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Review

Properties of Sustainable Earth Construction Materials: A State-of-the-Art Review

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Abstract: As a significant symbol of human civilization advancement, earth construction not only inherits traditional architectural culture but also enjoys worldwide popularity and widespread usage throughout China due to its economic and environmentally friendly nature, as well as its moisture absorption and heat storage advantages. Consequently, earth construction has garnered considerable attention from international scholars. This paper compiles relevant data to review the developmental trajectory of earth construction, while conducting an in-depth analysis of the performance characteristics of earthen materials. Furthermore, it provides a comprehensive overview of the impact of three modification methods on the mechanical and durability properties of earthen materials, along with a discussion on the research concerning the thermal and moisture performance of these materials. Simultaneously, discussions were held on the relevant research findings and potential directions for the development of earthen materials. Finally, conclusions were drawn, suggesting a comprehensive utilization of their thermal and moisture performance, emphasizing the enhancement of their mechanical and durability performance. Additionally, attention was urged towards the economic and ecological aspects during the construction and maintenance phases of earth construction. These recommendations aim to facilitate the sustainable development and widespread application of earthen materials in the future.

Keywords: earth construction; earthen materials; material modification; thermal and moisture performance; mechanical property

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1. Introduction

Earth construction, prevalent across various regions worldwide, stands as a significant component of traditional architecture [1]. It manifests in various forms, primarily categorized as cave dwellings, adobe buildings, and rammed earth construction [2–4]. As a traditional dwelling form, earth constructions possess multiple advantages. They capitalize on local resources, allowing for swift and efficient construction processes with relatively lower costs. Additionally, these constructions exhibit exceptional thermal performance, contributing to reduced energy consumption during both construction and operation phases. Meanwhile, the waste generated from earth constructions can be effectively recycled and reused, aligning with contemporary pursuits of sustainability and ecological equilibrium. Consequently, amid the escalating environmental and resource concerns, earth constructions play a proactive role [5–10]. Statistics show that more than 1 billion people still inhabit structures made from earthen materials around the world, a phenomenon that is particularly pronounced in regions such as the Middle East, North Africa, and Central Asia. The relatively slow development of these regions has contributed to earth construction being the only viable option for housing for many people [11,12]. In the context of China, earth construction finds concentrated manifestation within economically disadvantaged rural locales, spanning the expanse of the Loess Plateau, Southwest China, East China, the elevated terrain of the Tibetan Plateau, Xinjiang, Central China, and the southern reaches of the nation [13,14]. Despite misconceptions associating earth constructions with backwardness during the industrial civilization era, these structures, rooted in history, now exhibit increasingly prominent advantages in the context of heightened ecological awareness and emphasis on sustainable development [15,16].

However, traditional earthen materials, the primary component in earth construction, mainly comprise untreated natural soil, also known as raw soil materials. They are typically used in constructing walls, floors, and other architectural components. Furthermore, in road construction and dam engineering, earthen materials are extensively utilized as roadbed and embankment materials. They provide support and filling in roadbeds and embankments, enhancing engineering stability and increasing load-bearing capacity [17–19]. In contrast, conventional building materials, such as concrete, usually consist of cement, aggregate, and sand, with the aggregate typically sourced from quarries, presenting significant differences from earthen materials. The mechanical properties and durability of earthen materials are relatively poor, often leading to issues like wall cracks, which adversely affect the safety and thermal performance of earthen architectural structures. Consequently, the widespread adoption of earth construction faces severe constraints [20,21]. At present, a multitude of scholars from both international and domestic spheres are exerting their full efforts to enhance the mechanical characteristics and endurance of earthen materials. Through in-depth exploration of various modified materials, researchers have achieved a series of noteworthy outcomes in this field. Meanwhile, as energy-efficient construction gains increasing attention, experts in the field are progressively shifting their research focus towards the thermal and moisture performance of earthen materials. This performance has emerged as a focal point of considerable interest in recent years within the forefront of research aiming to enhance earthen materials [22,23]. Figures 1 and 2 show the distribution map of earth construction around the world and in China, where the highlighted areas represent the distribution of earth construction.

Figure 1. Distribution map of earth construction around the world [24].

Hence, this paper offers a comprehensive overview of earth construction materials. Firstly, it traces the historical development of earth constructions and thoroughly analyzes the performance characteristics of earthen materials. Subsequently, it highlights the current state of research on earthen material modification, encompassing chemical modification, component optimization, and composite modification methods employed by scholars globally, aimed at enhancing the mechanical and durability properties of earthen materials. Lastly, this paper presents an overview of the thermal and moisture performance of earthen materials, offering valuable reference points for future research and development endeavors.

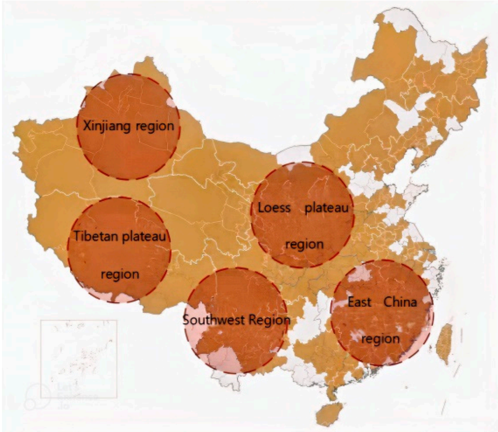


Figure 2. Distribution map of earth construction in China [25].

2. Development History of Earth Construction

2.1. Ancient and Glorious History

Earth constructions symbolize a pivotal characteristic of humanity's transition from primitive times to civilization [18,26]. As an original architectural form, the history of earth constructions is deeply rooted [27]. The development of earth constructions can be categorized into three distinct stages: subterranean structures (such as cave dwellings and pit houses), rammed earth systems, and adobe systems. Among these, one of the earliest forms was subterranean structures. Even in the Stone Age, ancient communities constructed semi-subterranean dwellings or pit houses using locally sourced soil and natural resources. These dwellings were covered with soil, forming subterranean structures. Archaeological sites from cultures like Majiayao, Peiligang, and Dadiwan, dating back approximately 7000 years, revealed circular and square semi-subterranean structures, showcasing the defining features of this construction method [28]. These early earth constructions provided fundamental living and shelter needs, emphasizing simplicity and integration with the natural environment. With the advancement of civilization, subterranean structures gradually evolved into rammed earth structures. During the Roman era, rammed earth techniques were extensively employed, supported by historical records from that time. The Roman historian Pliny recorded in "Natural History" that rammed earth techniques were in use during the first century BC in ancient Rome [29]. To this day, remnants of structures constructed with rammed earth during the time of Hannibal exist in Spain, including watchtowers and ridge turrets. These ancient constructions showcase human mastery and application of rammed earth techniques. Adobe systems represent a significant phase in the development of earth constructions due to their exceptional insulation properties, environmental adaptability, and relatively straightforward construction processes. The term "adobe" originates from the Egyptian word for "mud," translated as "at-tob" in Arabic and evolved into "adobe" in Spanish [30]. Adobe systems were extensively utilized in places like ancient Egypt, establishing them as a crucial form of earth construction. Adobe structures not only met human dependency on the natural environment but also achieved a certain level of aesthetic appeal. In many traditional regions such as Asia, Africa, and the American Southwest, adobe houses have been used consistently for hundreds of years [8]. In the developmental history of earth construction, various commonly used techniques for earthen materials have emerged. These techniques include fiber reinforcement, which involves adding local animal or plant fibers to enhance the material's crack resistance [31,32]. Additionally, there is the preparation of earthen-based composite materials, involving the addition of substances like lime, cement, and gypsum to enhance the material's characteristics [33,34]. Another technique involves the use of binders such as natural resins and starch to strengthen soil structures [35,36]. These techniques have played pivotal roles in different historical periods and regions, continually evolving with technological advancements to meet diverse environmental and architectural requirements.

2.2. Challenges Posed by Industrialization

The Industrial Revolution marked a significant turning point in human history, profoundly impacting the development of earth constructions. In 18th-century Britain, the Industrial Revolution sparked a wave of extensive industrial production and technological innovation, significantly propelling the processes of urbanization and modernization. During this era, earth constructions encountered unprecedented challenges and transformations. Firstly, the Industrial Revolution introduced new building materials and technologies, such as steel, cast iron, and concrete, offering higher strength and durability. These materials could meet the rapidly growing demands of urban construction at the time [37]. In comparison, the soil and natural materials used in earth construction have limitations in terms of structural strength and resistance to wind and seismic forces, making it challenging to compete with industrialized construction methods. Additionally, the Industrial Revolution brought about urbanization, with a significant population shift from rural to urban areas, demanding extensive residential and infrastructure development. The traditional construction methods and manual labor involved in earth construction could not meet the demands for large-scale efficient construction, whereas industrialized building techniques offered quicker standardized solutions. Consequently, driven by the Industrial Revolution, earth construction gradually became marginalized and deemed an outdated and backward architectural form [38,39]. Furthermore, the Industrial Revolution introduced new concepts and value systems, with the emergence of the modernist architectural movement in the early 20th century. Modernism emphasized functionality and technological progress, advocating for the use of industrially produced new materials and technologies. However, earth construction relies on natural materials and traditional construction techniques, emphasizing integration with the natural environment and sustainability. As a result, earth construction stands in contrast to the ideals of modernism, perceived as a symbol of tradition and conservatism.

2.3. Revival in the Era of Ecological Civilization

Amid rapid urbanization, excessive cement and reinforced concrete structures gave rise to urban heat island effects and environmental degradation. Gradually, people began to recognize that environmental protection and economic development should not be divorced, as such separation would lead to catastrophic consequences for the planet and human society [40]. In this social context, the concept of sustainable development emerged and gained widespread traction, prompting a reevaluation of earth constructions and an acknowledgment of their potential in environmental conservation and sustainability. Earth constructions, with their excellent insulation and moisture-regulation capabilities, contribute to improving indoor and outdoor temperature and humidity conditions, mitigating urban heat island effects, and promoting urban ecological balance. Today, as the era of ecological civilization dawns, the resurgence of earth constructions has taken on an almost unavoidable trajectory. Governments, scholars, and designers have intensified their research and promotional endeavors related to earth constructions. They have introduced corresponding standards and guidelines while fostering their integration into urban planning and architectural design practices. Several regions are presently reviving traditional construction methods to investigate the integration of earth constructions with contemporary lifestyle requirements, thereby pioneering advancements in sustainable architecture. Measures such as improving earthen materials, utilizing advanced compaction equipment and molds to produce high-quality adobe blocks, and applying new coatings and protective layers to enhance weather resistance have significantly elevated the quality and performance of earth constructions. Additionally, digital technology and advanced modeling tools have made the design and construction of earth constructions more precise and efficient. In developed nations such as France and the United States, earth constructions have found extensive application across diverse building typologies, encompassing both private residences and public structures [41]. Due to their alignment with the natural environment and intrinsic sustainability, earth constructions emerge as an optimal selection in the quest for a natural equilibrium and ecological harmony.

In summation, the developmental history of earth construction dates back to primitive societies, representing humanity's adaptation to the natural environment and the culmination of wisdom. It also showcases diverse architectural styles and cultural heritage. Despite being marginalized during the wave of modern industrialization, with the arrival of the ecological civilization era, earth construction is undergoing a revival. Driven by the forces of innovation and progress, earth constructions hold the potential to assume a pivotal role in the forthcoming landscape of architectural evolution, thereby making a substantial and affirmative contribution to the sustainable advancement of human society.

3. Performance Characteristics of Earth Construction Materials

3.1. Economy and Environmental Protection

The cost of earthen materials is significantly lower than conventional building materials such as fired bricks and concrete. Earthen materials derive directly from the surrounding natural environment, thereby obviating the necessity for costly firing procedures and energy-intensive manufacturing stages. Research indicates that the cost of the main structural materials of earth construction can be reduced by over 50% compared with conventional materials when considering raw materials, processing, and transportation [42,43]. A typical example is the "Mao Si Ecological Experimental Elementary School" project in Qingyang, Gansu Province, as shown in Figure 3. Initiated in 2004, the project cost only a little over CNY 600 per square meter, which is only two-thirds of the cost of equivalent seismic and insulating conventional brick–concrete houses [44,45]. Moreover, Wang et al. [46], based on structural models and architectural forms of representative earth residential structures, conducted an economic cost analysis of such dwellings, encompassing material expenses, labor costs, and mechanical charges. Through their calculations, the cost of constructing an earth structure residence amounted to CNY 63,057.00, and after incorporating seismic-resistant measures, the cost increased to CNY 67,350.64, significantly lower than the cost of masonry and concrete buildings. This analysis underscores the distinct economic advantage of traditional earthen materials over conventional construction materials.

Figure 3. Mao Si ecological experimental primary school [2].

The environmental performance of earthen materials is another notable characteristic. Earthen materials require no firing or chemical processing, resulting in energy consumption and carbon emissions that are, on average, only 6% of those of concrete and 3% of ordinary fired bricks [47]. Meanwhile, earthen materials possess excellent biodegradability [48]. After the demolition of a structure made from earthen materials, the materials can return to the land or be reused in constructing new buildings. Moreover, earthen materials interact with the natural environment, aiding in maintaining ecological balance. As depicted in Figure 4, the wall of an earth construction, after serving its purpose, can transform into fertile soil that reintegrates into the ecological cycle. This process is akin to nitrogen fertilizers, facilitating interactions with ions such as oxygen and nitrogen in the air, thereby enhancing soil fertility [49]. Certain comparative studies on carbon emissions [50] have additionally highlighted that earthen materials exhibit the lowest carbon emissions, underscoring their remarkable environmental performance, as illustrated in Figure 5. Against the backdrop of today's emphasis on sustainable development, earthen materials, serving as an eco-friendly and cost-effective architectural option, harbor substantial potential and promotional value.

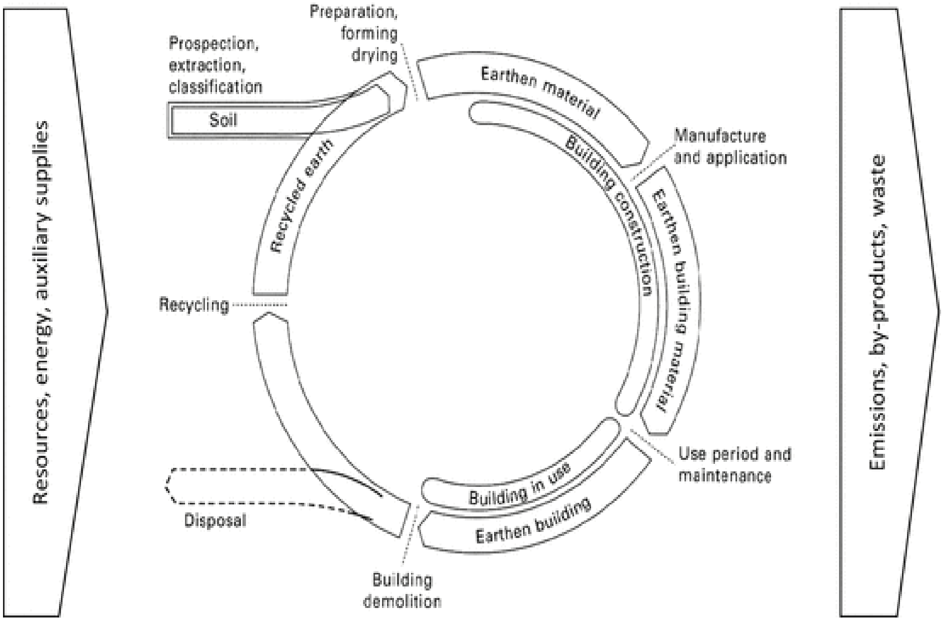


Figure 4. The sustainable cycle of the whole lifecycle of soil resources [51,52].

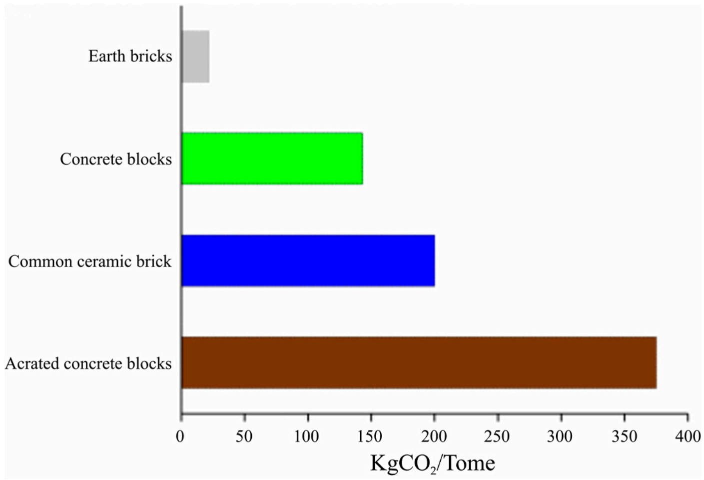
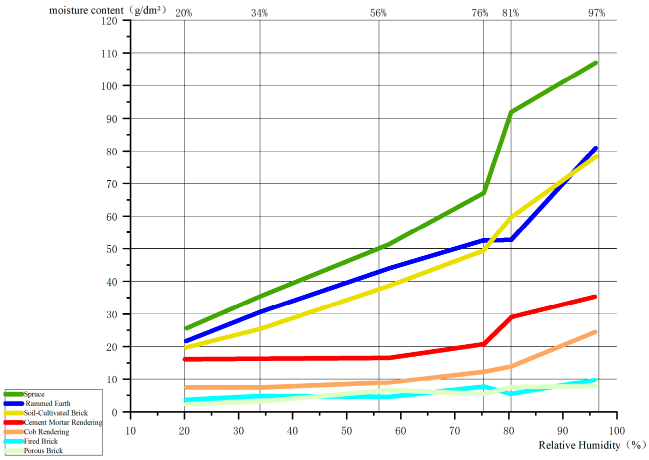


Figure 5. Carbon emissions of different masonry materials [50].

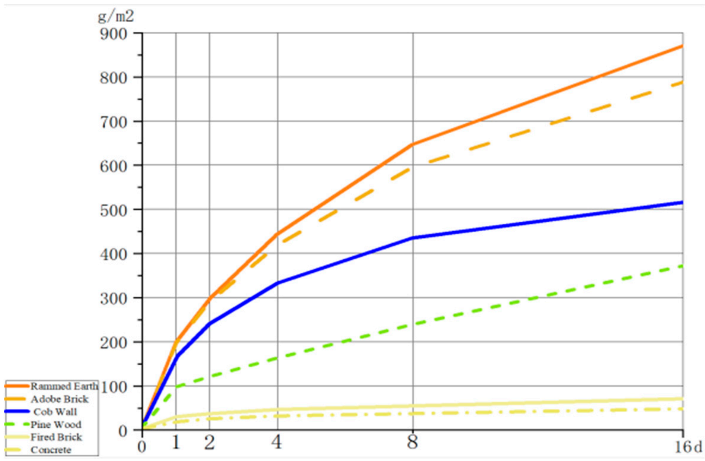
3.2. Moisture Absorption and Heat Storage

Earthen materials are often referred to as "breathing" materials due to their unique characteristics, making them a rare porous heavy material with high moisture-absorbing capacity. Extensive research [53–56] has indicated that earthen materials, utilized as a construction material, offer substantial capabilities in regulating indoor thermal and humidity conditions. According to humidity absorption experiments conducted by the Building

Research Experimental Center of the University of Kassel in Germany [57], at specific temperatures, and increasing relative humidity from 50% to 80%, the moisture absorption of concrete and fired bricks reaches saturation within two days. In contrast, earthen materials consistently maintain higher moisture absorption. At 16 days, the moisture absorbed by earth is 15 times that of concrete and 10 times that of fired bricks, as shown in Figure 6a,b.



(**a**)



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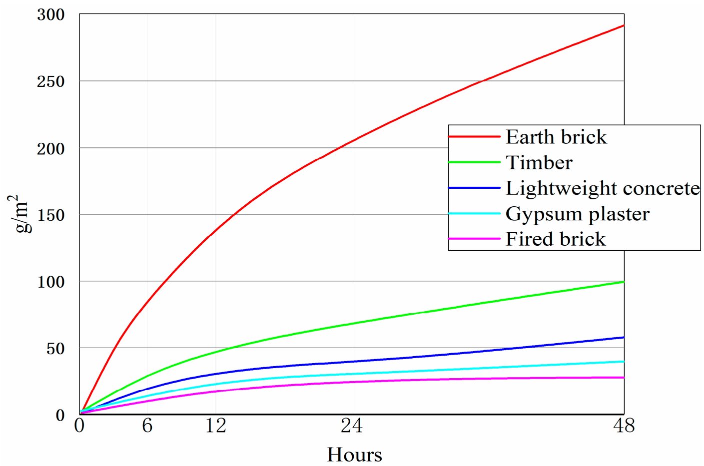


(**c**)

Figure 6. Hygroscopicity of different earthen materials [58,59]. (**a**) Comparison of equilibrium moisture content between raw soil and other materials [60]. (**b**) Comparison of hygroscopic performance between raw soil and other materials [58]. (**c**) Weight of water absorbed by different materials [59].

Studies also demonstrate that soil blocks can absorb 10 times the weight of moisture compared with ceramic tiles, as illustrated in Figure 6c. This is due to the equilibrium maintained between the relative humidity of the external environment and the relative humidity within the wall pores of earth structures [60,61]. Hence, the remarkable moisture absorption capability of earthen materials can effectively balance day–night indoor temperatures, enabling dehumidification in summer and insulation in winter, and creating a comfortable thermal and humidity environment.

Owing to its porous characteristics, the earthen wall becomes a heavy material with relatively balanced insulation and heat storage capabilities, as illustrated in Figure 7 [62–64]. This characteristic endows the earthen wall with the function of a "heat reservoir" in maintaining indoor temperatures. During the day, when ambient temperatures exceed the temperature of the earthen wall, it absorbs and stores a substantial amount of heat, preventing excessively high indoor temperatures. At night, as ambient temperatures decrease, the earthen wall gradually releases the stored heat from the day, preventing excessively low indoor temperatures. This unique heat performance of earthen walls contributes to energy conservation, providing a comfortable living environment and reducing the amplitude of indoor temperature fluctuations. This advantage enables earth constructions to effectively maintain indoor temperature stability under various climate conditions, aligning with the concepts of today's sustainable architecture.

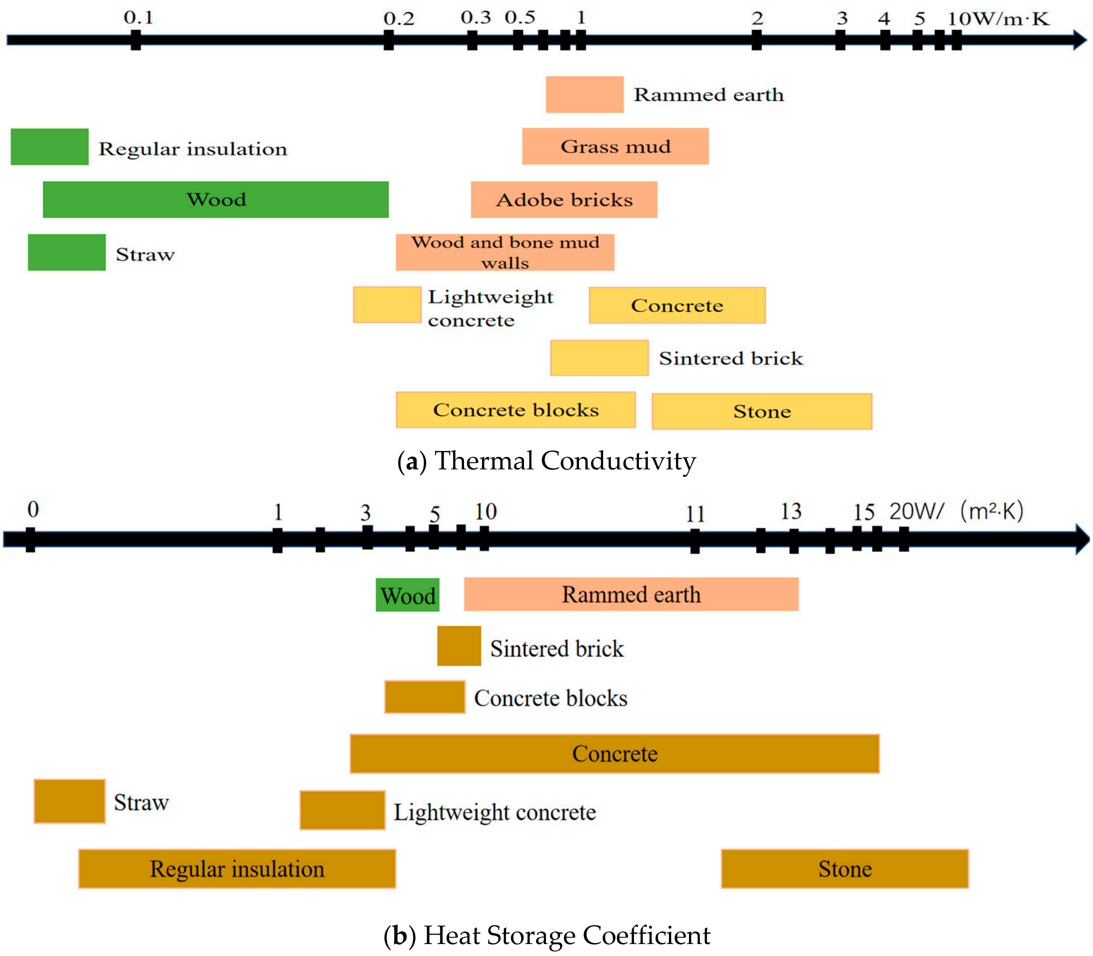


Figure 7. Comparison of thermal conductivity (**a**) and heat storage coefficient (**b**) between earthen materials and other conventional wall materials [65].

3.3. Mechanics and Durability Performance

The mechanical and durability shortcomings of earthen materials have been a persistent limitation in their development and application. Hence, residential earth constructions for civilian use typically do not exceed 6 m in height. Several research data have highlighted these issues. According to a national survey on rural dilapidated houses conducted by the Ministry of Housing and Urban-Rural Development of China from 2009 to 2011, the dilapidated house rate in rural areas remained around 30%. In regions such as the northwest and southwest, this high rate was mainly attributed to earth constructions. Compressive strength is an important parameter for evaluating the mechanical properties of earthen materials. However, due to variations in traditional earth construction techniques in China, the compressive strength of walls built using different techniques can differ significantly. Based on recent research by domestic and international scholars [65–76], the compressive strength of traditional rammed earth walls generally ranges from 0.3 MPa to 1.8 MPa, while that of traditional adobe bricks is around 1–1.2 MPa. Compared with conventional wall materials such as sintered brick and concrete, there is still a large gap in the compressive strength of raw soil materials, as shown in Figure 8.

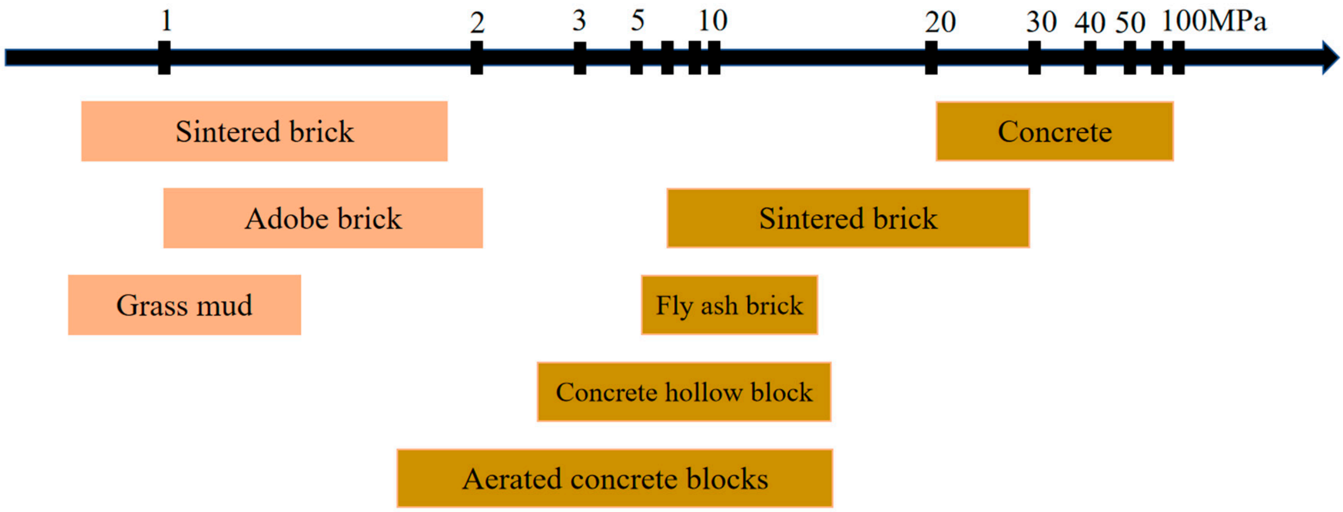


Figure 8. Comparison of compressive strength between earthen materials and other wall materials [65].

Furthermore, the durability performance of earthen walls is also an inherent issue. Bui et al. [77] assessed the durability performance of 104 stabilized and unstabilized rammed earth blocks exposed to natural weathering conditions for 20 years, as shown in Figure 9. The findings indicated that unstabilized rammed earth blocks exhibited the least favorable durability performance. Durability concerns of earthen walls manifest through various factors, encompassing diminished strength when exposed to moisture, susceptibility to shrinkage cracks, vulnerability to wind erosion and flaking, along with alkali corrosion observed at the base of walls. Despite the good moisture-absorbing property of earthen walls, their strength can be affected when exposed to water. This type of damage often occurs due to the effects of liquid water on the wall's surface, which causes weakening of the wall's strength through wetting and drying cycles and erosion [78,79].

(a) (b) (c)

Figure 9. Rammed earth masonry units exposed to natural weather conditions for 20 Years [77]. (**a**) Wall made of earth containing 5% lime. (**b**) Wall made of unstable earth (mixed earth). (**c**) Wall made of unstable earth.

4. Research Status of Modification of Earthen Materials

Traditional earth constructions have been impacted by external environmental factors such as rainwater erosion and freeze–thaw cycles, resulting in reduced mechanical and durability properties. This has led to issues like wall cracking, significantly impeding both the structural safety and thermal performance of earth constructions, thereby restricting their widespread application [80,81]. Therefore, research into the modification of earthen materials holds great significance for the development of earth constructions. Scholars both domestically and internationally have extensively explored various modification methods for earthen materials, including component optimization and chemical and composite modifications. The goal is to develop a range of new environmentally friendly earthen materials to address the deficiencies in strength and durability of traditional earthen materials [82–84]. Research into soil modification began earlier abroad, particularly in the field of soil stabilization, dating back to the early 20th century [85]. In China, research on the modification of earthen materials emerged in the 1980s, primarily focusing on applications in highway and railway subgrades, hydraulic engineering, and other areas. Initial research primarily concentrated on the modification of cohesive soils, yet substantial strides have been achieved in recent years [86].

4.1. Chemical Modification

Researchers from around the world have conducted extensive chemical modification studies on earthen materials. These methods involve combining chemically modified materials, either in a singular or mixed form, with earthen materials to create new products through chemical reactions, thereby enhancing the mechanical properties and durability of earthen materials [25]. Chemically modified materials commonly fall into two main groups: traditional binder materials like lime, cement, and gypsum [87], and industrial byproducts such as slag, fly ash, phosphogypsum, and rice husk ash [88].

4.1.1. Impact of Chemical Modification on Strength

Lime, as one of the oldest cementitious materials, has been widely used for the modification of earthen materials, with the historical heritage of European architecture demonstrating its effectiveness [89–92]. Several studies have indicated that adding lime to soil increases the concentrations of Ca^{2+} and OH^{-1} ions due to lime's hydration reactions. This prompts flocculation of soil particles, affecting soil plasticity and raising the pH of the soil. It also results in the dissolution of silicon dioxide and aluminum oxide in the soil, which then react with calcium to form calcium silicate (or aluminate) hydrates. These compounds act as binders, significantly enhancing the mechanical properties of earth constructions [93–96]. As early as 1802, a mixture of lime, clay, and stones known as "terre pise" was used in France, which laid the foundation for France's leading role in earthen material research [97,98]. Yang [99] and Ke [100] found that lime, as a modifier, yielded positive effects. With increasing curing time, the influence of lime becomes more evident, gradually raising the compressive strength. However, excessive use of lime is not necessarily better. Ke [100] demonstrated that the optimal improvement occurred when lime content reached 10%, and further increases did not significantly enhance strength. Similarly, Ávila et al. [101] indicated that optimal compressive strength and stiffness levels were achieved with a lime content of 12% during the modification of earth in southern Spain. These studies showcased the beneficial effects of lime modification in enhancing the performance of earth constructions.

Gypsum, due to its rapid setting and hardening properties, has been widely used in the modification of earthen materials, enabling quick solidification, and achieving high early strength. This aids in faster demolding and increased construction efficiency. Yin [102] and Isik et al. [103] observed that gypsum can accelerate the setting time of earthen materials and enhance their strength. Specifically, when gypsum is mixed with water, it rapidly forms dihydrate gypsum crystals, creating an overall framework that provides early strength. However, similar to lime modification, relying solely on gypsum modification also has limitations. Excessive gypsum content might not significantly enhance strength and could even increase costs, making it challenging to meet the requirements of modern construction. Chen [104] found that the optimal mechanical performance of earthen specimens was achieved when the gypsum content was 20%, with further increases showing minimal impact on compressive strength.

Currently, cement is the most important additive to improve the properties of earthen materials, and the use of cement modification can effectively reduce the shrinkage and cracking problem and improve the strength of earthen materials. According to existing research, the cement content in modification usually ranges from 4% to 20% [105–109]. Reddy et al. [110] studied the influence of different cement content on the compressive strength of earthen materials. Particularly, when the cement content increased from 5% to 12%, a significant increase in strength was observed. Additionally, Liu et al. [111] proposed an innovative method, that is, using metakaolin as the main raw material to prepare earth–polymer cement for modification. The results showed that after modification, the compressive strength of earthen materials reached 18 MPa within 28 days, and the softening coefficient was as high as 0.9. This achievement indicated the promising potential of this novel modification method in meeting the performance requirements of modern wall materials.

Figure 10 collects experimental test data related to the compressive strength of earthen materials modified by various types of cementitious materials. From the graph, it is evident that, with an increase in the content of cementitious materials, there is an upward trend in the compressive strength of earthen materials. Noteworthy is the fact that cement exhibits a more pronounced impact on enhancing the strength of earthen materials compared with traditional binders such as lime and gypsum, with lime's modifying effect ranking second. However, relying solely on cement addition is not a perfect solution. Under the situation of pure cement modification, the primary hydration product is fibrous calcium silicate hydrate (CSH). While this adheres to the pores of the soil, providing the modified soil with some strength, it does not sufficiently fill the soil pores, limiting the further enhancement of the soil's strength. Moreover, excessive cement content exceeding 20% can diminish soil fertility essential for agriculture, hindering waste soil reuse. From an economic standpoint, simply increasing cement content to enhance soil strength is not a wise approach.

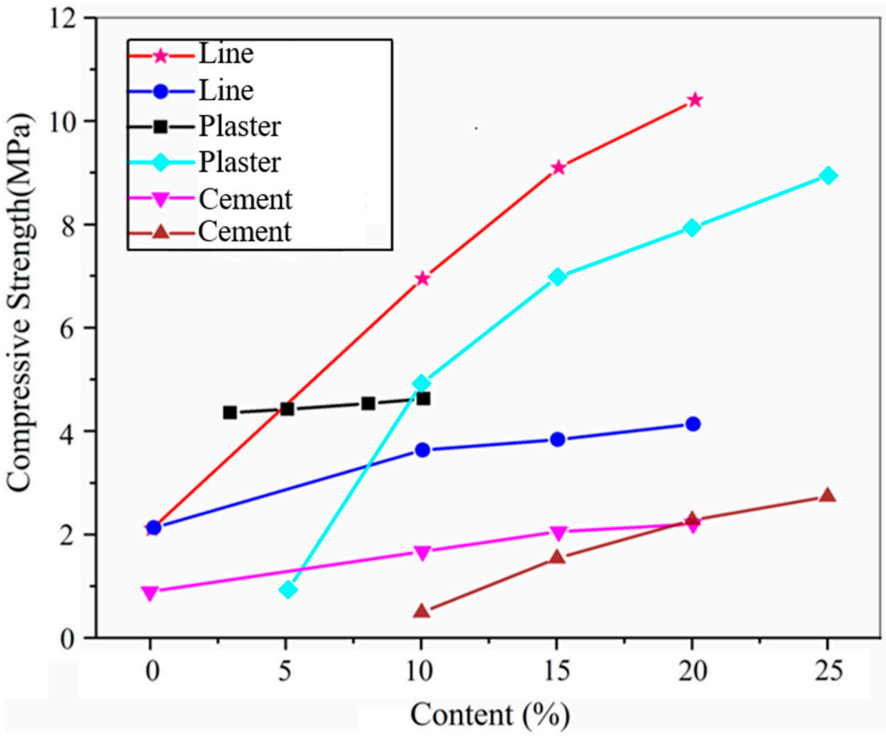


Figure 10. Compressive strength of earth modified with different cementitious materials. Adapted from references [102,104,112–114].

Consequently, in recent years, scholars have actively explored the composite blending of traditional binder materials with industrial byproducts like slag, fly ash, and phosphogypsum to enhance the performance of earthen materials. This approach yields substantial economic and societal benefits. Figure 11 compares the effects of single and compound blending methods on the compressive strength of earthen materials. It is noteworthy that the composite blending method significantly improves the strength of earthen materials. Liu et al. [115] indicated that the strength of modified earthen materials could increase by 3.6 times by adding phosphogypsum alongside a single addition of 10% cement. However, the strength enhancement effect from a single addition of 20% cement was slightly inferior. Nevertheless, some studies have indicated that excessive industrial byproduct content could lead to strength reduction. For example, Chen et al. [116] found that adding 5% phosphogypsum on the basis of 10% cement content resulted in a 49% increase in unconfined compressive strength at 28 days. However, beyond 5% phosphogypsum content, the compressive strength of the modified earth began to decrease. Islam et al. [117] also found that incorporating fly ash into cement can enhance strength, but beyond a certain threshold, strength begins to decline. This phenomenon is attributed to excessive industrial byproduct content possibly reducing particle-to-particle bonding and binding effects, leading to increased porosity and affecting strength.

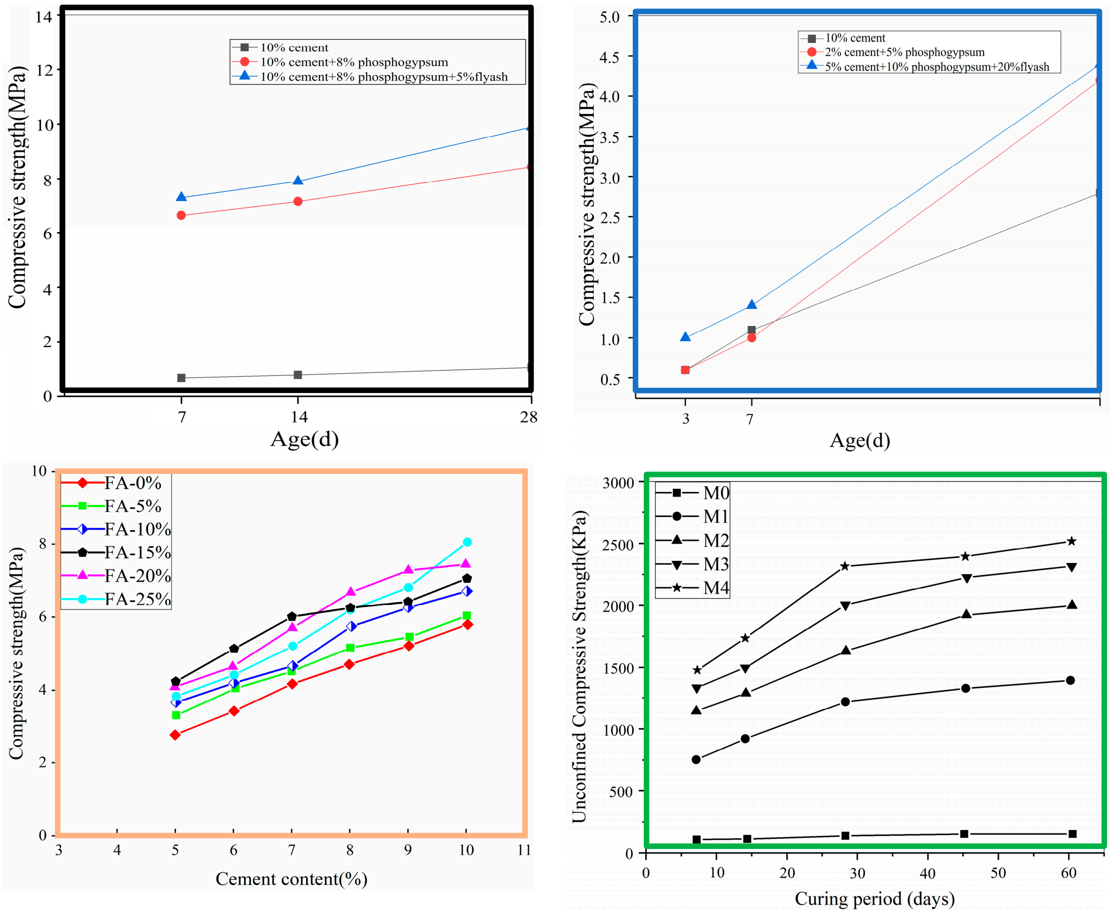


Figure 11. Influence of sole addition and co-blending on compressive strength. Adapted from references [112,115,117,118].

Additionally, scholars have explored utilizing industrial byproducts as aluminosilicate materials and employing alkali activators to enhance the mechanical properties of earthen materials. Du et al. [119] observed that, under the same binder content, the unconfined compressive strength of earth modified by alkali-activated slag increased by over 2 to 3.5 times compared with cement-modified earth samples. Singhi et al. [120] documented that, under similar binding conditions, the 28-day strength of earth modified with alkali-activated slag surpassed that of cement-modified earth by over 600%. These findings demonstrated that employing industrial byproducts along with alkali activation techniques can significantly enhance the mechanical properties of earthen materials, offering potential avenues for the development of sustainable construction materials.

4.1.2. Impact of Chemical Modification on Durability

Traditional earthen materials often display fragility and susceptibility to structural damage when exposed to rainwater erosion, particularly concerning their water resistance. To enhance this property, a common approach involves stabilizing the soil by adding lime or cement at a content equivalent to between 5% and 12% of the dry mass [17]. For instance, the treatment with cement stabilizer significantly reduces the water absorption and erosion rate of earthen materials, as demonstrated by Kariyawasam and Jayansinghe [121]. However, Shang et al. [122] and Wang et al. [123] suggested that adding gypsum alone does not effectively improve the water resistance of earthen materials. This phenomenon can be explained by gypsum being an air-hardening cementitious material that rapidly undergoes hydration reactions upon contact with water, resulting in the formation of a gypsum slurry. Conversely, adding cement, finely ground slag, or a mixture of lime and cement can significantly enhance the water resistance of earthen materials. This is because, in systems where cement, finely ground slag, fly ash, and hydrated lime are added, interactions occur between gypsum and hydrated lime or cement components, resulting in a more stable structure. Nurhayat Degirment et al. [124,125] proposed the addition of natural gypsum and phosphogypsum to earthen materials, and their research found that the water resistance of specimens was moderately improved, providing new insights for the engineering application of earthen materials.

Freeze–thaw damage is another significant factor contributing to earth degradation, particularly prevalent in regions with significant temperature fluctuations. Soils are susceptible to damage through repeated cycles of freezing and thawing. Figure 12 compares the effects of various modification materials on the freeze–thaw resistance of earthen materials. To mitigate this type of damage, Zhang et al. [126] added modification materials such as cement and slag-blended materials, which reduced the rate of compressive strength loss of earthen materials after freeze–thaw cycles, as shown in Figure 12a. This modification creates a stable internal structure, reduces internally generated stress, and subsequently reduces crack formation. This results in the material maintaining good compressive strength after freeze–thaw cycles. Assia et al. [127] found that the compressive strength loss rate of stabilized soil using white cement and industrial lime was negligible, as shown in Figure 12c. This indicates the excellent performance of this modification material in resisting freeze–thaw damage.

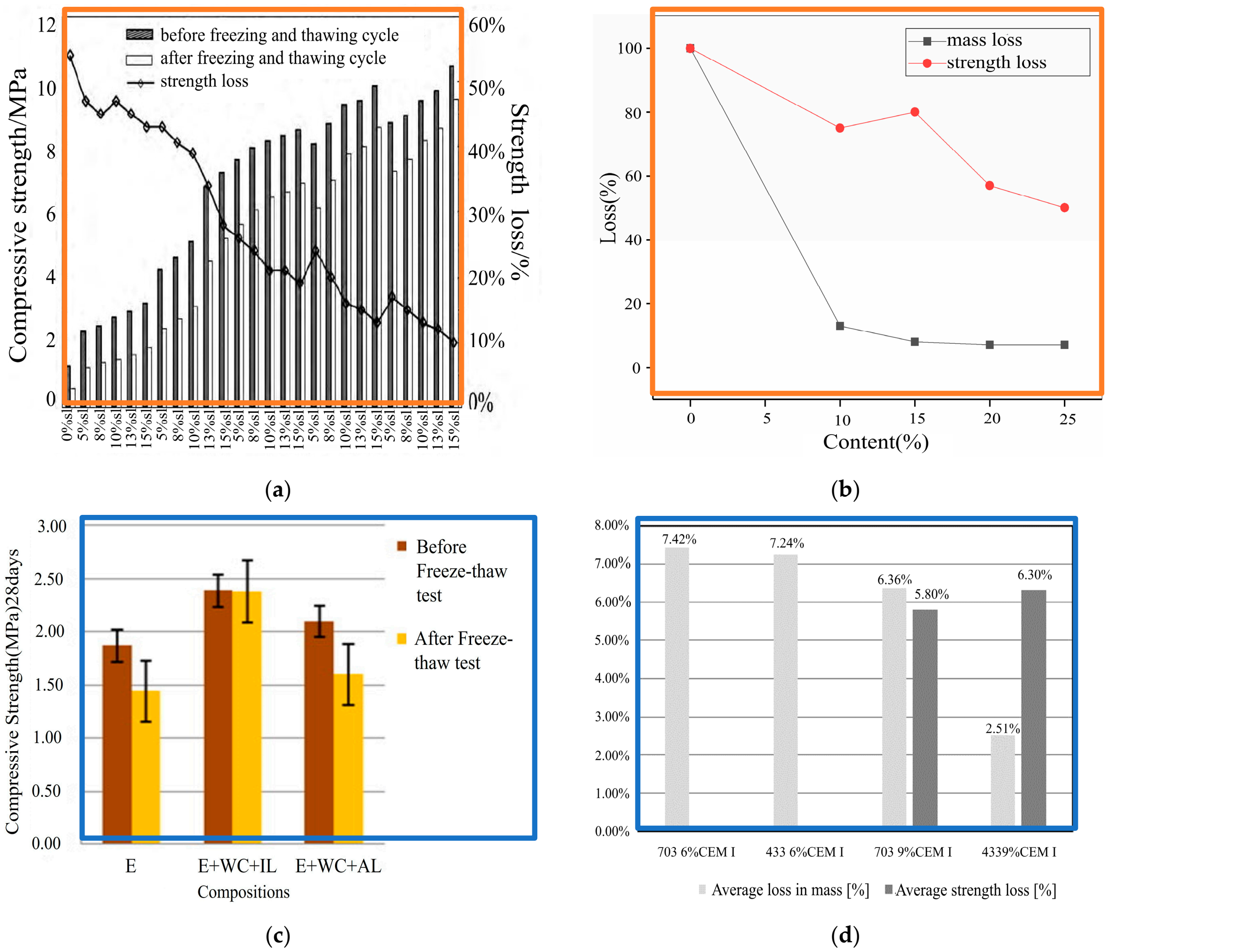


Figure 12. Influence of different modified materials on the frost resistance of earthen materials [126–129]. (**a**) Performance of chemically modified earthen materials before and after freeze–thaw cycles [126]. (**b**) Performance of chemically modified earthen materials before and after freeze–thaw cycles [128]. (**c**) Influence of freeze–thaw cycles on 28-day compressive strength [127]. (**d**) Performance of compacted soil samples after 25 freeze–thaw cycles [129].

To sum up, scholars worldwide have opted for a diverse array of modification materials and have conducted extensive experimental research to develop various modification techniques and formulations. Among these modification methods, chemical additives such as lime and cement are deemed primary modifiers [22]. Through these modification approaches, significant enhancements have been achieved in the mechanical properties, durability, and other pertinent physical attributes of earthen materials. These extensive research outcomes furnish valuable references for practical engineering applications and thereby open new possibilities for the application of earthen materials.

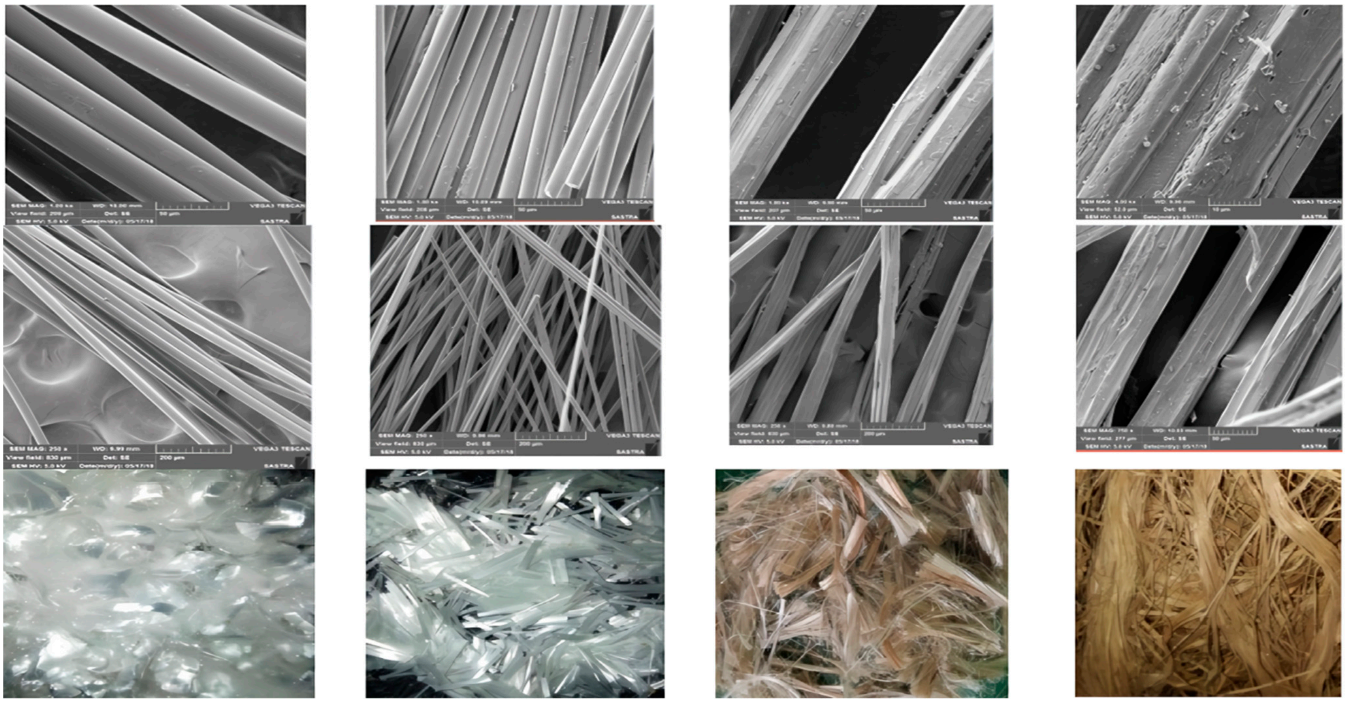
4.2. Component Optimization

Component optimization primarily involves adjusting the composition and structure of earthen materials. This method encompasses two main approaches: the addition of aggregate to alter the particle composition and gradation, thereby controlling the compressive strength of earthen materials, and the introduction of fiber materials into earthen substances. This utilizes the binding force between fibers and soil to restrain the soil and consequently enhance the strength and deformation capabilities of the earthen materials [130–132].

4.2.1. Effect of Component Optimization on Strength

Aggregates, including stones and sand, are widely used in component optimization. A typical example is the Fujian Tulou in China, where traces of manually added stones of different sizes are visible on the walls. Such modification aims to utilize the particle grading characteristics of aggregates to achieve closer compaction of the earth, thereby enhancing the overall strength, seismic performance, and durability of the soil structure. However, when using aggregates to improve the strength of earthen materials, it is important to consider the selection, content, and distribution of aggregates, as they play a pivotal role in strength enhancement. Optimal strength results can be achieved by judiciously choosing and incorporating appropriate amounts of aggregates. For example, Wang et al. [133] discovered that incorporating gravel into earthen materials can maintain the overall integrity and cohesion of the specimens at a moderate dosage. However, excessive gravel content might compromise cohesion and integrity, consequently leading to reduced strength. Additionally, Liu et al. [134] discovered that adding sand and gravel can enhance the compressive performance and deformability of earth, but the total content of sand and gravel should not exceed 32% of the total mass of the soil.

Another common component optimization method involves adding fiber materials, including plant fibers and synthetic fibers. Plant fibers include jute, sisal, straw, rice straw, weeds, pine needles, hemp, bamboo fibers, etc., while synthetic fibers encompass waste tire textile fibers, glass fibers, polyvinyl alcohol fibers, and polypropylene fibers, among others. Numerous studies show that the presence of fibers increases the surface area of the soil matrix, providing more interfaces for interaction between the soil and fibers, thereby enhancing compressive strength [135–137]. Recent trends indicate an upsurge in utilizing synthetic fibers for modifying earthen materials, demonstrating their efficacy in enhancing mechanical performance [138–140]. For instance, Kim et al. from South Korea [141] used discarded polyethylene fishing nets to modify lightweight soil. The results showed that adding an appropriate amount of discarded fishing nets significantly increased the unconfined compressive strength of the lightweight soil, with the maximum strength enhancement observed at a content of around 0.25%. This effect was attributed to the increased bonding strength between the fibers and the soil matrix and the friction at the fiber–soil interface. Another study by Winsley B et al. [142] involved the use of glass fibers to modify earthen materials, and the results demonstrated that the addition of glass fibers could improve the strength and crack resistance of the earthen materials. However, when compared with synthetic fibers, natural fibers offer a more pronounced effect in improving the strength of earth. This can be attributed to the higher surface roughness of natural fibers compared with smoother synthetic counterparts [143], as depicted in Figure 13. Figure 14 presents a comparative analysis of the impact of various fiber additions on compressive strength, vividly illustrating the superiority of jute fibers in enhancing the compressive strength of earthen materials, while discarded rubber showcases the least effective outcome.



(**a**) (**b**) (**c**) (**d**)

Figure 13. Microscopic images of (**a**) polypropylene fiber, (**b**) glass fiber, (**c**) jute fiber, and (**d**) banana fiber [143].

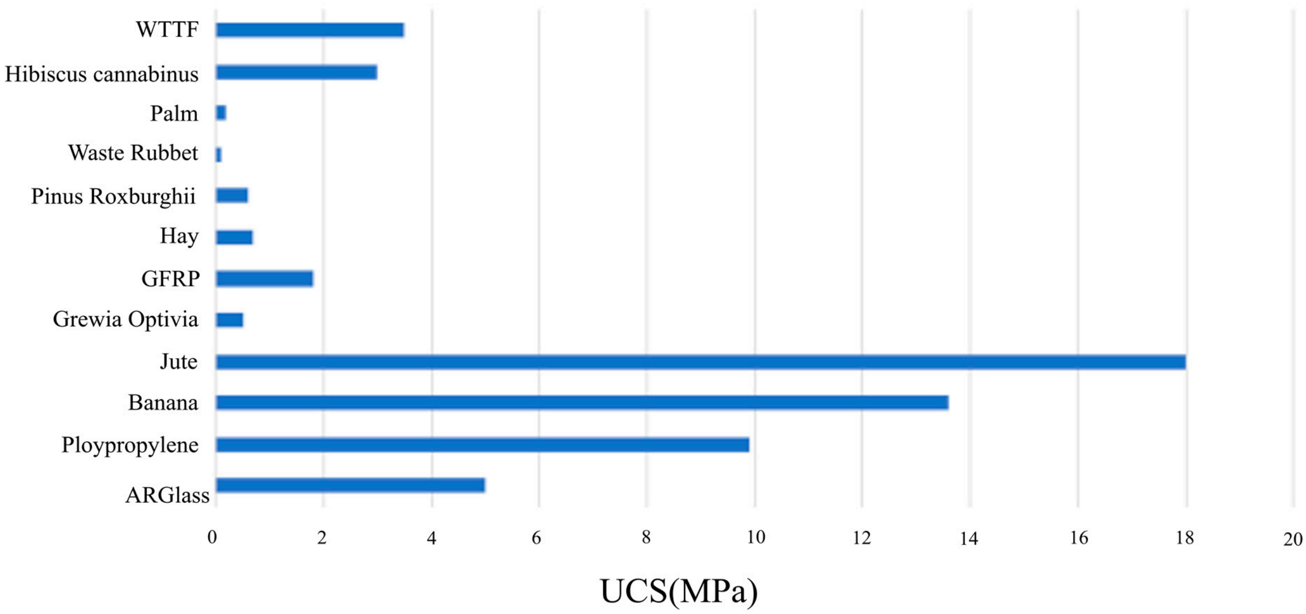


Figure 14. Effect of fiber addition on compressive strength. Adapted from references [143–150].

4.2.2. Effect of Component Optimization on Deformability

Numerous studies have indicated that employing fiber-modified earthen materials can not only enhance their strength but can also effectively augment their deformability [143,151]. These enhancements arise from the bridging action of fibers when cracks form, redirecting loads to the cracks and impeding their propagation, thus ensuring material ductility [152]. Figure 15 presents the influence of different natural and synthetic fibers on the ductility of earthen materials, clearly indicating the notable effectiveness of discarded tire textile fibers in enhancing ductility. This phenomenon is attributed to the twisting of rubber sheets and fibers, resulting in the formation of grooves and protrusions on the fiber surface. Consequently, this surface texture enhances the interaction between the soil and fibers [153]. Additionally, studies by Prabakar J, Pullen QM, and others [154–156] involved the modification of earth with plant fibers such as sisal, corn husks, and coconut fibers, and the analysis revealed that fibers inhibited crack propagation before specimen cracking, resulting in good ductility. Yang et al. [157] proposed adding bamboo reinforcement to wall structures and placing wooden pads under rafters to enhance overall mechanical performance. The results showed that adding bamboo reinforcement reduced the tensile stress of the soil, slowed down soil deformation, and thus improved overall performance. Pitthaya et al. [158] investigated the effects of seven different fibers as modification materials on the flexural performance of compacted cement-fibered sand (CCFS) at varying content levels (0.5%, 1%, 1.5%, and 2%), while analyzing the interaction mechanism between fibers and cement–sand interfaces through microanalysis. The results showed that 50 mm steel fibers exhibited the best flexural performance, while relatively short 12 mm polypropylene fibers exhibited poorer flexural performance. M. Mar Barbero-Barrera et al. from Spain [159] studied the effect of using three types of pine needles commonly found on the Iberian Peninsula as plant fibers added to adobe. The results demonstrated that these plant fibers not only controlled crack formation during drying but also provided good resistance and deformability to the adobe.

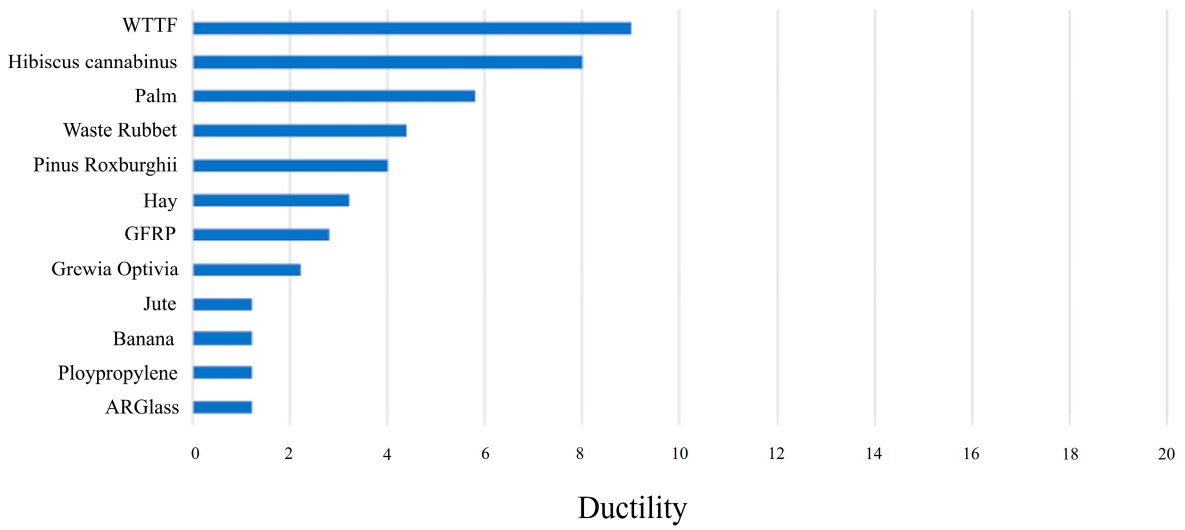


Figure 15. Influence of fiber addition on ductility. Adapted from references [143–150].

In summary, component optimization shows positive effects on earthen materials. While its effects might not be as immediately noticeable as those of chemical modification, the long-term benefits and environmentally friendly nature of component optimization make it a highly regarded improvement choice for enhancing the performance of earthen materials. This trend not only reflects the pursuit of more sustainable and environmentally friendly building materials but also brings new opportunities and prospects for the application of component optimization methods in both academic and practical fields.

4.3. Composite Modification

To fully enhance the performance of earthen materials, researchers often use composite modification in practical research and applications, combining both component optimization and chemical modification methods. This approach is realized through diverse combinations, including "inorganic binder + organic fiber," "inorganic binder + modifier," and "inorganic binder + organic fiber + modifier," among other variations [25].

Zhang et al. [160] used cement, lime, sand, and rice straw as modification admixtures to conduct compression tests on 120 samples of earth and modified earth. The results showed that the composite modification significantly improved the compressive strength and ductility of earthen materials, and lime was not suitable to be added to the soil as an additive alone. In a similar study, Kong et al. [161] employed native soil from the Chongqing region as the base material and utilized rice straw and slag as modification materials to create various proportions of earthen specimens. The study revealed that adding an appropriate amount of rice straw and slag both effectively enhanced the strength of earth. Notably, the chemical modification effect of slag outperformed the component optimization effect of rice straw. Li et al. [162] introduced modification materials such as hay reinforcement, fly ash, and cement into earth. Through orthogonal experiments and other methods, they systematically studied the variation of block strength under different dosages of each modification material and proposed the optimal mix design for modified earthen materials. Gomes, M.I. et al. [163] undertook experimental investigations employing binding agents (lime, cement) and plant fibers (hemp, flax) as soil modification agents. The results of the tests revealed that the inclusion of fibers exhibited favorable adhesion to the soil, mitigating crack propagation and thereby enhancing its mechanical attributes. Nevertheless, the introduction of fibers resulted in a decelerated drying process of the mortar, potentially posing a detrimental effect on the enduring durability of the earth structure. Shen et al. [164] employed desulfurized gypsum, lime, fly ash, and plant fibers as supplementary materials for modification experiments. They investigated the impact of these admixtures on the strength and durability of earthen materials and conducted an analysis of the micro-mechanisms of earthen materials using scanning electron microscopy. Their findings indicated that alterations in pore structure were the underlying cause for the improved shrinkage performance of earthen materials. Additionally, they identified the reinforcement of clay bonding strength as the fundamental factor behind the enhancement of both strength and erosion resistance. Additionally, the reinforcement of clay bonding strength contributed to improved strength and erosion resistance. Liu et al. [134] found a notable enhancement in compressive strength when combining cement and gravel, emphasizing the advantage of composite mixing for earthen material modification.

To summarize, given the constraints of singular modification approaches, composite modification has gained widespread acceptance in practical applications. This approach integrates the benefits of both chemical modification and component optimization, optimizing the pore structure of earthen materials and enhancing the bonding between particles, thereby improving the mechanical and durability properties of the material. This meets the performance requirements of modern construction for earthen materials.

5. Research on Thermal and Moisture Performance

Modern architecture demands not only favorable mechanical properties in building materials but also excellent thermal and moisture performance in accordance with green building principles. Ignoring the thermal and moisture characteristics and focusing only on the mechanical properties and durability of earthen materials will greatly limit the further development and application of these materials [165]. Thus, to ensure the enhanced utility of earthen materials, there is a pressing need for intensified research into their thermal and moisture characteristics.

5.1. Thermal Performance Research

In practical applications, modifications are frequently employed to enhance the mechanical robustness and durability of earthen materials. However, such modifications can exert a notable influence on the thermal behavior of earthen materials. Certain researchers [146,166–169] have investigated the thermal attributes of modified earthen materials through the incorporation of fibers like barley straw, Hibiscus cannabinus fibers, millet waste fibers, and date palm fibers. The outcomes reveal that an augmentation in both fiber quantity and length results in a marked reduction in the thermal conductivity of the modified earthen materials, as illustrated in Figure 16. This decline is attributed to the presence of fibers, which yield a diminished bulk density and an augmented presence of air voids, thereby curtailing heat conduction. Thus, fiber-based modification holds the potential to heighten the insulation efficacy of earthen materials. Conversely, contrary results reported by certain researchers [170–172] indicate that the incorporation of cement and other cementitious materials leads to adverse effects on the thermal performance of earthen materials. The hydration products of cement tend to occupy void spaces within the earth, resulting in a reduction in porosity and subsequently leading to increased heat conduction. Consequently, an increase in cement content will result in a higher thermal conductivity of earthen materials, consequently reducing their insulation performance.

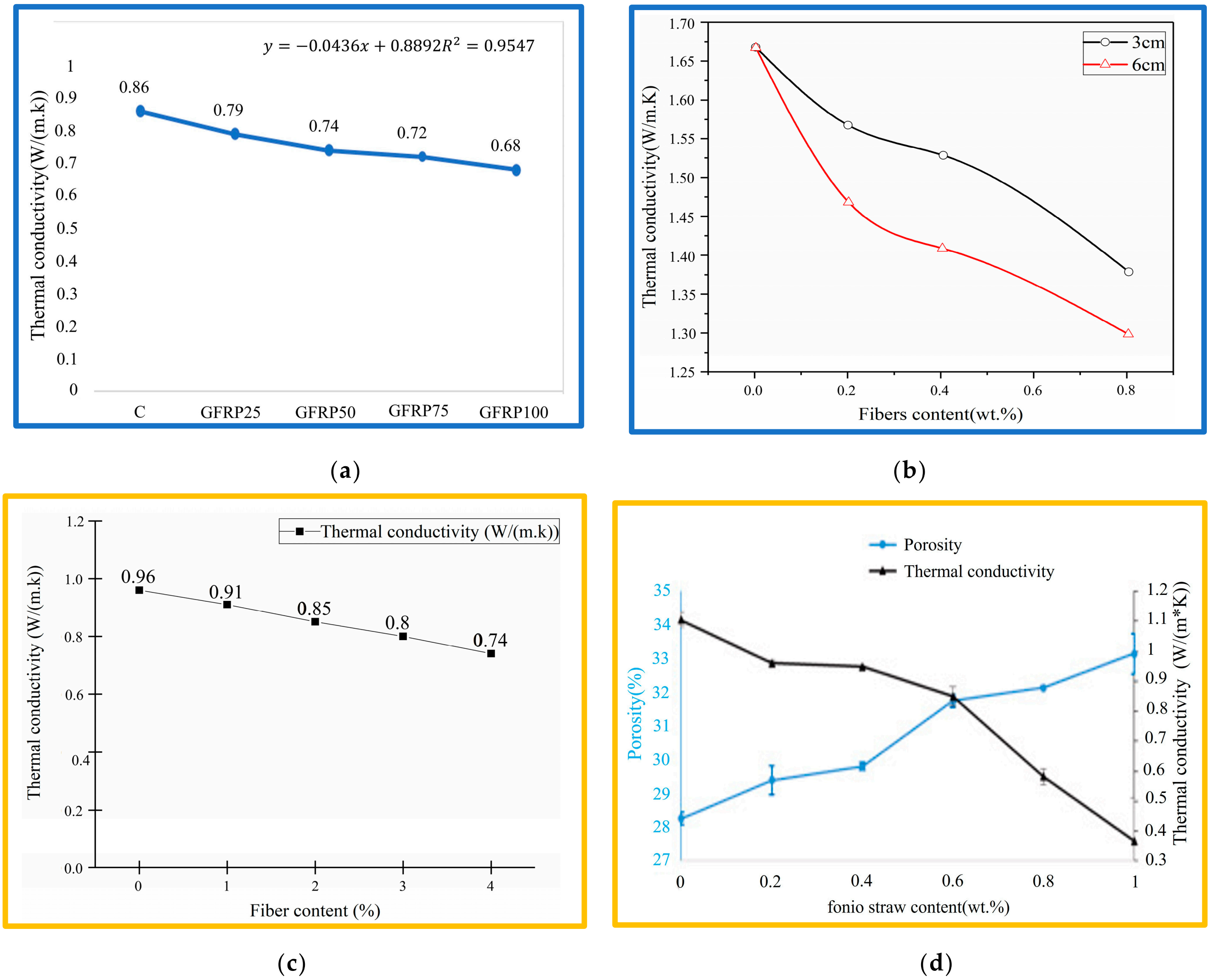
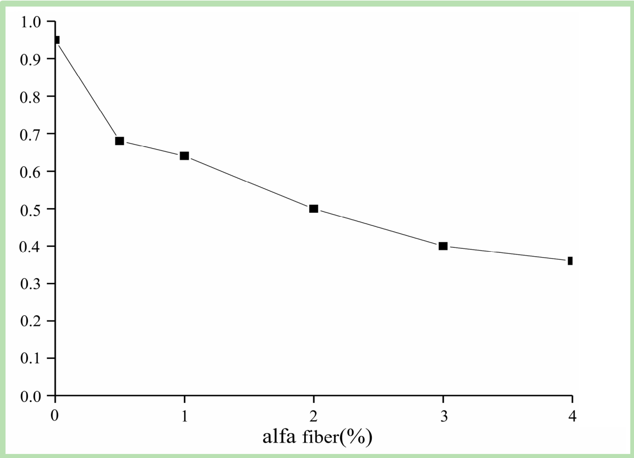
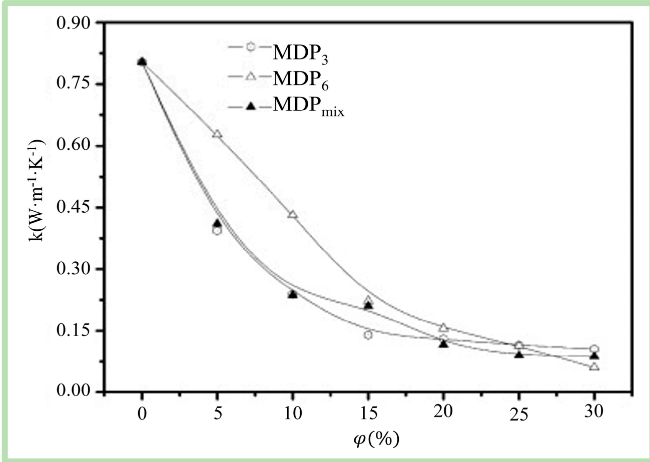


Figure 16. *Cont.*



(**e**)



(**f**)

Figure 16. Thermal conductivity with different fiber additions [146,166–170]. (**a**) Glass fiber [146]; (**b**) Hibiscus cannabinus fibers [169]; (**c**) Millet waste fibers [167]; (**d**) Fonio straw [168]; (**e**) Alfa fiber [169]; (**f**) Date palm fibers [170].

Apart from modified materials, scholars have also explored the impact of factors like bulk density, moisture content, and mineral composition on the thermal performance of earthen materials. Bulk density, as a key parameter, significantly affects the thermal conductivity of earthen materials. Lower bulk density observed by Mansour and Liu [173,174] generally translates to higher porosity and increased air voids, reducing heat conduction pathways and enhancing insulation performance. Hall and Tang [175,176] studied the thermal conductivity of compressed earth bricks and found that higher moisture content increased the material's thermal conductivity. Water has relatively high thermal conductivity, so when there is more moisture in the material, heat conduction increases, lowering its insulation performance. Apart from bulk density and moisture content, mineral composition has also been shown to play a crucial role in the thermal performance of earthen materials. Liuzzi and Cagnon [177,178] compared the thermal conductivity of bricks from different regions and found that differences in mineral composition had a significant impact on the thermal conductivity of the bricks. Earthen materials with high thermally conductive minerals (such as iron and aluminum) have higher thermal conductivity because these minerals are more effective at transferring heat, enhancing the overall heat conduction capacity. Conversely, earthen materials containing low thermally conductive minerals (such as silica and quartz) exhibit lower thermal conductivity due to their poor heat transfer capacity.

5.2. Moisture Performance Research

Relative to the thermal performance of earthen materials, research on their moisture performance remains relatively limited both domestically and internationally. Ashour and Taallah [179,180] highlighted that the introduction of fibers into earth tends to raise its equilibrium moisture content, suggesting that modified earthen materials with fibers possess higher moisture absorption capacities. In contrast, the incorporation of cement, lime, gypsum, and other cementitious materials reduces the equilibrium moisture content of earthen materials. This phenomenon can be explained by the fact that the presence of fibers increases the material's pore space, enhancing its moisture absorption capacity. On the other hand, cementitious materials fill the pore space in earth, thereby reducing its moisture absorption capacity. Shang et al. [181] similarly identified that the equilibrium moisture content of unmodified earthen materials is considerably higher than that of earthen materials modified with cementitious substances. This observation implies that earthen materials inherently possess exceptional moisture absorption and desorption characteristics, which tend to diminish following modification. Gypsum-modified earthen materials excel in terms of equilibrium moisture content, closely trailed by lime-modified earthen materials. Xia et al. [182] noted that under isothermal conditions with a relative humidity of 52.89%, the equilibrium moisture content of modified earthen wall materials notably increases with higher cement content. Conversely, with increased lime, fly ash, and moisture content, the equilibrium moisture content displays a trend of initially decreasing and subsequently increasing. Hu et al. [183] explored the use of steel slag from iron and steel plants as modified admixtures, uncovering that such additives not only improved mechanical properties and durability but also maintained micropore capillary effects, resulting in superior humidity regulation. Additionally, Saidi et al. [170] studied the moisture adsorption isotherms of compressed earth bricks with different modifiers and found that the addition of cement or lime reduces the water vapor permeability of earthen materials.

In addition to studying the influence of modified materials on the moisture performance of earthen materials, some scholars have explored the effects of density, capillary action, and environmental conditions on this aspect. McGregor et al. [184] studied the moisture adsorption isotherms of compressed earth bricks with different modifiers and found that the addition of cement or lime reduced the water vapor permeability of earthen materials. Additionally, Zhang et al. [185] observed that, with increasing relative humidity, the dry pores on the surface of compressed earth bricks tended to adsorb water vapor molecules from the surrounding environment. This occurs because water vapor molecules exhibit stronger adsorption forces on the surfaces of dry pores, leading to their absorption into the pores, consequently increasing the moisture content within the pores and improving the material's moisture performance. In contrast, Jiang et al. [186] demonstrated that when indoor relative humidity remains constant and increases, the interior surface of the wall absorbs more moisture, resulting in an increase in the average moisture content of the wall. This is because as indoor temperature rises, the difference in water vapor pressure between indoor and outdoor environments increases, driving more moisture to enter the interior of the wall, thereby enhancing the moisture performance of the wall.

In conclusion, the current standardization level of experimental schemes for evaluating the moisture performance of earthen materials is relatively low, making it somewhat difficult to compare results. However, considering the excellent moisture performance of earthen materials, it is anticipated that exploration and development of new types of building products could be carried out, reducing the adverse impact of construction on the environment and creating more comfortable and efficient indoor environments. Therefore, for the design and application of such building materials, in-depth research into their thermal and moisture characteristics is of the utmost importance. This will provide crucial scientific support for future sustainable architecture and environmental design.

6. New Perspectives

Earthen materials, as a natural and environmentally friendly construction resource, play a crucial role in the sustainable building industry. To explore potential future directions, it is essential to comprehensively consider advancements in their thermal properties, ecological characteristics, structural mechanics, and reuse technologies to achieve broader applications and comprehensive sustainability.

Firstly, leveraging the advantages of earthen materials in thermal performance, establishing a lifecycle-based carbon emissions' calculation model and decarbonization methods are paramount. These models should comprehensively assess the carbon emissions throughout the lifecycle of earthen materials—from harvesting, production, use, to disposal—and propose targeted emission reduction strategies. Integrating circular economy principles by reducing raw material consumption, optimizing production processes, and enhancing material reuse rates can significantly minimize the carbon footprint of earthen materials across their lifecycle. Secondly, while maximizing the retention of the green ecological properties of earthen materials, there is a need to enhance their structural mechanics through material modifications. This endeavor aims to strike a balance by preserving their natural attributes while bolstering their performance in diverse engineering environments. Utilizing modern technological means for nano-level material modifications can elevate the durability, compressive strength, and weather resistance of earthen materials, thereby expanding their application scope. Simultaneously, integrating earthen material modification techniques with the reuse of construction waste holds promise in expanding their technological applications, driving research into green recycled materials. By effectively integrating and utilizing discarded construction materials, novel high-performance green recycled materials can be created, promoting not only resource recycling but also propelling the construction industry towards more eco-friendly and sustainable practices. However, to realize the aforementioned potential directions, one of the current challenges—lack of standardized testing and evaluation for earthen materials—needs addressing. Future research should prioritize addressing this issue, establishing comprehensive and scientific testing standards and evaluation systems for earthen materials, thus fostering their broader applications.

In summary, the future development directions for earthen materials encompass advancements from carbon emission calculations to enhancing structural mechanics and innovative application of reuse technologies. This comprehensive development trajectory will bring forth greater possibilities in the field of green construction, propelling the construction industry towards a more environmentally friendly and sustainable future.

7. Conclusions

The rapid development of urbanization and modernization presents a significant challenge for earth construction today. As environmental consciousness deepens, there is a growing interest among people in buildings that possess ecological value, consequently garnering increased recognition for earth construction's advantages. This article, by consolidating the current research status of earthen materials domestically and internationally, highlights:

(1) Enhancement of engineering mechanical performance while preserving the thermal and moisture characteristics of earthen materials. Future modifications should target comprehensive performance improvements, not only elevating the mechanical and durability aspects but also holistically considering the effects of modifications, emphasizing the overall enhancement of building performance metrics like resistance to dry–wet cycles, thermal insulation, and heat retention. This contributes to heightened energy efficiency and indoor comfort in constructions.

(2) Application in non-load-bearing structural components of buildings. Deploying earthen materials in load-bearing wall materials often falls short of meeting contemporary architectural demands. Conversely, employing earthen materials in non-load-bearing walls, insulation, and heat retention material areas allows for a more effective utilization of their inherent features such as insulation, moisture regulation, and thermal properties.

(3) Emphasis on research and construction combining local resources in practical application engineering. Currently, most studies are either in the stage of theoretical exploration or improvement research. To effectively apply earthen materials, targeted research is imperative, focusing on local soil resource characteristics, modification methods, performance, durability of earthen wall materials, as well as environmental and economic indicators.

(4) Varied significance of the economic aspect of earthen materials in different scenarios. When selecting earthen materials, a comprehensive consideration of diverse factors is necessary, balancing economic viability with other elements pertinent to specific application contexts. This facilitates the optimal utilization of earthen material advantages and propels their extensive application across different domains.

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