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Clay Crack Initiation and Propagation Resistance Mechanism Using Municipal Solid Waste

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Abstract

This study investigates the potential of black seed flour (Nigella sativa) as an additive to enhance the crack resistance of clay-based landfill liners, aiming to mitigate gas transfer and leachate formation in landfill environments. Two distinct clay types were mixed with varying proportions of black seed flour (10%, 20%, and 30% by weight). The crack propagation resistance was assessed through desiccation tests over short (24 hours) and medium (72 hours) durations. Parameters such as crack morphology, fracture toughness, and crack propagation time were analyzed using image analysis and mechanical testing. The addition of black seed flour significantly influenced the crack morphology and propagation characteristics. Clay type 2 exhibited optimal fracture toughness at 10% and 30% black seed flour concentrations. The presence of black seed flour delayed crack initiation and reduced crack width, indicating improved crack resistance. Comparative analysis with existing literature suggests that the incorporation of natural additives like black seed flour can enhance the structural integrity of landfill liners. This research introduces black seed flour as a sustainable, cost-effective additive to improve the mechanical properties of clay-based landfill liners. The study provides new insights into utilizing natural materials for environmental engineering applications, contributing to the development of more resilient and eco-friendly landfill liner systems.

Keywords: Clay; Black Seed Flour; Fracture Toughness; Fracture Time; Fracture Morphology.

1. Introduction

Accurately predicting the timing of crack initiation and subsequent propagation in clay is essential for ensuring slope stability. Cracks may originate from inherent mineralogical characteristics of the soil or from external loading. The precise moment at which cracks form warrants further detailed investigation. Once a crack is present in a slope, it accelerates soil saturation and shortens the time to structural failure. Moreover, shrinkage-induced cracking in clay undermines slope stability by causing nonlinear settlements and deformations. These deformations can enhance the rate of gas migration and promote the development of leachate-seeping fissures within landfill slopes.

Soil cracking arises from various factors, including freeze-thaw cycles induced by seasonal temperature fluctuations, leading to significant volume changes [1], Furthermore, fluctuations in soil volume can lead to structural damage in

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buildings founded on such soils [2]. Effectively managing soil cracking is crucial for ensuring the long-term stability and integrity of structures.

Seismic loading propagates existing fractures within the soil, exacerbating preexisting cracks [3], and induce cyclic variations in the soil's saturation levels [4]. Cracks form as a result of volumetric changes in the soil during freeze-thaw cycles. Continuous swelling and shrinkage lead to nonlinear deformations, which progressively accelerate soil cracking [1]. Cyclic loading induces cracking in both saturated and unsaturated soils. Moreover, soil fracturing can occur in the absence of external loads and moisture fluctuations, presenting a complex challenge. For instance, chemical reactions between soil and waste materials during the fracturing process require further investigation. The timing of clay fracturing is a critical factor in landfill protection, especially when the landfill is capped with clay soil.

The soil includes both brittle and deformable elements. Depending on its characteristics, the behavior of pre-existing cracks in clay changes under compression conditions [5, 6]. Crack initiation and propagation reduce the strength of the clay [7]. Experimental results indicate that swelling in the clay induces micro-cracks [8, 9]. Moreover, when clay is exposed to elevated temperatures, mineralogical transformations occur [10], it is expected that these thermal effects trigger chemical reactions that lead to crack initiation and growth. In addition, interactions among minerals accelerate these chemical reactions, further promoting the formation of cracks.

The cracks in brittle materials tend to follow a single direction [11], whereas cracks in clay propagate in multiple directions. Clay in loose conditions is extremely susceptible to desiccation cracking, this phenomenon occurs during extended droughts, and later provides pathways for water to penetrate the earth’s structure in the rainy season. Desiccation cracks have been reported on many infrastructure surfaces [12], such cracks develop due to chemical interactions that occur during intense soil evaporation. In addition, recycled aggregate was used in simulating the seismic behavior of the embankment-subsoil model [13]. Municipal solid waste (MSW) has become a major challenge in modern life, yet it also offers an opportunity: its use in the construction industry can be both sustainable and cost-effective. In this study, black seed flour is proposed as an additive in soil-MSW blends to evaluate its ability to improve soil crack resistance. A discontinuous crack pathway in clay can reduce the rate of gas emission by up to threefold [14]. In this study, adding an appropriate amount of black-seed flour to the clay reduced the discontinuity of fractures. To determine the optimal mixture for each clay type, field-based experimental observations are necessary.

The characteristics of clay are intricately linked to its evaporation mechanisms, which govern moisture loss, shrinkage, and the development of desiccation cracks [15]. A significant relationship exists between the intensity of cracking in clay and its interaction with specific waste materials; however, the precise mechanisms and optimal material combinations remain inadequately defined [16]. The research gap on fracture mechanics parameters, such as tensile strength and fracture toughness, in relation to black seed flour-modified clay have not been adequately addressed. This gap presents an opportunity to assess the efficacy of black seed flour as a sustainable additive to improve the mechanical properties of clay liners, thereby enhancing landfill stability and reducing environmental risks.

A detailed investigation is needed into the shrinkage-cracking behavior of clay modified with black seed flour, especially in terms of fracture mechanics parameters such as tensile strength, type I fracture toughness, and moisture retention. Studies enhancing crack resistance in clay using municipal solid waste materials remain scarce. In this work, black seed flour is evaluated as an additive to delay crack initiation and inhibit crack propagation, with the aim of improving the clay’s resistance to cracking. Such enhancements would make the clay more effective as a landfill cover, thereby minimizing gas migration and leachate transmission.

1.1. Declarations

Desiccated clay undergoes crack propagation during volume changes, transitioning from swelling to shrinkage as it loses water and its cohesive, flexible characteristics diminish. Moisture content fluctuations induce continuous swelling and shrinkage, leading to fracture initiation and propagation. The fracture toughness of clay, influenced by its shrinkage properties, is observable in the field, as depicted in Figure 1. Field observations reveal that crack propagation on the clay surface is nonlinear. These surface cracks compromise the integrity of clay liners, undermining their role in controlling moisture and gas migration. To enhance the effectiveness of clay liners in landfill covers, it is essential to minimize permeability, improve fracture toughness, and bolster erosion resistance. The major and sub-cracks observed in Figure 1 illustrate this phenomenon, with major cracks exhibiting greater thickness compared to sub-cracks. Figure 2 illustrates the occurrence of erosion in the field, highlighting the reduction in clay liner thickness covering the slope. The clay liners present in the field have been naturally formed, constructed through compaction processes, or enhanced using various methods. The observed fractures exhibit nonlinear morphological characteristics, with variations in fracture thickness during the initial stages of fracture development in situ. If the clay liner becomes completely partitioned, its coverage fails to support slope stability. The erosion patterns, as depicted in Figure 2, correspond to the local water flow paths during rainfall events. Significant erosion is observed on the upper side of the slope, near the crest, with considerable accumulation of displaced clay at the slope's heel. Overall, the erosion has manifested in a nonlinear pattern across the entire slope face. It is anticipated that lower permeability will occur at the slope's heel. Clay Type 1, as identified in Figure 2, has been selected from the slope's heel for further analysis.

Figure 1. The clay crack in situ

Figure 2. The clayey slope contains erosion and fracture

2. Material and Methods

Municipal Solid Waste (MSW) holds potential as a resource for various industries, including construction. In geotechnical engineering, there is a pressing need to explore sustainable methods for integrating MSW into construction materials to mitigate environmental pollution. Despite its potential, significant research gaps exist in the application of MSW as a construction material within the geotechnical sector. In the present study, the crack resistance, crack initiation time, and crack morphology of clay were modified using black seed flour and cement in varying proportions. The material mixtures were prepared at a room temperature of 31.4°C with 53.6% humidity in the soil mechanics laboratory, maintaining constant environmental conditions throughout the experimental period. Figure 3 shows flowchart for entire investigation.

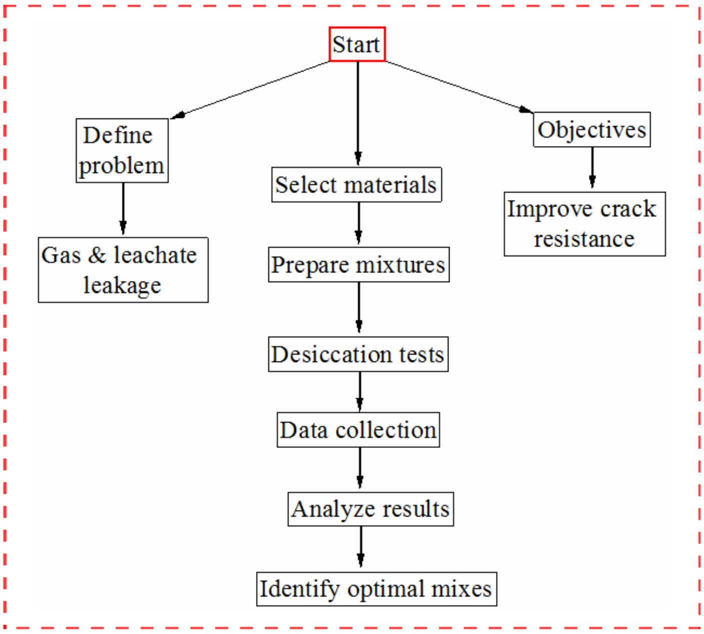

Figure 3. The flowchart for entire investigation

Figure 4 depicts the preparation of specimens using black seed flour and clay. Specimen preparation followed the guidelines outlined in Tables 1 and 2. Prior to mixing, the clay was screened to ensure uniformity. The initial experimental design involved monitoring crack initiation and propagation over periods of 12, 24, and 48 hours. Subsequent analyses focused on fracture development at intervals of 24 hours, 48 hours, 7 days, and 60 days. At the conclusion of the experimental period, the fractures developed in all specimens were compared to assess the influence of the additives on crack resistance and morphology.

Clay type 1 Clay type 2

Black seed waste solid Black seed flour

Figure 4. The materials were used for preparing the specimens

Table 1. Initial design for the specimen build up

Specimen name	Black seed flour (gr)	Clay type 1 (gr)	Water (cc)
A0	-	400	200
A1	40	360	200

Table 2. Final design for the specimen build up

Specimen name	Black seed flour (gr)	Clay type 1	Water (cc)	Specimen name	Black seed flour (gr)	Clay type 2	Water (cc)
A0	-	400	300	A0	-	400	300
A1	40	360	300	A1	40	360	300
A2	80	320	300	A2	80	320	300
A3	120	280	300	A3	120	280	300

Table 1 outlines the preliminary specimen design aimed at investigating fracture mechanism control. In this initial design, 200 cc of water was used to saturate either 400 g of Clay Type 1 or a 400 g mixture of Clay Type 1 and black seed flour. During specimen preparation, it was observed that incorporating 10% black seed flour reduced the workability of the mixture. Consequently, the final specimen design, as presented in Table 2, was adjusted to include 300 cc of water for both Clay Types 1 and 2, mixed with black seed flour, to achieve optimal workability.

2.1. Experimental Design

The experiment was designed to address a geo-environmental engineering challenge, significantly contributing to sustainable development. Figure 5 illustrates the crack development mechanism observed during the study.

Clay type 1 Clay type 1 + 10% black seed flour

After 12 hours

Clay type 1 Clay type 1 + 10% black seed flour

After 24 hours

Clay type 1 Clay type 1 + 10% black seed flour

After 48 hours

Figure 5. The materials were used for preparing the specimens

After 12 hours, cracking initiated at the specimen's corner composed of 90% Clay Type 1 and 10% black seed flour mixture. At the 24-hour mark, crack thickness increased, indicating further propagation. By 48 hours, cracking was evident in the specimen made entirely of Clay Type 1. This procedure necessitates an extended investigation incorporating additional mixture designs and fully saturated specimens to simulate materials in accordance with landfill cover requirements.

3. Experimental Results and Discussion

Figure 6 illustrates the specimens immediately after assembly, displaying no fractures. Both clay types 1 and 2 are free from any cracks during the initial setting phase. This absence of visible defects suggests that the specimens have been properly mixed and compacted, allowing for uniform hydration and minimizing the risk of early-stage cracking. In contrast, Figure 7 depicts the specimens 24 hours post-assembly, showing minor fractures. These sub-cracks developed as a result of the mixture design in both specimens. The presence of these minor cracks indicates that the specimens are undergoing internal stresses, likely due to differential drying or shrinkage. Such stresses can cause the material to contract unevenly, leading to the formation of small fissures.

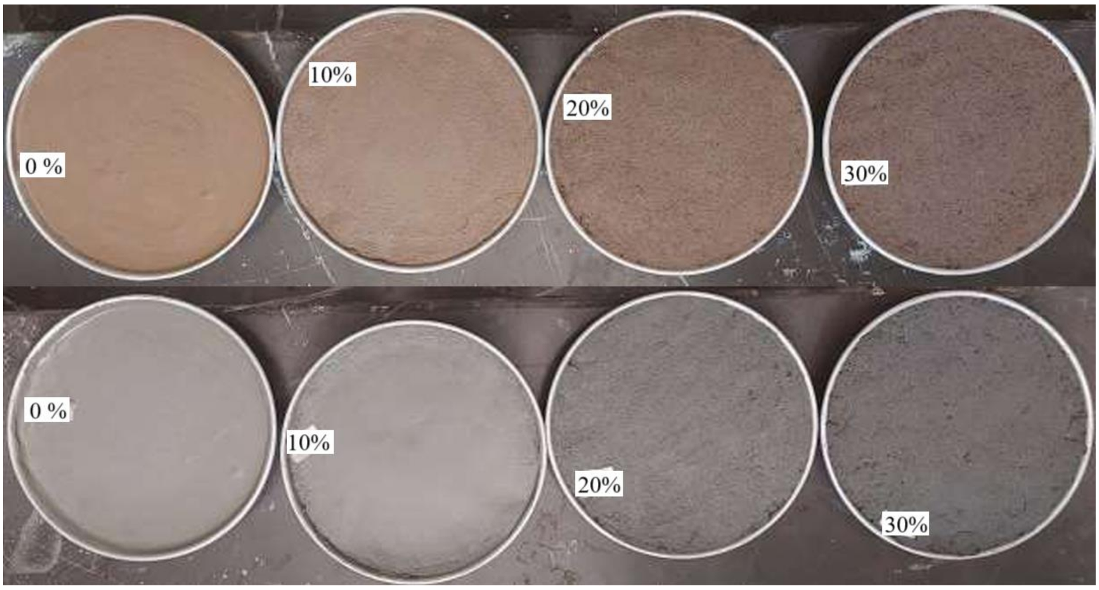

Figure 6. The specimens immediately after assembled without the fracture

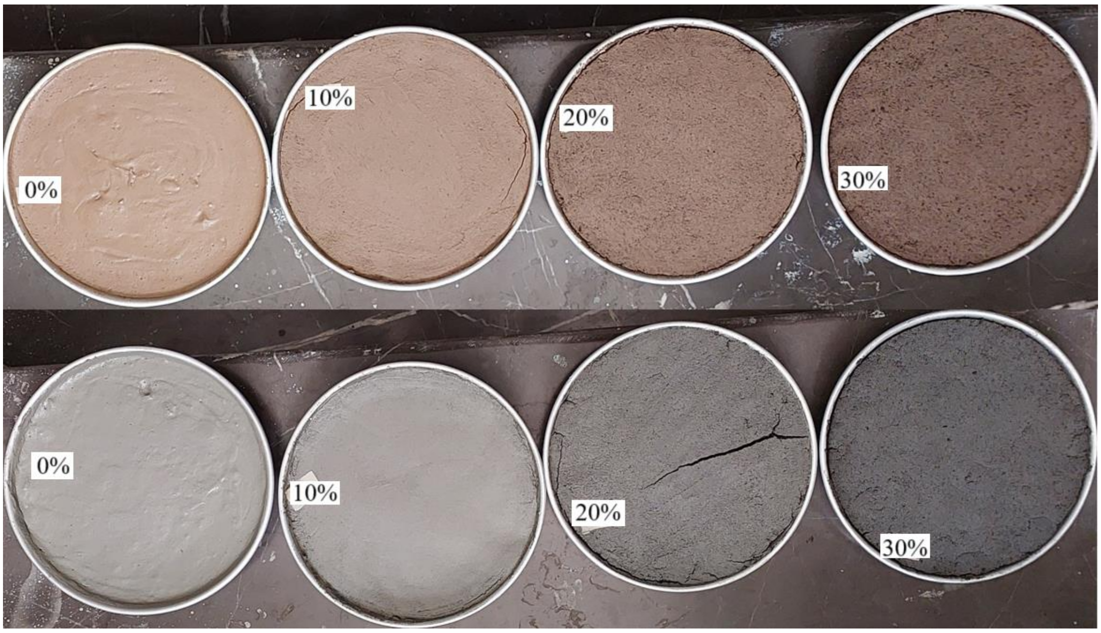

Figure 7. The specimens after 24 hours assembled with minor fracture

The major cracks initiated subsequent to the formation of the sub-cracks. This progression suggests that the initial minor fractures acted as stress concentrators, facilitating the propagation of larger cracks over time. The development of these major cracks can compromise the structural integrity of the specimens, highlighting the importance of addressing the underlying causes of the initial cracking. Cracking commenced due to internal shrinkage stresses in the weaker regions of the specimens, which developed as a consequence of the mixture design. These internal stresses arise from the differential drying rates within the material, where certain areas lose moisture more rapidly than others, leading to uneven shrinkage and the formation of cracks. The mixture design, including the proportions and types of materials used, plays a crucial role in determining the susceptibility of the specimens to such shrinkage-induced cracking. The appearance of minor cracks initially serves as an early indicator for landfill maintenance, provided the landfill cover is under continuous monitoring. Regular inspection and monitoring of the landfill cover are essential to detect early signs of cracking, which can be indicative of underlying issues such as settlement or gas migration. Early detection allows for timely intervention, preventing the progression of minor cracks into major failures that could compromise the containment system.

As the major cracks widen, distinguishing them from the sub-cracks becomes more straightforward. The increased size and visibility of the major cracks make them easier to identify and assess. However, by this stage, the structural integrity of the landfill cover may already be compromised, necessitating more extensive repairs and potentially leading to increased costs and environmental risks. The rate of desiccation correlates with the material composition, influencing the nonlinearity of shrinkage strain and leading to crack initiation in certain specimens. Materials with higher clay content or specific mineral compositions may exhibit higher shrinkage rates upon drying, increasing the likelihood of crack formation. Understanding the relationship between material composition and shrinkage behavior is crucial for designing materials with improved resistance to cracking. Additionally, the interaction of mineral compositions, modified in association with black seed flour and clay mixtures, subsequently affects the fracture toughness. The incorporation of additives such as black seed flour can alter the microstructure of the material, potentially enhancing its ability to resist crack propagation. Fracture toughness is a critical property that determines a material's resistance to crack growth under stress. Enhancing fracture toughness through material modification can lead to more durable and resilient specimens, reducing the likelihood of failure under applied loads.

Figure 8 illustrates that sub-cracks typically form perpendicularly to the major crack, generally at angles close to 90 degrees. The crack networks in the two clay types differ significantly. The mechanism governing crack formation is influenced by the stress release criterion of the clay. Internal tensile stresses lead to crack initiation and propagation. The shear strength of the specimens contributes to the landfill cover's high fracture resistance. In clay type 2, maximum tensile cracks occur at the centre of the specimen, whereas the major crack morphology in clay type 1 differs. The impact of black seed flour on each clay type varies in developing internal shrinkage stresses.

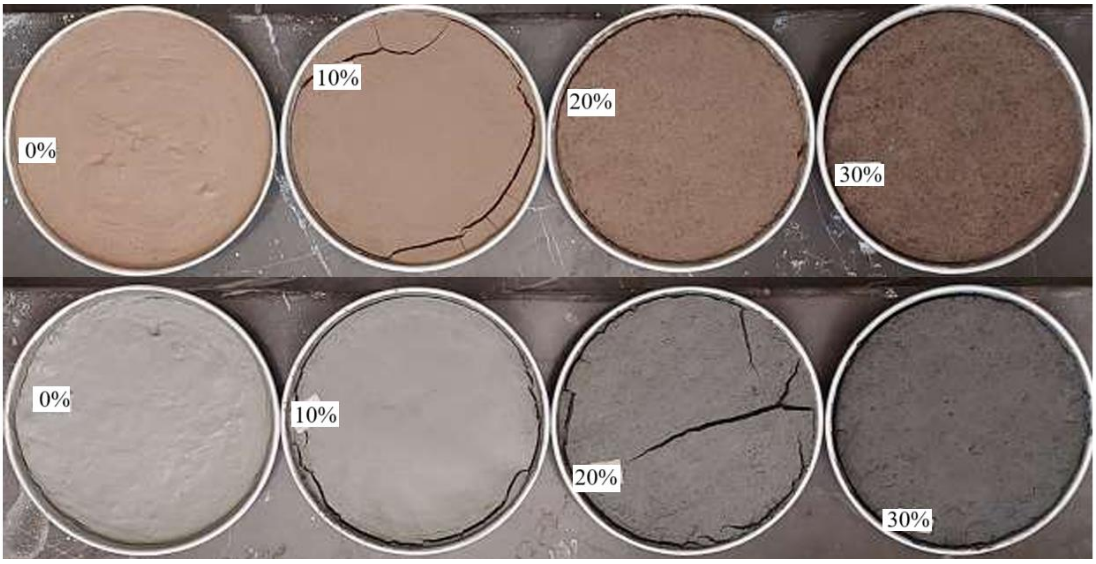

Figure 8. The specimens after 48 hours assembled with fracture

Figure 9 shows the specimens one week after assembly, exhibiting major fractures. With linear shrinkage, the cracks have been minimized. The formation of tensile cracks varies among specimens; the type of clay and the clay-black seed flour mixture design play a significant role in crack development.

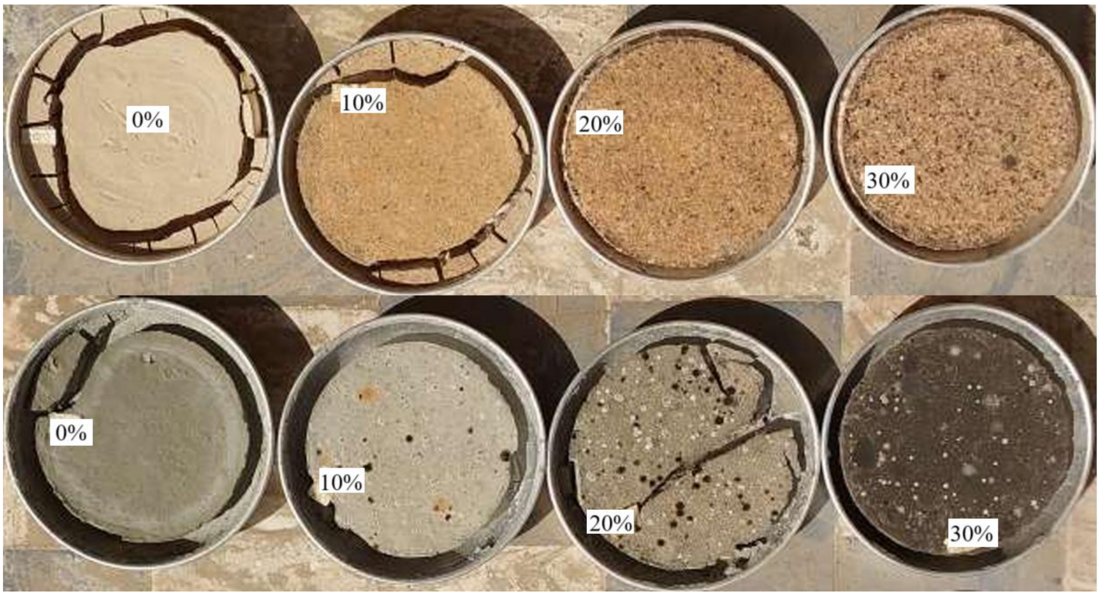

Figure 9. The specimens after a week assembled with major fracture

All specimens were placed in molds under loose conditions. The volumetric deformation of the materials changes with each mixture design. Experimental observations revealed that fractures initiated from the surface and extended to the depth of the specimens as crack propagation progressed.

3.1. Fracture Development

Figure 10 shows the specimens after two months of curing, before any fractures occurred. With increasing proportions of black seed flour, the specimens' coloration becomes noticeably darker, indicating incorporation of the additive. The fracture-toughness behavior of the mixed specimens is found to depend markedly on their specific mixture design. In particular, the optimal fracture toughness was achieved in the clay type 2 mixtures containing 10 % and 30 % black seed flour; in these mixtures no fractures were observed even after two months of curing. In contrast, all specimens derived from clay type 1 developed fractures within the same period. The addition of black seed flour fibers substantially enhanced the specimens' fracture toughness, prolonged fracture initiation time, and altered the fracture morphology toward more favorable patterns. These improvements are attributed to modifications in the evaporation dynamics, specifically, how moisture loss influences interparticle suction and bonding which in turn affect how soil particles lock together. Overall, these results suggest that both the clay type and the dosage of black seed flour are critical in optimizing toughness, with clay type 2 and intermediate flour proportions yielding the best performance.

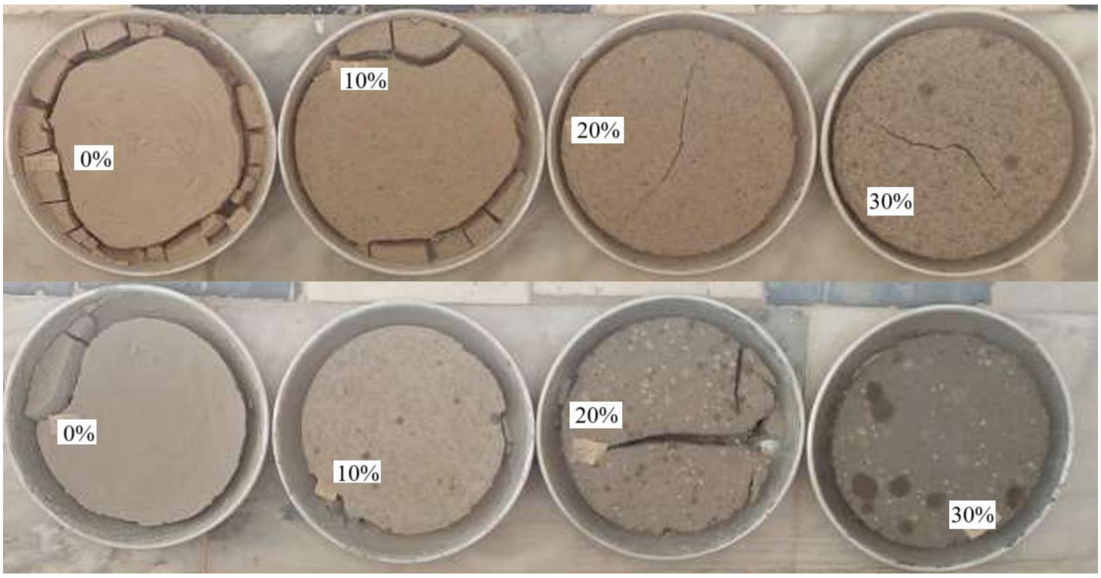

Figure 10. The specimens after two months assembled

Fractures appeared across the specimens with varying thicknesses, reflecting the complex interplay between mixture composition, setting time, and drying behavior. In particular, mixtures of clay type 1 containing 20 % and 30 % black seed flour developed fractures concentrated at the center of the specimen, which were notably thinner than those seen in other specimens. This suggests that above a certain additive percentage, crack development localizes and manifests more subtly but perhaps more destructively. The observed temporal fracture mechanisms indicate that an inappropriate (i.e. either too high or too low) percentage of black seed flour in any clay type accelerates fracture initiation and changes the nature of fracture morphology, leading to a net reduction in fracture toughness. In other words, while fibers/flour may reinforce the matrix to some extent, there is a threshold beyond which the structural integrity is compromised. As the setting time of specimens increases, overall crack density decreases: fewer cracks appear, but those that do tend to occur more centrally. This may be because over time, moisture gradients even out, and outer layers finish drying first; central regions sustain residual moisture longer, delaying crack initiation until later stages.

Also, as cracks form and relieve stress, they may divert or absorb some of the tensile forces, reducing further crack nucleation. The discontinuous morphology of crack pathways, that is, fractured paths that are not straight, continuous, or uniform, has significant implications for shear strength of the earth structure. Cracks that meander or split, or that have branches, intersections, or voids, serve as potential weak planes, lowering cohesion and allowing shear displacement along them under loading. In contrast, straight, fewer, or centrally located cracks might concentrate damage but leave other volumes intact. There is an optimal content of black seed flour for toughening; too much or too little is detrimental. Drying- induced tensile stress, matric suction, and moisture gradients are key drivers of crack initiation and morphology. Crack development is time- dependent; central regions may be more vulnerable over longer curing/drying periods. The pattern, density, and continuity of cracks strongly affect mechanical properties, especially shear strength.

3.2. Clay Fracture Experimental Validation

Natural minerals influence the cementation mechanism by producing microfibers, which subsequently modify the mechanical properties of the material [10]. The interlocking microfibers improve fracture resistance by impeding crack propagation and enhancing energy dissipation mechanisms. In the black seed flour-clay mixture, the reduction in crack thickness is primarily attributed to modifications in the microstructure and chemical composition of the specimens.

Due to the advantageous permeability, the intensity and direction of gas transfer enhance the formation of dryness-cracks. It was observed that desiccation cracks most often begin at the midpoint of each container [14]. In this study, cracks in the clay initially developed at the center. However, when clay properties were modified by adding black-seed flour in the mixture design, the cracks shifted toward the corners. These experimental findings are in good agreement with those reported in the literature.

The crack intensity in clayey soil increases with the extent of evaporation [15]. A significant relationship was observed between evaporation rate and crack intensity in clay [16]. A higher rate of evaporation is expected in specimens with more extensive crack formation. The resistance to cracking is influenced by chemical reactions, which alter the fracture discontinuities in the clay.

3.3. Landfill Stability

Utilizing municipal solid waste to create or strengthen construction materials offers a sustainable path forward [17]. To minimize the transfer of moisture, heat, and gases from the landfill to surrounding areas, the theoretical framework explains how to optimize the landfill cover design [18]. An optimized landfill-cover design is essential, utilizing soils and recycled materials available on site. Employing appropriate cover materials leads to professional management of leachate and effective control of gas migration.

Landfills are the third-largest source of anthropogenic methane emissions globally, following oil and gas systems and agriculture. Extracellular polymeric substances (EPS), produced by microorganisms within landfill cover soils, play a crucial role in mitigating methane emissions. These EPS facilitate microbial methane oxidation by providing structural support and enhancing microbial adhesion, thereby reducing the overall methane flux from landfills [19]. Table 3 presents the materials introduced to enhance various aspects of landfill design.

Table 3. Suitable materials for landfill improvement

Study goal	Material	Research method	Application	Prediction	References
Reduce environmental pollution	Recycled concrete	One-dimensional (1D) soil column test and numerical simulations	Construction landfill cover	Design for 100 years	Guo et al. [17]
Optimize landfill cover design	Loess-gravel capillary barrier cover	Theoretical model	Simulate Landfill cover	Moisture, heat, and gas transfer	Wu et al. [18]
Hydraulic barricade for landfill cover	Steel slag and bentonite mixtures	Experimental	Construction Landfill cover	Compaction and hydraulic connectivity	Zhan et al. [20]
Identify methane emission quantity	Extracellular polymeric substance	Experimental	Control methane emission from landfill cover	Methane emission over time	Zhang et al. [19]
Landfill stability	Paper mill sludge	Simulation (using PLAXIS)	Landfill cover and base of landfill	Landfill displacements	Balkaya [21]
Assessment long term methane emission	Biosolids compost, yard waste and leaf compost	Experimental	Bio-based landfill cover	Pollution assessment	Niemczyk et al. [22]
Expansive soil improvement	Waste tire textile fibers	Experimental	Landfill for liners and covers	Fracture propagation	Narani et al. [23]
Innovate landfill cover material	Biochar-added sludge compost	Experimental	Smell control of landfills	Microbial structure causes different odor	Ding et al. [24]
Decrease fracture risk	sewage sludge and red gypsum	Experimental	Landfill cover	Improve compressive strength	Rosli et al. [25]
Crack intensity factor due to water infiltration	High-plasticity clay	Experimental	Landfill cover	Water infiltration in clay poses	Apriyono et al. [26]

A unified landfill cover without significant fractures effectively minimizes methane emissions. As shown in Figure 10, the cracking time of the suggested landfill cover material correlates with the type of clay used over time. The clay-black seed flour mixture demonstrates potential as a landfill cover material, leading to a reduced methane oxidation rate. Figure 11 indicates that the methane oxidation rate reached its maximum on day 6, but this peak varied depending on the characteristics of the landfill cover. Over time, the methane oxidation rate decreased. Additionally, timely addition of extracellular polymeric substances (EPS) significantly influenced methane emission control. Based on these findings, we recommend the injection of suitable materials into older landfills to effectively control methane emissions.

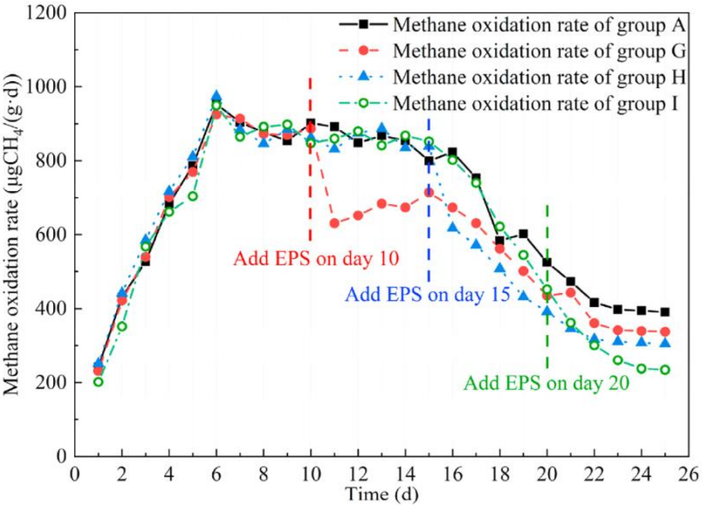

Figure 11. The methane oxidation emission rate over the time [19]

Forecasting crack mechanisms in clay substrates presents a significant challenge to sustainable development, especially in extreme climates exacerbated by rising global temperatures. Implementing effective techniques to identify and predict crack propagation is essential for designing resilient landfill covers. Understanding the relationship between crack propagation mechanisms and the inherent characteristics of clay materials requires further investigation, particularly considering the factors that induce cracking in clay substrates. Additionally, incorporating municipal solid waste (MSW) to enhance the fracture resistance of clay can provide insights into the seasonal variations of clay properties. This necessitates a comprehensive series of analyses on clay crack propagation. Table 4 summarizes the findings from clay crack analyses, supporting the design of landfill covers with appropriate functionalities. To design an effective landfill cover, it is crucial to observe the correlation between increased fracture toughness mechanisms and the attributes of the clay. Experimental results presented in Figure 10 indicate that major cracks and sub-cracks developed under higher thicknesses over time.

Table 4. Crack analysis of clayey soil

Study goal	Research Method	Soil	Additive material	Crack reason	Crack type	References
Crack and erosion resistance	Experimental	Sand-clay mixtures	Microbial biopolymer and palm fibers	Desiccation	Primary cracks and sub-cracks	Liu et al. [27]
Crack and permeability resistance	Experimental	Clay Liner	Nano-SiO$_2$ and Sisal Fiber	De-wetting cycle	Nonlinear	Tao et al. [28]
Crack and hydraulic conductivity resistance	Experimental	Black clay	Microplastic	Improper clay improvement	-	Xie et al. [29]
Crack connection ratio related to hydraulic conductivity	Experimental	Fine-grained clays	Moisture	Shrinkage strain	Shape and connection of crack change	Zhou et al. [30]
Improve tensile strength of soil to reduce crack	Experimental	Clay	Polypropylene fibers	De-wetting cycle and vibration	Shrink-Swell cracks	Khalid et al. [31]
Analysis crack due to de-wetting	Experimental	Clay	-	De-wetting cycle	Change due to De-wetting cycle	Luo et al. [32]
Crack impact slope factor of safety	Numerical models and field surveys	Red clay	Vegetation	Temperature	Surface crack with S-shaped	Gao et al. [33]
Surface shrinkage crack ratio	Experimental	Compacted clay liner	-	Shrinkage strain	Shrinkage cracking	Wan et al. [34]
Desiccation crack assessment	Experimental	Bentonite	Coal Ash + Fly ash	De-wetting cycle	-	Gahlot et al. [35]
Crack initiation and propagation	Experimental	Clay	Flax fiber	Shrinkage strain	-	El Hajjar et al. [36]
Desiccation cracking under different temperature	Experimental	Clayey soil	-	Temperature	Crack with square pattern network	Tang et al. [37]
Desiccation cracking under different water content	Experimental	Compacted clayey soil	-	Changing moisture content	Mostly at the edge of specimens	Tang et al. [38]

Variations in moisture content, whether in a single phase or cyclic conditions, lead to cracking in clay [27, 28], an appropriate amount of microplastic influences both crack resistance and hydraulic connectivity [29]. Shrinkage strain induces cracking at connection points [30]. Furthermore, increasing the unit dry weight reduces crack intensity [31]. The landfill cover should be compacted to effectively minimize leachate migration. Moisture content plays a crucial role in the crack resistance of clayey soils. Devastating cracks form as temperatures rise [37, 38], therefore, in this study, the water content in the mix design was kept constant across all specimens.

Table 4 presents a summary of key previous studies on crack formation in clayey soils. These studies highlight that soil moisture content is a primary factor influencing the initiation and propagation of cracks. Additionally, the occurrence of wetting-drying cycles accelerates desiccation cracking. During these cycles, shrinkage-induced strains create fatigue within the soil structure, reducing its fracture resistance. Repeated cycles of drying and wetting exacerbate this effect, leading to more severe cracking. Figure 12 illustrates the morphological development of desiccation cracks over multiple drying-wetting cycles. Furthermore, both natural and synthetic materials have been shown to enhance the crack resistance of clayey soils. It is important to note that the shape and extent of cracks vary with different soil types and the methods employed to improve soil fracture resistance.

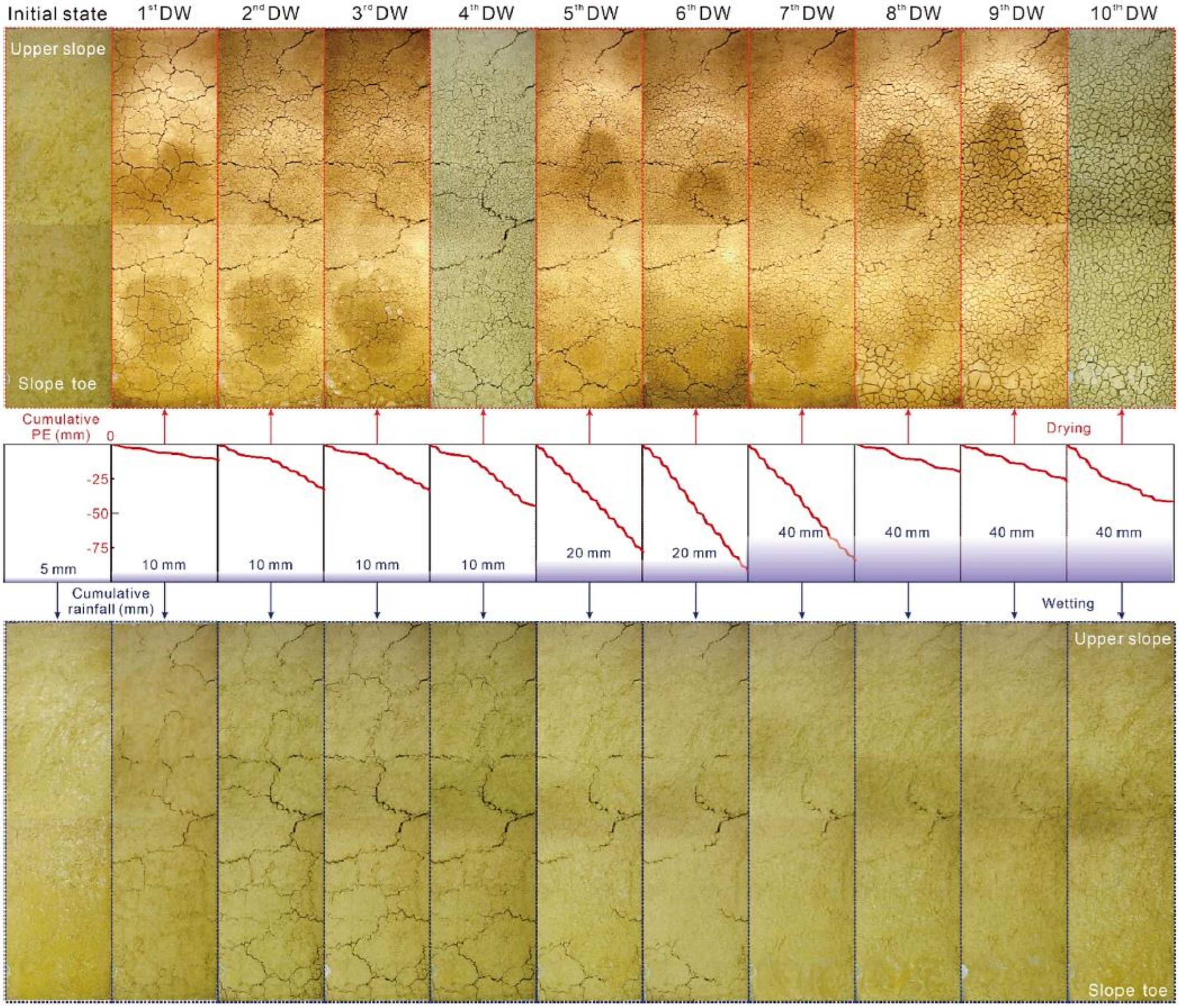

Figure 12. Desiccation cracks formation on slope in multi drying-wetting cycles [32]

Reinforcing landfill slopes with geogrids enhances slope stability by maintaining the soil's tensile strength, thereby improving overall slope stabilization. However, increased rainfall elevates soil moisture content, which can compromise slope stability [39]. In the present study, a tailored mixture of clay and black seed flour was utilized to enhance landfill stability. This composite effectively maintains moisture content throughout the entire landfill body and increases shear strength in the cover area. A well-constructed landfill cover resists uplift and lateral movements, thereby reducing the likelihood of structural collapse. Unacceptable deformations, which could lead to eccentricity in the landfill structure, are minimized by controlling lateral movements. As illustrated in Figure 10, specimens subjected to fracture exhibited indirect tensile strength and toughness, characterized by minimal damage and delayed failure. Moreover, the ideal specimens demonstrated maximum tensile strength and toughness without the formation of major or sub-cracks.

Displacement occurs in most landfills because municipal solid waste generates heat [39-42]. Municipal solid waste in landfills can reach temperatures ranging from about -6 °C to as high as 60-90 °C under certain conditions. Climate, as well as the age of the waste, are significant factors influencing landfill temperature. The highest rises in temperature are typically observed shortly after the waste is placed. In addition, the gases produced by landfills are one of the main contributors to global warming [42, 43]. The level of heat produced also depends on the composition of the municipal solid waste, which varies from region to region. Additionally, as landfill waste ages, both settlement and temperature tend to decrease. This occurs as the void ratio of the waste-the volume of empty space-shrinks. Light compaction of waste in successive layers reduces long-term settlement and helps prevent cracks in the landfill cover. As a result, uncontrolled movement of leachate and emission of gases are minimized. Lower waste settlement contributes to reducing global warming.

Different types of cracks have been observed in the landfill structure during the initial placement, middle-age, and long-term aging stages [40, 42, 44], such cracks initiate differential settlement and can lead to landfill failure. Cracks in the landfill allow heat to transfer through to the cover layer. The factors that cause cracking in landfills are summarized in Table 5.

Table 5. The crack on the landfill

Type of crack	Material can be use for landfill cover	Load	Failure mode	Remark	References
Tension cracks	-	Experimental simulated seismic load	Differential displacement	Tension crack developed due to growth of pore volume	Li et al. [40].
Single initial tension crack	Clay	Numerical simulated seismic load	Differential displacement	Right thickness of clay covered landfill needs to be designed	Namdar et al. [3].
Horizontal cracks on slope	Clay	Construction tensile load	Weak tensile strength	Intense rainfalls and cracks leads to crack	Cortellazzo et al. [39].
Flexural crack	Compacted clay	Static load	Settlement induces crack	Compaction improves tensile strength toughness and minimized crack	Mukunoki et al. [41].
Thermal crack	-	Thermal stress	Mechanical deformation mechanisms due to temperature	Recycle temperature accelerates erosion, and settlement and releasing greenhouse gases	Akhtar et al. [42].
Shrinkage crack and surface crack	Sand-bentonite- glass fiber mixture	Static load	Mixed mode failure	Improve shear strength to prevent from sliding	Mukherjee & Mishra [45].
Yielded cracks	Lime	Landfill long term self-weight	Crack was initiated with moisture reduction	Nonlinear distribution of plastic in landfill was reduced landfill stability	Li et al. [44].
Freeze and thaw cracking	Sludge with high-strength PVC	Squeezing force	Higher thawing/freezing frequency	Direct relationship between cracking and MSW particles size and initial water content in freezing process	Wu et al. [46].
Predict potential cracking area	Marine Soil + landfill mined soil+ expansive soil	Shrinkage Stresses	Tensile failure	Complete cracking mitigation and controlling swelling of expansive is possible	Patil et al. [47].
Tensile crack	Clay-straw fiber mixture	Dehydration causes internal soil horizontal tension force	Tensile failure	The cracking area and crack intensity reduced with suitable percentage of the fiber	Qiang et al. [48].
Multiple cracking patterns for all specimens was developed	Two type of clays, 1-bentonite-silty soil mixture 2-kaolin clay-sand combination	Flexural distress	Tensile failure	Optimized soil-fiber interactions improve crack resistance	Divya et al. [49].

A complete mitigation of cracking and control of swelling in expansive soils is possible to predict [47]. By using appropriate landfill materials in the design of material mixtures, we can still achieve control of cracking, even though the composition of municipal solid waste varies from region to region because of cultural differences in consumption.

When the total tensile stress in frozen landfill material approaches its tensile strength, crack formation can be predicted. Also, Young's modulus increases as the temperature decreases [50], this alteration of the material's mechanical properties makes the landfill more susceptible to crack development. Table 6 shows the impact of temperature fluctuations on landfill behavior. Landfill geometry and the composition of municipal solid waste (MSW) play key roles in controlling landfill temperature [51]. Cracking in landfills can be effectively managed through thoughtful design of landfill geometry.

Table 6. Impact of temperature on landfill

Research situation	Landfill status	Temperature variation	Study goal	References
Elastic soil	Frozen	Decreased in winter and increased in depth	Identify depth of crack	Andersland & Moussawi [50]
Modification leachate movement	Normal	Depend on landfill geometry and MSW type	Impact of temperature on leachate	Collins et al. [51]
Rise temperature accelerates CH_4 removal	Normal	From 8 ◦C to 22 ◦C	Temperature and oxidation relationship	Al-Heetimi et al. [52]
Considering thickness of landfill, leachate quantity, landfill age, landfill and liner temperature	Changing age	14 ◦C to 87 ◦C for landfill body and at landfill cover changed from 7 ◦C to 60 ◦C.	Landfill age-temperature analysis of 3300 years	Rowe & Islam [53]
Assess the ammonia half saturation value	Normal	22 ◦C, 35 ◦C and 45 ◦C	Ammonia half saturation value increases in respect to increase temperature	Berge et al. [54]

3.4. Application in Industry

Utilizing compacted clay as a landfill barrier is recommended to reduce gas transmission, owing to its relatively low permeability. Moreover, controlling desiccation-induced cracking can further decrease gas emission rates [14]. An appropriate mixture of clay and black seed flour can be employed to control landfill gas emissions. This approach offers a conceptual framework for managing gas transfer in landfill safety construction and design, particularly for long-term operations that do not involve compaction of clay covers.

3.5. Key Theoretical Concept for Clay

Clays are layered silicates: tetrahedral + octahedral sheets (1:1, 2:1, mixed-layer types). Isomorphous substitution (e.g. Al for Si in tetrahedral sheet, Mg or Fe for Al in octahedral) gives the layers a negative structural charge. That charge is balanced by interlayer cations (Na^+, Ca^{2+}, etc.), which together with water impact swelling, surface reactivity, and adsorption [55]. How water interacts with clay (adsorption, interlayer water, hydration forces), leading to swelling. The dynamics of hydration (changing interlayer spacing, changes in mechanical & transport properties) is central especially for smectites [56]. Ahead of a propagating crack, a damage zone often forms, characterized by microfracturing, particle rearrangement, or densification. This zone alters the structure before the main crack advances, influencing the overall fracture behavior.

4. Comparison Results

The When waste plastics undergo catalytic pyrolysis under high temperature anaerobic conditions, they are thermally cracked to yield useful byproducts such as oil, gas, and solid residue. The process can convert even slightly contaminated feedstocks and, for high- quality plastics, achieve oil liquefaction at temperatures of 500 °C or higher. [57, 58].

Improved bonding between soil particles and fibers helps redistribute tensile stresses, significantly reducing crack formation and width. Various fibers, including polypropylene, polyethylene, glass, and steel have been shown to enhance mechanical properties of soils by increasing toughness, controlling crack propagation, and improving post-crack strength. For example, polypropylene- fiber reinforced soil exhibits decreased crack width and altered crack form (from vertical to more oblique cracks) as fiber content increases [59]. Steel and glass fibers also improve tensile, flexural, and splitting strengths in concrete-soil composites, often more effectively than polymer fibers when higher stiffness and crack resistance are required [60]. In comparing the present work with these are available in the literature novelty in the research works are as following,

- Use of black seed flour is a natural, low-cost, sustainable additive for enhancing crack resistance in clay landfill liners. This is novel compared to more common synthetic fibres or engineering additives.
- Quantification of mixture proportions (10%, 20%, and 30%) and how these different dosages affect crack initiation, width, morphology, and fracture toughness. The specific finding that clay type 2 has optimal performance at 10% and 30% is a concrete, new insight.
- Combination of desiccation testing plus mechanical and image analysis methods over different time durations (24 h, 72 h), showing temporal behavior of crack propagation.
- Implications for landfill liner integrity: reducing leachate and gas transfer by enhancing crack resistance. Emphasizing the environmental engineering application adds significance.
- Sustainability and cost-effectiveness: using agricultural/biological by-product (black seed flour) vs. expensive synthetic fibres or industrial catalysts.

5. Conclusions

To address significant geo-environmental challenges, a fracture-tough, environmentally friendly mixture of clay and black seed flour has been specifically engineered to control leachate and gas transmission in landfills through a cost-effective approach. This study investigates the fracture toughness, fracture time, and fracture morphology within this clay-black seed flour mixture.

- The crack resistance of the clay was assessed to understand the impact of municipal solid waste (MSW) on the fracture process. Solid bonding was linked to water evaporation concerning the specimen mixture design. Beyond the cohesion of the clay, fiber-clay interaction plays a critical role in crack initiation and propagation. The optimal fracture toughness was found in a clay type 2 mixture with 10% and 30% black seed flour; in these specimens, no fractures were observed after two months.
- Cracking time varied in association with clay types.
- Collapse and crack propagation times are directly related. The speed of crack propagation aids in predicting soil structure collapse time.

- For methane emission control in old landfills, suitable material injection into the landfill cover is required. Controlled methane emission presents an opportunity to extract methane from MSW, achievable through crack control in landfills.
- Light compaction of landfill layers minimizes long-term settlement and cracking of the landfill cover due to temperature variations and differential settlement. Consequently, uncontrolled leachate movement and gas emissions are reduced. Reduced landfill settlement contributes to mitigating global warming.
- Crack development in landfills is associated with landfill design geometry and MSW composition.
- Clay mineral interactions with natural minerals govern cracking behavior. Crack formation decreases with increasing amounts of black seed flour in the clay mixture. Utilizing an appropriate amount of black seed flour enhances cracking resistance.
- The incorporation of black seed flour as an MSW component in clay mixtures significantly contributes to minimizing environmental pollution. An appropriate clay-black seed flour mixture can be employed to control gas emission transfer rates in landfill covers.
- Long-term microstructural studies of clay should be conducted to identify crack initiation and propagation mechanisms.

6. Declarations

6.1. Author Contributions

Conceptualization, O.M., S.K., A.N., and M.S.; validation, M.S. and M.A.; formal analysis, S.K. and A.N.; investigation, O.M.; resources, M.A. and A.N.; data curation, O.M.; writing—original draft preparation, A.N. and M.S.; writing—review and editing, M.S. and S.K.; visualization, M.A.; supervision, O.M. and M.A.; project administration, O.M.; funding acquisition, O.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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