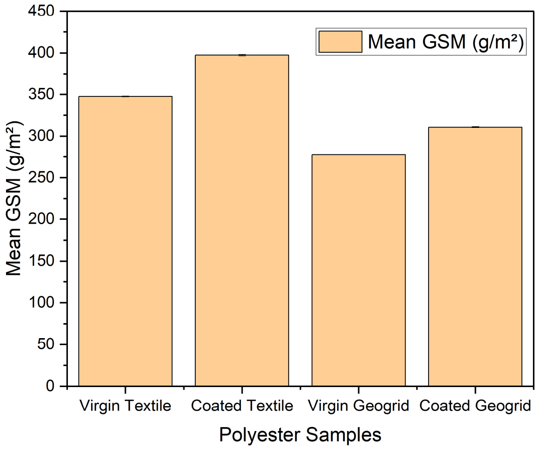

Figure 3 : GSM for Coating uptake Assessment

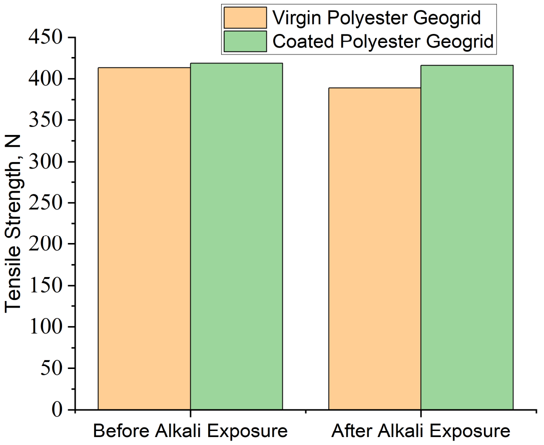

Figure 4 TS for evaluation of Alkaline Resistance

Each GSM value represents the mean of five independent replicates, ensuring statistical reliability. The associated standard deviations were minimal across all samples, confirming excellent repeatability and consistent coating application. Figure 3, presents the relationship between GSM, The virgin polyester textile exhibited a mean GSM of 347.575 g/m², while the coated textile showed an increased GSM of 397.305 g/m², corresponding to an approximate 14.3 % mass gain. This increase can be attributed to the uniform deposition of the crosslinked PVA coating over the textile fibers, indicating effective wet pickup and strong adherence of the coating layer. Similarly, the virgin geogrid demonstrated a mean GSM of 277.145 g/m², which increased to 310.655 g/m² after coating an increment of 12.1 %. The slightly lower percentage increase in geogrid GSM compared to the textile suggests that the open structure of the geogrid allows less polymer retention compared to the denser textile surface.

3.5 Effect of Alkaline Exposure on GSM Retention

Post-exposure GSM measurements were compared with pre-exposure values to determine percentage mass loss. The virgin polyester textile exhibited a -3.20% reduction in GSM, while the coated textile displayed only a -0.10% loss under identical conditions. Similarly, the virgin polyester geogrid experienced a -3.61% GSM reduction, whereas the coated geogrid showed a negligible -0.20% loss. This significant difference highlights the protective efficacy of the crosslinked PVA coating against alkaline hydrolysis. The marked degradation observed in uncoated polyester is attributed to the hydrolytic cleavage of ester linkages in the polymer backbone, which accelerates in highly alkaline environments. In contrast, the coated specimens retained nearly their entire mass, indicating that the crosslinked PVA layer acted as an effective diffusion barrier, preventing direct contact between the polyester surface and the aggressive alkaline medium.

3.6 Tensile Strength Evaluation Before and After Alkaline Exposure

Figure 4, presents the relationship between tensile strength of the virgin and coated polyester geogrids. Tensile strength was determined to assess the influence of the crosslinked PVA coating on mechanical integrity and durability, both before and after alkaline exposure. Each reported value represents the mean of five replicates to ensure statistical accuracy and reproducibility. Before exposure to the alkaline medium, the virgin polyester geogrid exhibited a mean tensile strength of 413.24 N, while the coated polyester geogrid demonstrated a slightly higher mean strength of 418.42 N. This marginal increase (~1.25%) indicates that the PVA coating did not adversely affect the intrinsic mechanical properties of the polyester substrate. Instead, the coating contributed to a minor improvement, likely due to the formation of a thin, crosslinked polymer layer that enhanced fiber–fiber frictional resistance and load distribution during tensile loading. Following alkaline exposure distinct differences were observed between the coated and uncoated samples. The virgin polyester geogrid experienced a substantial decline in tensile strength to 389.02 N, corresponding to a 5.86% reduction compared to its original value. This degradation is attributed to the alkaline hydrolysis of ester linkages in the polyester backbone, resulting in chain scission, molecular weight reduction, and surface erosion, which collectively weaken the fiber structure. In contrast, the coated polyester geogrid retained a tensile strength of 416.46 N after alkaline exposure, showing only a 0.47% reduction relative to its pre-exposure value. The negligible loss in tensile strength clearly indicates the excellent barrier protection provided by the crosslinked PVA coating. The coating effectively inhibited alkaline species from diffusing into the polyester matrix, thereby preventing hydrolytic degradation. This finding aligns with the GSM retention results, where the coated specimens exhibited minimal weight loss (<0.2%) under identical test conditions.

These results collectively demonstrate that the crosslinked PVA coating preserves both dimensional stability and mechanical strength of polyester geogrids when exposed to high-pH environments. The combination of high tensile retention and low GSM variation after exposure confirms the chemical inertness, structural integrity, and long-term performance reliability of the coated material.

4. Conclusion

This study demonstrated the successful development of a crosslinked PVA coating for enhancing the alkaline resistance of polyester-based geosynthetics. The coating, applied using a padding mangle process and thermally cured at 150 °C for 4 minutes, produced uniform and adherent films on both polyester textiles and geogrids. The GSM analysis confirmed effective coating deposition, showing increased areal weight and consistent uniformity. After exposure to an alkaline solution, the coated samples exhibited negligible GSM loss (< 0.2 %), whereas uncoated materials showed about 3–4 % weight reduction, indicating strong chemical resistance of the coating layer. Mechanical testing further validated the coating performance: coated geogrids retained over 99 % of their tensile strength after alkaline exposure, compared to a 5–6 % drop in the uncoated specimens. These results confirm that the crosslinked PVA layer effectively prevents alkaline hydrolysis, maintaining the structural and mechanical integrity of the polyester substrate. Overall, the developed coating provides a durable, sustainable, and easily scalable solution for improving the long-term chemical stability of polyester geosynthetics. Its compatibility with existing industrial processes makes it highly suitable for civil and geotechnical applications where alkaline exposure is a concern.

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