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Research Status of Termite Secretion Simulants

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Abstract: As a complex biochemical system, termite secretions exhibit unique functional properties in soil improvement and geotechnical engineering. This paper systematically analyzes the main chemical components of termite secretions, including formic acid, enzymes, polysaccharides, proteins, etc., and deeply explores their influence mechanisms on the physical, chemical and mechanical properties of rock and soil. Studies have shown that termite secretions significantly alter soil properties th rough multiple mechanisms such as biological cementation, acid-base regulation and enzymatic hydrolysis. The concentration of formic acid can reach 3.8%, and the secretions increase soil strength by 10 times with a compressive strength of up to 32 MPa. Based on bionic principles, this paper focuses on the widely used simulants in academia and engineering, including microbial-induced calcium carbonate precipitation (MICP) technology, chitosan and its derivatives, heshutin, and synthetic termite saliva. Thro ugh comparative analysis, it is found that MICP technology has the most significant effect in improving strength and reducing permeability, with the compressive strength of treated soil reaching 1.5-8.0 MPa and permeability reduced by 1-3 orders of magnitude; chitosan has advantages in simulating biocompatibility and pH regulation; heshutin performs prominently in water retention and nutrient release. These simulants show differentiated applicability in different soil types, providing importan t technical support for the application of biological materials in geotechnical engineering.

Keywords: Mechanical Properties, Permeability Characteristics, Termite Secretions.

1. Introduction

As one of the oldest social insects on Earth, termites have evolved a complex and sophisticated chemical composition in their secretion system through long-term evolution. Termite secretions not only play important roles in group life such as defense, digestion and information transmission, but also exert a profound impact on the rock and soil environment they inhabit. Studies have shown that termite secretions can significantly change the physical structure, chemical properties and mechanical strength of soil, with both positive soil improvement effects and potential hazards to engineering structures. In the engineering field, the impact of termites on soil properties is dual. On the one hand, the strength of termite nest soil can reach 10 times that of surrounding soil, and in some cases, the compressive strength is even close to 32 MPa. This natural biological cementation provides important inspiration for the development of new building materials. On the other hand, the tunnel networks constructed by termites in engineering structures such as dams and building foundations may form seepage channels, seriously threatening engineering safety [1]. Statistics show that more than 90% of reservoir dams and dikes in China suffer from varying degrees of termite damage, and nearly 20% of dams have termite-induced piping problems. In recent years, with the rise of the green building concept and the requirements of sustainable development, the application of biomimetic materials in geotechnical engineering has attracted increasing attention. In-depth research on the chemical composition and mechanism of action of termite secretions, and the development of bionic alternative materials with similar functions, can not only solve engineering problems caused by termite damage, but also promote the development of environmentally friendly building materials. At present, academia and engineering have developed a variety of materials simulating the functions of termite secretions, including microbial-induced calcium carbonate precipitation, chitosan, heshutin, etc. These materials maintain or enhance the original functions while having better controllability and environmental friendliness. This paper aims to systematically sort out the chemical composition of termite secretions and their influence mechanisms on soil properties, and focus on investigating the main types, technical characteristics and application effects of current substances used to simulate termite secretions. Through a comprehensive analysis of existing research results, it provides a scientific basis and technical guidance for the application of biological materials in geotechnical engineering.

2. Chemical Composition and Functional Characteristics of Termite Secretions

Termites have a complex exocrine gland system, mainly including frontal glands, salivary glands, sternal glands, tergal glands and mandibular glands. These glands are distributed in different parts of the termite body, each performing its own duties, and together constitute the complex chemical communication and defense system of termites. The frontal gland is one of the most important defense glands of termites, mainly located in the head, and is the main site for soldier termites to secrete defensive chemicals. In the Nasutitermitinae, the frontal gland is specialized into a tubular structure, forming a unique "frontal gun" that can spray defensive secretions over a long distance. This structure enables nasute termites to carry out effective chemical defense without direct contact with enemies. Salivary glands exist in all castes and developmental stages of termites. In worker termites, they mainly secrete food-marking pheromones and digestive enzymes, while in soldier termites, they have defensive functions. The sternal gland is considered the only source of termite trail pheromones, located on the ventral surface of the abdomen. Worker termites secrete trail pheromones through the sternal gland to leave chemical markers on foraging routes. The acidic component in termite secretions is mainly formic acid, a highly corrosive organic acid. Formic acid plays an important role in the defense and digestion of termites, and its concentration varies by species and gland. Studies have found that the concentration of formic acid in the saliva of some termite species can reach 3.8%, corresponding to a pH value of 2.3. This strongly acidic environment not only helps termites digest food, but also strongly inhibits invasive pathogens and natural enemies. In some ant species, the concentration of formic acid can even be as high as 54%, showing extremely strong corrosiveness. In addition to formic acid, termite secretions contain a small amount of other organic acids such as acetic acid and propionic acid. The synergistic effect of these organic acids enhances the acidic environment of termite secretions, helping to dissolve and soften wood fibers and improve digestion efficiency [2]. At the same time, acidic secretions can also change the chemical properties of soil and promote the dissolution and transformation of certain minerals. It is worth noting that there are differences in the concentration and type of acidic substances secreted by different castes of termites. Soldier termites usually secrete higher concentrations of acidic substances, mainly for group defense; while worker termites secrete relatively low concentrations of acidic substances, more involved in food digestion and nest construction. Enzymes in termite secretions are the key to their efficient degradation of lignocellulose. These enzymes mainly include cellulases, hemicellulases, ligninases, etc. They work together to decompose complex plant cell wall components into absorbable simple sugars. In lower termites, endoglucanase (EG) is mainly distributed in salivary glands, accounting for 77.8% of the total activity, while β-glucosidase (BG) accounts for 23.9% in salivary glands. These endogenous cellulases belong to the glycosyl hydrolase family 9 (GHF9) and can effectively decompose the β-1,4-glycosidic bonds of cellulose. In addition to the cellulase system, termite saliva also contains a variety of hemicellulases, such as xylanase, mannanase, etc. These enzymes can decompose various glycosidic bonds in hemicellulose. Studies have shown that the saliva of some termite species also contains ferulic acid esterase, which can break the ester bonds between lignin and hemicellulose, separate lignin from hemicellulose, and thus improve the accessibility of cellulose. In terms of lignin degradation, termites mainly rely on the ligninase system secreted by intestinal symbiotic microorganisms, including lignin peroxidase, manganese peroxidase and laccase. The pheromone system of termites is the chemical basis of their complex social behavior, mainly including trail pheromones, sex pheromones and alarm pheromones. Trail pheromones are one of the most important pheromones of termites, mainly secreted by the sternal gland. Studies have found that (Z)-Dodec-3-en-1-ol is a newly discovered termite trail pheromone with short-lived recruitment function and long-lasting orientation function. In some species, trail pheromones also include syn-4,6-dimethyldodecane and other compounds. Sex pheromones play a key role in the reproductive behavior of termites. The sex pheromone secreted by female termites is mainly (5E)-2,6,10-trimethylundeca-5,9-dienal, a compound that attracts male termites for mating. In some higher termites, females also secrete (3R,6E)-nerolidol, a sesquiterpene alcohol associated with fertility. Male termites secrete syn-4,6-dimethyldodecane as a sex pheromone. Alarm pheromones are mainly secreted by the frontal glands of soldier termites for group defense. The alarm pheromones of some termite species are mainly monoterpenoids such as α-pinene, which have a strong pungent odor and can quickly activate the group's defense response. The cementing and adhesive components in termite secretions are the key substances for them to build strong nests. These components mainly include mucopolysaccharides, cellulose derivatives, protein and amino acid complexes, etc., which act as "biological cement" in the nest construction process [3]. Mucopolysaccharides are the main cementing components in termite saliva, with strong viscosity and cementing ability. Studies have found that termite saliva contains a large amount of cellulase and mucopolysaccharides, which can digest cellulose into β-glucose or shorter polysaccharides and oligosaccharides. These polysaccharides are important sources of soil stability and cementing performance. Protein and amino acid complexes are another important type of cementing component. Studies have shown that the protein content in termite nest soil is significantly higher than that in surrounding soil. In termite nests in the Gunung Kidul area, the protein content is 0.17%, 0.19% in Kulon Progo, 0.15% in Bantul, while the protein content in surrounding soil is only about 0.1%. These proteins not only provide cementing effect, but also provide nutrient sources for soil microorganisms. In addition to direct cementing effect, termite secretions can also enhance soil stability through indirect mechanisms. Certain components in the secretions can promote the agglomeration of soil particles to form larger aggregate structures.

3. Influence Mechanism of Termite Secretions on Soil Properties

Termite secretions affect soil physical properties in many aspects, mainly reflected in particle gradation, pore structure, density and permeability. In terms of particle gradation, termite activities significantly change the distribution of coarse and fine soil particles. Studies have shown that at a depth of 2 cm from the surface, the fine particle content in termite-active areas is 14% higher than that in control soil. This difference is mainly due to the selective transport of soil particles by termites. Termites have the ability to transport deep soil particles to the surface, with a transport depth of up to 20 m. More importantly, termites have obvious selectivity for soil particles. X-ray diffraction analysis shows that termites preferentially select clay particles such as kaolinite, gibbsite and iron oxides (hematite and goethite) rather than larger particles such as quartz. The change of pore structure is another important aspect of termites affecting soil physical properties. Termite nesting activities form a complex pore network in the soil, including main nests, secondary nests, ant tunnels, ventilation pipes, etc. These pores have obvious hierarchical characteristics: macropores mainly refer to cavities and channels with a diameter greater than 1 mm, which are the main spaces for termite activities; micropores refer to the pores between soil particles, whose size and distribution are affected by the cementation of secretions. Studies have found that termite nest soil has multi-scale pore characteristics, and fractal dimension analysis shows that it has a multi-pore structure, which is of great significance for enhancing evaporative cooling and structural stability. In terms of density change, termite-modified soils from different sources show significant differences. Research data show that the maximum dry density of termite-modified soil from quartzite is 1974 kg/m^3, 1534 kg/m^3 from gray gneiss, and 1755 kg/m^3 from granite gneiss. This difference reflects the influence of parent rock type on termite activity and secretion composition. At the same time, the cementation of termite secretions makes the soil more compact and reduces the porosity. The change of permeability is one of the key factors for termites affecting soil physical properties. Studies have shown that the permeability of termite-modified soil can be 100 times higher than that of normal soil. This extremely high permeability is mainly due to microcracks and small pores induced by termites. The impact of termite secretions on soil chemical properties is mainly reflected in pH value changes, nutrient content, ionic composition and mineral composition. The change of pH value is an important manifestation of termite activities affecting soil chemical properties. However, there are different research results on the impact of termites on soil pH. Some studies show that termites prefer an acidic environment, and their activities will increase the pH value of nest soil. This may be related to the alkaline characteristics of termite saliva, which can neutralize acidic substances in soil. Other studies have found that acidic substances such as formic acid secreted by termites will reduce soil pH, which is conducive to inhibiting the growth of harmful bacteria, promoting microbial decomposition of organic matter and releasing nutrients. The significant increase in nutrient content is one of the most positive effects of termite activities on soil chemical properties. Studies have shown that the contents of organic carbon, nitrogen, phosphorus, potassium and other nutrients in termite nest soil are much higher than those in surrounding soil. In some areas, the organic carbon content of termite nests can reach 2.82%-3.46%, while that of surrounding soil is only 2.06%-3.00%. The contents of nitrogen, phosphorus, potassium and other macro elements also show a similar increasing trend. The sources of these nutrients include: organic substances in termite secretions, decomposition products of dead termites, and nutrient-rich particles transported by termites from deep soil. The change of ionic composition is mainly reflected in the increase of exchangeable cations [4]. Studies have found that the contents of exchangeable calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K) in termite nest soil are significantly higher than those in adjacent soil. This enrichment phenomenon is mainly because many termite species select particles in clay-rich soil layers to build nests, and clay usually has a high cation exchange capacity. At the same time, organic substances in termite secretions can also increase the cation exchange capacity of soil. The change of mineral composition reflects the selectivity of termites for soil particles. X-ray diffraction analysis shows that the content of clay minerals such as kaolinite, gibbsite, hematite and goethite increases in termite nest soil, while the content of coarse particles such as quartz decreases relatively.

The impact of termite secretions on soil mechanical properties is the most important aspect of its engineering significance, mainly reflected in strength parameters, compressibility and stability. In terms of strength parameters, the cementation of termite secretions can significantly improve soil strength. Studies have shown that the cementation produced by termite secretions and excreta can increase soil strength by 10 times. This significant increase in strength is mainly due to the cementation of organic substances such as mucopolysaccharides and proteins in the secretions. In some cases, the compressive strength of termite nest soil can reach 32 MPa, close to the strength of ordinary concrete. This high strength enables termite nests to resist wind and rain erosion and remain intact for decades. However, the impact of termite activities on soil strength is complex and variable. The strength parameters obtained from different studies vary greatly: the friction angle ranges from 2.83° to 24.77°, and the cohesion can reach up to 50.11 kN/m². This difference is mainly related to various factors such as termite species, soil type, nest structure and environmental conditions. For example, a study in Nigeria found that the California Bearing Ratio (CBR) of termite-modified soil is 22%-36%, among which termite soil from quartzite performs the best, reaching 36%. The change of compressibility is another important aspect of termites affecting soil mechanical properties. The cementation of termite secretions usually reduces soil compressibility and improves its ability to resist deformation. In terms of stability, the impact of termites on soil stability is dual. From a positive perspective, the cementation of termite secretions can enhance the overall stability of soil, especially in slopes, dams and other projects. Moderate biological cementation can improve anti-sliding stability. Studies have shown that termite activities can promote the formation of soil aggregates, which helps to enhance soil strength and stability. However, termite nesting activities may also pose a serious threat to engineering stability. Termites nest densely in dams, forming numerous ant nests and connected tunnels, some of which even penetrate the inner and outer slopes of dams. Under high water level conditions, these channels may become seepage paths, leading to dangers such as piping and seepage, and in severe cases, dam failure accidents [5].

Termites cause various hazards to engineering structures, especially to water conservancy projects. China is one of the countries most seriously affected by termite damage in the world. More than 90% of reservoir dams and dikes suffer from varying degrees of termite damage, and nearly 20% of dams have termite-induced piping problems. During the catastrophic flood in the Yangtze River Basin in 2020, many provinces experienced termite-induced dangers on dikes. In the Jiangxinzhou levee of Zongyang County, Tongling, Anhui, serious piping occurred, spraying a water column more than 1 meter high. Expert investigation confirmed that termite holes were the main cause of piping and seepage. In the Hutoushan levee section of Tuan River, Shishou City, Jingzhou, Hubei, 14 serious termite hole dangers occurred, and 209 overflow termite holes were found. The muddy water holes caused by termites developed into large collapse pits. The case in Qingyuan, Guangdong is even more shocking. During the flood season in 2022, the Beijiang River in the Pearl River suffered an extraordinary flood once in a hundred years. The Qingdongwei Dayanhe branch levee in Qingcheng District suffered piping danger due to termite damage. On-site investigation found that termites had built a huge nest system in the dam, with a main nest cavity of 170 cm×150 cm×130 cm, 3 m deep from the slope surface, and 9 large ant tunnel openings with a bottom diameter of 5-7 cm at the bottom of the cavity leading to the inner and outer slopes of the dam. Hundreds of fungus gardens were excavated. Termite damage is also serious in small water conservancy projects. The dam of Xinping Reservoir in Xiuwen County, Guiyang City is a homogeneous clay dam. Termite nesting has caused ant tunnel hollowing, dam damage by excavation and pipe flow seepage in the dam body. The case of the North Suburb Reservoir in Zaoyang City is also typical. The reservoir suffered seepage due to termite damage. After on-site exploration and excavation, technicians confirmed that the seepage was caused by termite activities. In addition to water conservancy projects, termites also cause serious damage to other types of engineering structures. In traffic engineering, termite nesting near the pier foundations of mountain highway bridges leads to soil loosening, uneven settlement of piers, cracks on bridge pavements, and structural safety is in jeopardy. In construction engineering, termites not only damage wooden structures, but also nest in building foundations, affecting the stability of foundations. These cases fully illustrate the severity and universality of termite damage, and highlight the urgency of developing effective prevention and utilization technologies [6].

4. Research Status of Termite Secretion Simulants

Microbial-induced calcium carbonate precipitation (MICP) technology is currently one of the most mainstream methods to simulate the cementation function of termite secretions in the field of geotechnical engineering. This technology uses the metabolic activities of certain microorganisms to induce calcium carbonate crystals in soil pores, so as to achieve soil cementation and reinforcement. The core of MICP technology is urease-producing bacteria, such as Sporosarcina pasteurii, Bacillus sphaericus, etc. These bacteria produce urease during metabolism, which can catalyze the hydrolysis of urea: $CO(NH_2)_2+3H_2O\rightarrow 2NH_4^++CO_3^{2-}$. The produced carbonate ions combine with calcium ions in the environment to form calcium carbonate precipitation: $Ca^{2+}+CO_3^{2-}\rightleftharpoons CaCO_3\downarrow$.

In practical applications, MICP technology shows excellent performance. Studies have shown that the compressive strength of treated soil can reach 1.5-8.0 MPa, consistent with the strength trend of 32 MPa of termite nest soil (varying due to soil type differences). At the same time, soil permeability is reduced by 1-3 orders of magnitude, forming low permeability characteristics similar to termite nest soil. In a study, non-sterile enriched urease-producing bacteria were used to treat sandy soil. After treatment with 2M equimolar cementing solution, the unconfined compressive strength of sandy soil increased to 2.7 MPa, and the permeability decreased to 10^{-6} m/s. These results are equivalent to the biological treatment effect using pure urease-producing bacteria.

The advantages of MICP technology lie in its environmental friendliness and controllability. Compared with traditional chemical reinforcement methods, the raw materials used in MICP technology (urea, calcium chloride, etc.) are relatively environmentally friendly, and the reaction product is natural calcium carbonate, which will not pollute the environment. At the same time, by controlling parameters such as bacterial concentration, nutrient concentration and reaction time, the amount and distribution of calcium carbonate can be precisely controlled to achieve directional improvement of soil properties. However, MICP technology also has some limitations. The first is the cost problem, which requires certain expenses for bacterial culture and nutrient supply. The second is technical complexity, which requires precise control of reaction conditions and high technical requirements for operators. Chitosan is a natural polysaccharide biopolymer obtained by deacetylation of chitin in arthropod exoskeletons and fungal cell walls. Chitosan molecules are rich in amino and hydroxyl groups, with good biocompatibility, biodegradability and antibacterial activity. In simulating termite secretions, chitosan mainly functions through the following mechanisms: first, forming electrostatic bonds with negatively charged clay particles using its electropositivity; second, combining with soil particle surfaces through hydrogen bonds and van der Waals forces; third, forming a gel network structure to cement soil particles together. Studies have shown that chitosan shows good effects in soil improvement. In a study on sandy soil, the addition of chitosan biopolymer can enhance the bonding between particles and significantly improve the mechanical properties of sandy soil. Molecular dynamics studies at the atomic level reveal huge entanglement between sandy soil particles and biopolymers through van der Waals interactions. Unconfined compressive strength test results show that chitosan increases the compressive strength of sandy soil by about 320 kPa. In addition, triaxial tests show that the application of chitosan increases the cohesion of sandy soil by 34.2 kPa. Permeability test results show that the hydraulic conductivity decreases from 1.6×10^{-6} m/s to 5.7×10^{-7} m/s, a reduction of about 35%. In another study, wood samples coated with 5% chitosan showed only about 0.53% weight loss after exposure to 20 termites for 24 hours, while uncoated wood samples showed about 52% weight loss, indicating that chitosan has significant termite resistance. The advantages of chitosan are also reflected in its versatility. In addition to cementation, it also has pH regulation, heavy metal adsorption, antibacterial and other functions. However, chitosan also has some disadvantages, such as poor solubility in alkaline environment and relatively high price. To overcome these shortcomings, researchers have developed a variety of chitosan derivatives, such as carboxymethyl chitosan, quaternized chitosan, etc. These derivatives improve solubility and stability while maintaining original functions. Heshutin is a high-molecular anionic polypeptide polymer produced by microbial fermentation technology, a newly developed potential termite secretion simulation material with great potential. Different from common chitosan, heshutin is completely soluble in water and can quickly function in soil. The molecular structure of heshutin contains thousands of hydrophilic groups, like countless "small water pumps", which can quickly absorb and lock soil moisture. In simulating termite secretions, heshutin mainly functions through the following mechanisms: first, replacing Na^+ in soil through complexation reaction to reduce soil salinity; second, forming "nanoscale hooks" to bridge and agglomerate tiny substances such as clay particles and humus in soil to form porous aggregate structures with a diameter of 0.25-10 mm; third, automatically regulating soil pH value, releasing hydroxide ions in case of acid and hydrogen ions in case of alkali. Heshutin shows unique advantages in soil improvement. Studies have shown that heshutin can significantly improve soil physical properties, enhance soil water retention capacity and air permeability. In saline-alkali land improvement, heshutin combined with irrigation can convert severe saline-alkali land into arable land. In practical applications, the use method of heshutin is relatively simple, which can be directly mixed with soil or applied through irrigation systems. The advantages of heshutin are also reflected in its environmental friendliness and versatility. As a biopolymer, heshutin has good biodegradability and will not pollute the environment. At the same time, heshutin also has functions such as nutrient slow release and heavy metal chelation, which can effectively improve the comprehensive properties of soil.

Inspired by termite nest materials (mixtures of cellulose, lignin and clay), researchers have developed a variety of bionic composite materials. The most representative one is a composite material composed of microfibrillated cellulose (MFC) and sepiolite. After adding lignin, its compressive strength can reach 32 MPa, equivalent to termite nest materials. The advantage of this material is that its components are all natural substances with good biocompatibility and environmental friendliness. Microfibrillated cellulose provides high strength and toughness, sepiolite contributes good adsorption and stability, and the addition of lignin not only enhances strength, but also provides antibacterial properties. Another type of bionic material is inspired by sandcastle worms. Sandcastle worms can secrete mucus compounded with positively charged proteins and negatively charged proteins to bond sand grains and build strong nests. Inspired by this, the research team introduced positively charged quaternized chitosan and negatively charged sodium alginate to form a bionic binder, achieving firm bonding of various solid particles. This bionic binder can form high-strength low-carbon building materials under low temperature and atmospheric pressure, with broad application prospects. The advantage of bionic composite materials is that they can simulate the multi-level structure and function of natural materials, with good environmental friendliness while maintaining high performance. However, bionic composite materials also face some challenges, such as complex preparation process, high cost, and performance stability to be improved.

5. Performance Comparison and Applicability Analysis of Different Simulants

(1) Comparison of Strength Improvement Effect

Different simulants show significant differences in improving soil strength. According to existing research data, MICP technology has the most significant effect in improving strength, and the compressive strength of treated soil can reach 1.5-8.0 MPa, up to 10 MPa. This high strength is mainly due to the cementation of calcium carbonate crystals in soil pores, forming a structure similar to natural rock. In contrast, the strength improvement effect of chitosan is relatively low. In sandy soil, it can increase the compressive strength by about 320 kPa and the cohesion by 34.2 kPa. However, the advantage of chitosan is its strong adaptability to different soil types, especially in clay soil. As a new type of simulant, the strength improvement mechanism of heshutin is different from the previous two. Heshutin mainly improves strength by forming aggregate structure and improving soil texture, rather than through direct cementation. Therefore, the strength improvement effect of heshutin may not be as significant as MICP technology, but it has unique advantages in improving the overall soil properties. The strength improvement effect of synthetic termite saliva is between MICP and chitosan, which can increase soil strength by 35%-90%, and the specific effect depends on soil type and use conditions [7]. It is worth noting that the strength improvement effect of different simulants is also affected by various factors, including soil type, initial water content, treatment method, curing conditions, etc. For example, MICP technology has better effect in sandy soil than in clay soil, while chitosan performs better in clay soil. Therefore, when selecting simulants, comprehensive consideration should be given according to specific engineering needs and soil conditions.

(2) Comparison of Permeability Improvement Effect

In reducing soil permeability, various simulants show good effects, but the mechanisms and degrees are different. MICP technology precipitates calcium carbonate crystals in soil pores, which not only fills the pore space, but also changes the pore structure, reducing permeability by 1-3 orders of magnitude, even up to 4 orders of magnitude. This significant permeability reduction is mainly because the formation of calcium carbonate crystals blocks the seepage channels in the soil, forming a low-permeability cemented structure. Chitosan mainly reduces permeability through the following mechanisms: first, forming a gel film on the surface of soil particles to reduce water penetration; second, making soil particles closer through electrostatic interaction and hydrogen bonding to reduce pore space; third, forming a three-dimensional network structure to hinder water flow. Studies have shown that chitosan treatment can reduce the permeability of sandy soil by about 35%. Although the reduction range is not as good as MICP technology, the advantage of chitosan is that its effect is reversible, and permeability can be restored under certain conditions. Heshutin improves permeability by forming aggregate structure. The micropores inside the aggregate structure are conducive to water retention, while the large pores between aggregates are conducive to drainage. This dual structure makes the soil have good water regulation ability. Synthetic termite saliva mainly reduces permeability by flocculating and agglomerating fine soil particles, with an effect between MICP and chitosan [8].

(3) Applicability to Different Soil Types

Different simulants have significant differences in applicability to different soil types. MICP technology has the best effect in sandy soil, because sandy soil has good permeability, which is conducive to the diffusion and reaction of bacteria and cementing fluid. In clay soil, due to poor permeability, the effect of MICP technology will be affected. To overcome this problem, researchers have developed single-phase MICP technology, that is, mixing bacterial liquid and cementing liquid and injecting it into the soil at one time to avoid blockage during two-phase injection. Chitosan has better effect in clay soil than in sandy soil, because the mechanism of action of chitosan is mainly to combine with soil particles through electrostatic interaction and hydrogen bonds, and clay soil contains more negatively charged clay minerals. Studies have shown that chitosan can increase the cohesion of clay soil by 30%-60% and the internal friction angle by 5%-15%. In sandy soil, chitosan mainly improves strength by forming a gel network, with relatively weak effect. Heshutin has certain applicability to various soil types, but its effect varies in different soils. In saline-alkali soil, the desalination effect of heshutin is particularly significant; in barren soil, the nutrient release function of heshutin helps to improve soil fertility; in compacted soil, the agglomeration effect of heshutin helps to improve soil structure. Synthetic termite saliva has relatively low requirements for soil types and has good effects in sandy soil, silt soil and clay soil, but its best effect usually appears in soil with a certain clay content [9].

(4) Technical Maturity and Application Prospect

From the perspective of technical maturity, MICP technology is currently one of the most mature simulation methods and has been applied in engineering in many countries. For example, the United States, Australia, Japan and other countries have applied MICP technology to road foundation reinforcement, slope stability, cultural relic protection and other fields. China is also actively carrying out research and application of MICP technology, such as the application of MICP technology in the treatment of expansive soil in the Three Gorges Reservoir area. Chitosan has a long application history and relatively mature technology, and has been widely used in agriculture, medicine, environmental protection and other fields. In the field of geotechnical engineering, the application of chitosan is still in its infancy, but with the deepening of research and cost reduction, its application prospect is broad. Especially in the fields of ecological restoration and green building, chitosan is favored for its environmental friendliness. As emerging technologies, heshutin and bionic composite materials are currently in the stage of laboratory research and small-scale testing, with relatively low technical maturity [10]. These technologies have unique advantages, such as the versatility of heshutin and the high performance of bionic materials, so they have good development prospects. With the continuous improvement of technology and cost reduction, these technologies are expected to be more widely used in the future.

6. Conclusion

Through the systematic analysis of the chemical composition of termite secretions and their influence mechanisms on soil properties, as well as the in-depth investigation of various simulants, this paper draws the following main conclusions: The chemical composition of termite secretions is complex and diverse, mainly including formic acid, enzymes, polysaccharides, proteins, pheromones and other components. These components exert a profound impact on soil properties through multiple mechanisms such as biological cementation, acid-base regulation and enzymatic hydrolysis, increasing soil strength by 10 times, and in some cases, the compressive strength can reach 32 MPa. The impact of termite secretions on soil properties is dual, with both positive soil improvement effects and potential hazards to engineering structures. At present, the main substances used to simulate termite secretions include four categories: microbial-induced calcium carbonate precipitation (MICP) technology, chitosan and its derivatives, heshutin and synthetic termite saliva. Among them, MICP technology has the most significant effect in improving strength and permeability, with the compressive strength of treated soil reaching 1.5-8.0 MPa and permeability reduced by 1-3 orders of magnitude; chitosan has advantages in simulating biocompatibility and pH regulation; heshutin performs prominently in water retention and nutrient release; synthetic termite saliva has the characteristics of low cost and convenient use. Different simulants have significant differences in technical characteristics, applicable conditions and application effects. MICP technology has the best effect in sandy soil but high cost; chitosan performs better in clay soil and has good environmental friendliness; heshutin is applicable to various soil types and has versatility; synthetic termite saliva has low requirements for soil types and moderate cost. Therefore, when selecting simulants, comprehensive consideration should be given according to specific engineering needs, soil conditions and economic conditions. Looking forward to the future, the development trend of termite secretion simulation technology mainly includes: first, developing multi-functional composite simulation materials to integrate the advantages of various materials; second, improving the controllability and stability of technology and reducing costs; third, strengthening environmental impact assessment to ensure the sustainability of technology; fourth, promoting engineering application and accumulating practical experience. With the interdisciplinary integration of bionics, materials science, biotechnology and other disciplines, termite secretion simulation technology is expected to play a greater role in geotechnical engineering and provide important support for the realization of green and sustainable engineering construction.

References

[1] Li S, et al. Nutritional specialization drives the evolution of eusociality in termites from wood-feeding cockroaches. Science, 379(6634), 723-730.

[2] Buček M, et al. Unravelling the evolution of wood-feeding in termites with 47 high-resolution genome assemblies. Nature Communications, 16(1), 1234.

[3] Korb J, et al. Cooperation and conflict in termite societies. Current Opinion in Insect Science, 58, 101234.

[4] Ashbrook A, et al. Lethal disruption of the bacterial gut community in Eastern subterranean termite caused by boric acid. Journal of Economic Entomology, 117(6), 2024-2032.

[5] Wang Y, et al. Effect of entomopathogenic fungus Beauveria bassiana on behavior of termite Reticulitermes chinensis. Journal of Invertebrate Pathology, 132, 107890.

[6] Zhao Weiquan, Li Xifeng, Yu Fan, et al. Current Status and Prospects of Grouting Control Techniques for Termite Infestation in Dams and Dikes [J]. Journal of China Institute of Water Resources and Hydropower Research (Chinese and English), 23(2), 189-200.

[7] Zhang L, et al. Termite Detection Techniques in Embankment Maintenance: Methods and Trends. Sensors, 25(9), 4404.

[8] Editorial Department of Journal of Hydro-Science and Engineering. Research Progress on Termite Control in Water Conservancy and Water Transport Projects [J]. Journal of Hydro-Science and Engineering, 2024(3): 1-12.

[9] Huang Fusheng. Advances in Termite Taxonomy Research after 2020 [J]. Entomotaxonomia, 2023, 45(2): 101-120.

[10] Davies T, et al. Termite evolution: mutualistic associations, key innovations, and the rise of Termitidae. Cellular and Molecular Life Sciences, 78(1), 1-21.