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Review

A Review of Ant Nests and Their Implications for Architecture

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Abstract: This paper discusses the latest progress in research on ant nests and explores innovative scientific concepts associated with underground ant nests from the perspective of bionics. The methods used by scholars to study the structure of ant nests and the interaction between the structure itself and the individual ants are investigated. The structural characteristics of the ant nest, its internal environment and ventilation characteristics are discussed in detail. In addition, this paper presents an innovative project in which the effect of underground ant nests on soil geotechnical properties and the effect of calcined ant nest soil powder, from the perspective of civil engineering, are addressed. Practical examples of the application of the structural and inter-relational aspects of subterranean ant nests in the field of architectural bionics are also provided, from the perspectives of construction, morphology, function and material. This review attempts to integrate civil engineering, architecture and biology, enlighten architects and biologists on converging their thinking, provide new ideas regarding underground ant colony nests, and provide references for long-term human habitation.

Keywords: civil engineering; architecture; biology; underground ant nests; structure; interaction; calcined ant nest clay powder (CANCP); compressive strength; bionics; ventilation

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1. Introduction

Humans have long sought inspiration from the natural environment. By observing and learning from different creatures, we have achieved many feats beyond the capabilities of nature. In nature, a variety of simple insects can build complex and dynamic structures, and the mechanisms behind these structures has become a hot topic for researchers. Scientists and engineers are hopeful that they might use their understanding of these intricate and coordinated behaviours, from the construction of social insect nests to the relationships between individual insects in insect collectives, to solve human-related issues.

The intricacy and diversity of social insect structures are evocative of humans [1]. However, they are constructed by completely different rules. Unlike man-made structures, which are usually made up of characteristic and standardised units assembled in exact sequence, more irregular parts make up social insect structures, and their assembly is the result of self-organising distributed processes, with little or no supervision [2,3]. As a result, they are less standardised in structure, but more able to adjust conformation to changes in conditions of location [4]. The architectural field has been very interested in the parallels and contrasts between structures built by social insects and those built by humans [5,6]. Since ancient times, designers and architects have drawn inspiration from the natural world. In the 19th century, biology and architecture came into contact, which had a significant impact on how people thought about design [7]. Architects are now investigating self-organising phenomena and emerging forms of living things to reconsider the way constructions and urban areas are created, by imitating the computing capacity of natural systems [8].

Ants are excellent architects in the animal kingdom. The activities of "design", "material selection" and "construction" of their nests are full of magical secrets. After hundreds of millions of years of survival of the fittest, the nests of each species of ant are generally characterised by reasonable structure and good mechanical performance, and also reflect the law of "obtaining large and solid living space with the least amount of material". The complex underground ant colony nest system is large in scale, stable in internal environmental characteristics, has excellent ventilation, appropriate humidity and temperature, and makes use of natural barriers, such as thin grasses, trees, sand and stone, around entrances and exits, as well as having good physical structure, resistant to pressure, water, heat and moisture. Ants have very strict requirements on the size, weight, lustre and colour of the building materials for the nest, such as soil particles. As social insects, ants are responsible for the site selection and materials selection of their nests, the design of the whole nest, organising and coordinating the grand construction process, and managing the nest. This series of biological processes have triggered various architectural experts to think about the basic performance of the underground ant colony nest structure, in terms of the following: carrying capacity, ensuring constant temperature and humidity in the living environment, completing the large-scale, building behaviour, and the special material properties of the soil of the ant nest. Understanding these aspects of ant nest structure can inspire human architecture and improve human ecological bionic building materials.

With the above issues in mind, this review attempted to integrate civil engineering, architecture and biology, to enlighten architects and biologists in converging their thinking, to provide new understanding of underground ant colony nests, and to provide references for human long-term residences.

2. Biological Perspective

2.1. Underground Ant Nest

2.1.1. Research Methodology

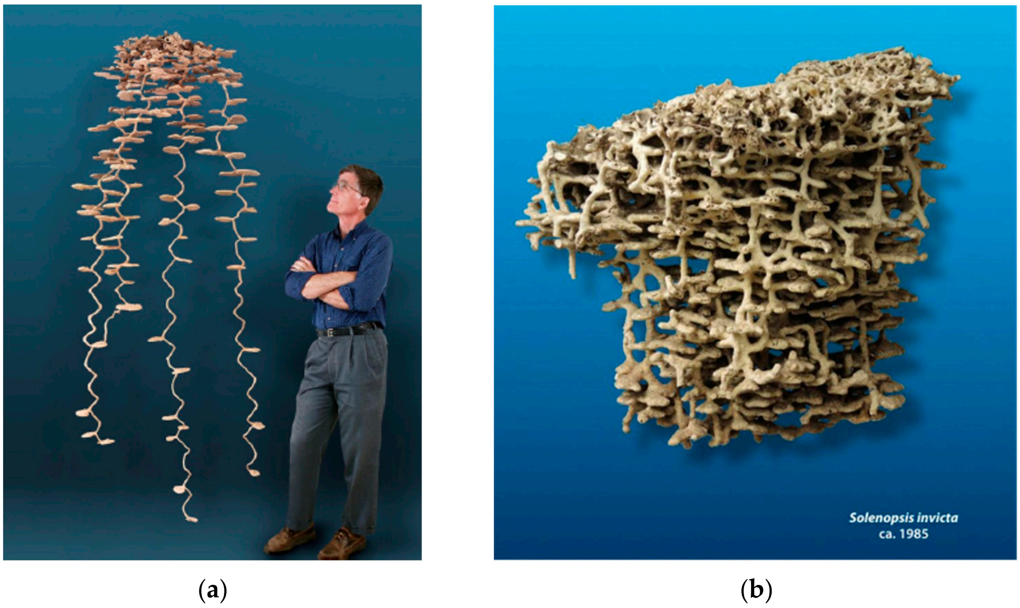
The structure of ant nests has rarely been carefully and quantitatively studied, largely because most ant nests are underground. Ant nests are generated via earth removal, rather than above-ground build, and may be based on various behavioural programmes, in contrast to well-studied wasp and bee nests. Most publications only give brief verbal descriptions or crude drawings premised on excavations, and rarely include quantitative details of the collective distribution of ant colonies or the construction of ant nests [9]. The fact that ants dig underground nests was reinforced in studies by Tschinkel (2004) [10] and Moreira et al., (2004) [11]. Most ant nests are made up of two fundamental components: a vertical axis and a horizontal chamber. Variations in the quantity, size, shape and order of these fundamental components result in the architectures typical of the species [9].

Underground ant colony nests are comprised of voids generated in the soil substrate and are located below ground level, making them difficult to observe and measure. Although researchers can easily excavate nests from some soil, it is difficult to effectively make the voids visible so as to acquire a complete, realistic, and accurate model of ant nest structure. This is the first problem to be solved. Walter R. Tschinkel proposed two methods to study ant nest structure in his research [12].

The first method required digging a pit next to the nest, starting at the top and exposing only one nest at a time. The orientation and depth of each exposure were documented, the contents were collected for subsequent measurement and counting, and the shape was traced on transparent acetate paper. Tschinkel used this approach to thoroughly excavate and count 35 Florida harvester ant nests (Pogonomyrmex badius), that ranged in depth from 2 to 3.5 metres and had 150 chambers [13,14]. The approach rendered 2D contours and geographical distribution of the horizontal chambers reasonably well, and generated a detailed record of the distribution of members in the group inside the nest, but did not record the vertical tunnels connecting the horizontal chambers.

The second method was first proposed by Williams et al. in 1988 [15]. This method required filling ant nests with thin orthodontic plaster slurry to produce three-dimensional renderings of potentially perfect nest gaps. The hardened castings were dug up and then reassembled into finished castings. To reassemble, the chamber was supported by steel rods inserted into holes in the backplane. When the tunnel diameter was large, the dilute slurry probably filled the entire nest to 3 m depth. However, in the case of narrower tunnels, the gypsum slurry possibility ceased to flow at a moderate level, in which case it might need to be poured several times. All castings were formed by filling cavities in the nest. The thin orthodontic gypsum slurry used for casting was best suited to very sandy soil, which could harden it. Heavy clay would not allow air to drain out of the chamber and so would create incomplete plaster filling and voids.

Tschinkel produced and rebuilt well established underground nests for nine ant species in the Apalachicola National Forest in northern Florida by using the plaster casting approach. Only the Pogonomyrmex badius nest [10] and the Solenopsis invicta nest [16] are used as examples in this review, and are shown in Figure 1.



(**a**) (**b**)

Figure 1. A plaster cast of (**a**) Pogonomyrmex badius nest and (**b**) Solenopsis invicta nest.

With advances in technology, castings of subterranean nests have yielded precise reproductions of the hollow chambers that compose the nests [9]. Tschinkel's 2010 study described methods and equipment for the development of several different mould materials (including toothpaste, molten aluminium, molten zinc, paraffin wax, etc.), as well as their advantages and limitations [17]. Toothpaste, as the initial material used, has the advantages of low price, ease of use, less required equipment, and fine casting. However, toothpaste is ineffective in casting nests with extremely small tunnels, and the castings invariably break up when excavated. As a result, the pieces need to be transferred to a laboratory, dried, and bonded together with epoxy resin. Regarding gypsum as the mould material, as with paraffin (see below), this material can capture ants where they are at the time of casting, as the mould material approaches the chamber from the shaft, sweeping chamber items towards the chamber's outer perimeter. Plaster as the mould material can be disassembled after it has been analysed and photographed, and the plaster dissolved, by putting the pieces in fine mesh bags and putting these in flowing water. This process takes 4–6 weeks and, when it is finished, the ants buried in the plaster may be retrieved. Unfortunately, ants are generally split into bits, and only a small percentage of ants are retrieved (an example of plaster casting is shown in Figure 2A). Paraffin as the mould material has the advantage of requiring only simple equipment, and, if the casting is melted, buried ants can be recovered quickly and are usually intact. Considering that wax is a delicate substance, the downside is that the casting could perhaps bend and distort. A more severe downside is that the melted paraffin wax can seep into the earth, absorbing it and mixing it into the casting. As a result, the casting has much more hollow space than the interior (Figure 2D shows an example of a paraffin casting). The obvious advantage of aluminium for mould casting is that it is very light and strong, often resulting in unbroken castings. The major downsides are that ants cannot be retrieved from casts made from aluminium, a lot of equipment is required and there are safety considerations (an aluminium casting example is illustrated in Figure 2B). A nest with tiny channels, in which heat quickly dissipates, cannot be easily cast with aluminium because aluminium's melting temperature (659 °C) is higher than other metals, such as zinc (420 °C). Zinc is a superior alternative for such nests because zinc has a lower melting point and is ideal for nests with narrower tunnels and finer construction. Zinc, in fact, may enter shafts as tiny as 1 mm, or even smaller (a zinc casting example is illustrated in Figure 2C). The drawbacks of zinc in casting are that it is difficult to obtain, dense and brittle, and, if overheated, can readily ignite and burn, leaving a thin coating of zinc oxide fluff that prohibits pouring. Since huge zinc castings are exceedingly heavy, and might even shatter, due to their own weight, large castings should be produced from aluminium. Metal castings, such as zinc castings, are excellent for analysing buildings and exhibits but not for correlating architectural details with ant populations. Most metals either freeze before entering the nest or melt at temperatures that are too high to be valuable. Lead is an exception. Although it is costly and hazardous, its fragility and extreme density mean it may be useful for specific applications, such as ant nests with extremely thin axes. Another option is tin, but just like lead, it is exceedingly costly and has no scrap origins.

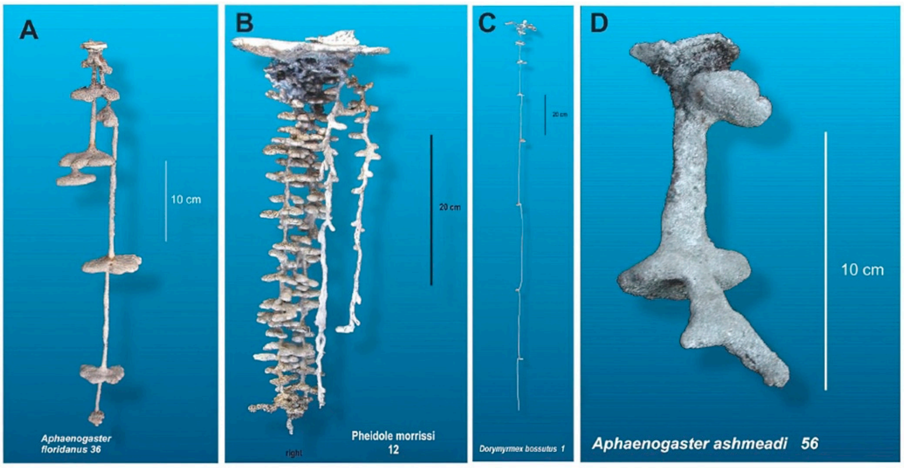


Figure 2. Examples of casts made of different materials. (**A**) Aphaenogaster floridana, dental plaster; (**B**) Pheidole morrisi, aluminium; (**C**) Dorymyrmex bossutus, zinc; (**D**) Aphaenogaster ashmeadi, paraffin wax.

2.1.2. The Interaction between Structure and Individual

Several fields have recently begun to explore how physical structure influences the interactions between individuals and emergent collective outcomes. The idea of how the built environment impacts interactions, and the ensuing collective behaviour, encompasses a diverse variety of academic subjects and majors, including physics, biology, architecture, and social science. The wide span of disciplines and the intersection of multiple majors make it difficult for scholars to study in this direction. In this regard, Pinter-Wollman's integrated methods and theories point the way to our understanding and research of these complex forms of cooperation [18]. Pinter-Wollman proposed three steps: quantification of structure, quantification of motion within the structure, and merging space and motion. The methodology of biology, physics, and architecture is reviewed in order to create a universal library of approaches to allow multidisciplinary research to explore the influence of the built environment on collective behaviour.

Studies have already shown that ants performing similar tasks interact with each other more frequently [19]. The interaction rate is an important regulatory signal that activates and inhibits workers from performing specific tasks [20]. Due to the isolation of activities within the nest, specialists in a certain set of tasks are more inclined to interact with other workers who exhibit comparable behavioural patterns, which enhances their capacity to exchange pertinent information about their favoured jobs. Additionally, as workers age and adopt new behavioural patterns, they may progressively move inside the nest to locations that are more in line with their new preferences. Pinter-Wollman showed that nest structure affected the collective behaviour in Harvester ant colonies [21]. By utilising network analysis to examine nest structure and link it to group foraging in real environments, we can see how nest structure influences collective behaviour. The collective behaviour of ant colonies results from interactions between worker ants. Harvester ant colonies moderated their foraging through interactions between worker ant antennae, which took place in the chamber most closely adjacent to the nest entrance, also referred to as the "entrance chamber" [22]. The interaction locations inside the entrance were spatially heterogeneous [23], establishing the structure of the interaction network and affecting who interacted with whom [24]. The speed at which information was transferred by groups, for example, about food sources, was affected by network topology. Therefore, for the regulation of collective behaviour, spatial constraints that formed interactions within the nest might influence the collective behaviour of harvester ants.

This research uncovered a link between colony function and nest construction, shedding light on how building formed collective outcomes through affecting social interactions. The findings implied that the dynamics of collective foraging were determined by the structure at the top of the nest rather than the quantity of ants the nest could house. The diversity of places where ants could be recruited to work outdoors rose as the quantity of chambers, linked by the entrance chamber, increased, altering the available foragers in the entrance chambers and, thus, the regulation of foraging [23]. Furthermore, the greater the number of connections between network nodes (nest chambers), the quicker information (for instance, regarding new food sources) disseminated across the network, resulting in faster recruitment. Eventually, the greater redundancy of connections between chambers gave alternate avenues for ant recruitment from within the nest, boosting its robustness. Further laboratory studies to prove a causal link between nest structure and collective behaviour is guided by these field data. Previous research demonstrated how nest construction might regulate gas exchange or temperature [25] and how the age distribution of the nest's workers buffered the physical environment [14]. Pinter-Wollman et al. were among the first to directly link naturally occurring nest structures to the collective behaviour of the groups inhabiting them.

Taken together, ant colonies have the ability to reshape their nests through intra-group interactions as they expand in size or as environmental factors, like temperature, humidity, and light, change. Thus, the essential question is how these extremely efficient mouldable structures are constructed? How do ants interact and coordinate millions of building actions? How do ants perfectly adapt their nests to external conditions? Little research has addressed these concerns since Grasse pioneered the notion of stigmergy [26], and even less research has offered experimental validation of stigmergy. The basic principle of stigmergy is that one insect can indirectly influence the behaviours of other insects within the same collective, resulting in the emergence of coordinated collective behaviour [27]. Prior to Anais Khuong, understanding of animal–structure interactions were restricted to rudimentary two-dimensional constructions constructed by ants and other animals. Three-dimensional nest building in ants is still little analysed, and hardly any investigations have tried to link thorough quantitative descriptions of individual building behaviour to growth dynamics and the structure of the resulting nests. Understanding the construction behaviour of social insects is a provocative assignment owing to the difficulty of accessing the activities of workers inside the nest. Anais Khuong et al. used a combination of experiments and modelling to construct a 3D model to decompose coordination mechanisms at work. This was unprecedented in the field and it was the first study to address the three-dimensional nest morphogenesis of social insects using a tight collaboration between experimental and data-driven methodologies [28]. According to the findings, architectural actions were generally coordinated through two interactions: (I) stigmergic-based interactions, which controlled the amplification of sediment and the appearance of pillars at certain sites, and were attributed to pheromones added by the ants to the building materials; and (II) template-based interactions between the body of the ant and the structure being built, which governed the altitude at which the ant built a roof from an existing column. This model demonstrated that a straightforward set of interaction and construction rules might accurately mimic the major characteristics of construction dynamics, including regular column patterns, lids on columns and subsequent incorporation, and remodelling, of building structures. The study described a similar mechanism concerning self-organisation and templating in the construction and size regulation of enclosure walls in the ant Leptothor. At the same time, shared coordination mechanisms might govern the development and adaptation of nest structures in ant colonies. For L. Niger, the integration of material patterns and information provided by local pheromone concentrations expanded the abundance of stimuli that ant workers use to guide their construction activities.

2.2. Constructional Bionics of Underground Ant Nest Structures

Constructional bionics refers to the conscious or subconscious use of the idea of bionics in construction technology to innovate construction techniques, improve construction technology and perfect construction management. Ants established their own society 80 million years ago, while humans have been civilised for only 5000 years. The fact that many large human cities are plagued with urban diseases, while tiny ants managed to build complex cities with complete systems, makes one want to explore the mysteries of ant nesting and construction to inspire human constructions.

The nest construction behaviour of Camponotus japonicus was observed in a highly light-transmissive seaweed gel, as shown in Figure 3. Through observation, it was found that the queen played the role of leader and decision-maker during the nest construction process of the ants, and took the lead in the work, which determined the key aspects of the nest site selection and construction initiation. When the queen was present in the nest, two teams of ants dug down simultaneously from both directions at the top of the nest passage, always meeting in the middle of the passage, and opening it up without any measurement or calculation. When the queen was removed, two teams of ants digging down from the top of the nest in both directions at the same time could not meet in the middle of the passage, but each team opened the passage from the other side, creating two passages. The queen was, thus, the chief engineer and dispatcher of the nest, and used pheromones to control the entire construction process throughout the nest's construction period.

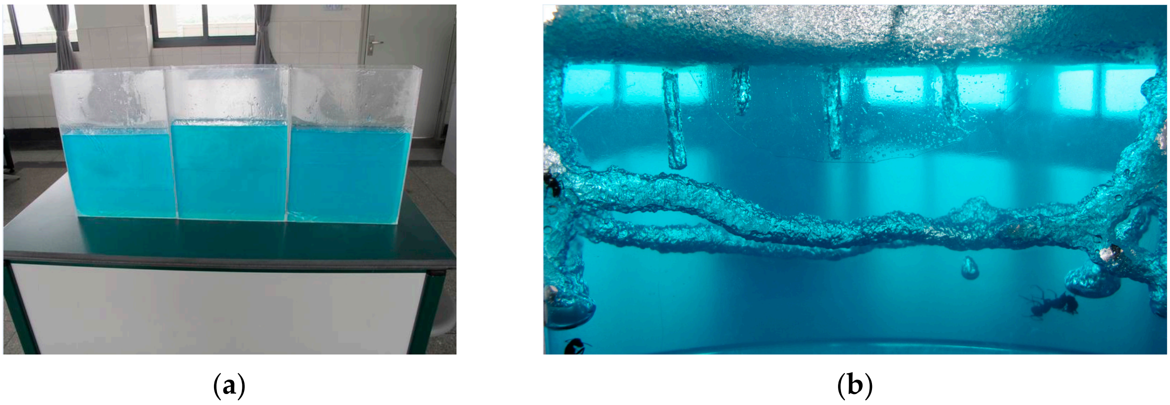

(**a**) (**b**)

Figure 3. (**a**,**b**) The process of nesting construction of Camponotus japonicus.

3. Architectural Perspective

3.1. Characteristics of Underground Ant Nest Structures

Moreira et al. [11] studied the internal and external structure of Atta bisphaerica nests by casting them in cement at Santana Farm, Brazil, as shown in Figure 4. Based on multiple castings and/or excavations conducted by Tschinkel and Moreira et al., the generality of the nest structure was confirmed, but the total size of the nest varied greatly from one population to another, ranging from a depth of 20–30 cm to a huge underground fort extending to a depth of nearly 3.5 m (Figure 1a). Although each species builds a nest typical of its species, some elements are identical. The most visible features are the vertical tunnels that connect greater or lesser horizontal chambers. However, the tunnels are varied; for example, Figure 1a, shows a helical tunnel. Variations in the shape, size, quantity and positioning of the fundamental parts result in the species-typical construction of numerous nests. The majority of this variance is due to changes in elemental properties. The consequence is that the diameter of the tunnel, the horizontal perimeter, area and shape of the chambers, the distance between chambers, and so on, may all change. As shown in Figure 1, the sum of this variation produces unique, species-typical architectures. For example, the nest of Solenopsis invicta (Figure 1b) is more complex compared to the nest of Pogonomyrmex badius (Figure 1a) as it consists of many units of chambers and tunnels, which are closely packed together. In addition, Rabeling et al. [29] studied the nest structure of the ant species Mycocepurus goeldii and Mycocepurus smithii in an agroforestry habitat near Manaus, Brazil. The two species were found to construct their nests in two distinct ways, as shown in Figure 5. The nests of the former possessed a 'tree-like' structure and those of the latter displayed a 'necklace-like' structure. The nest systems of M. goeldii and M. smithii consisted of 1–21 or 1–15 chambers, respectively, and the nest chambers constructed by workers of M. smithii were noticeably smaller than those of M. goeldii.

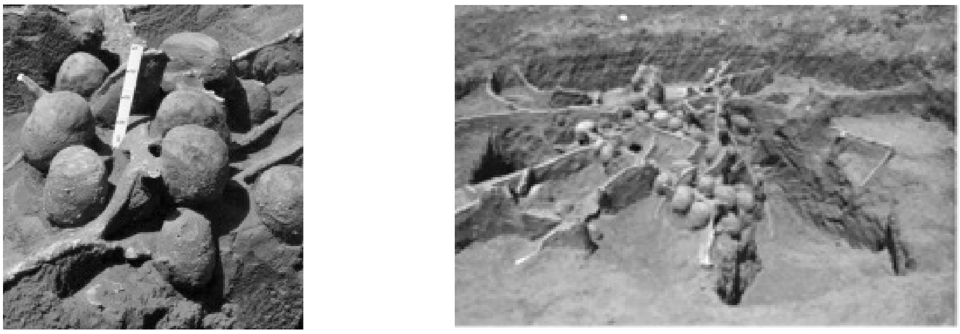

(**a**) (**b**)

Figure 4. Atta bisphaerica nest: (**a**) chamber and tunnel details and (**b**) radial distribution of foraging tunnels.

An ant's nest is built in a complex structure that contains irregular descent axes, horizontal chambers, and tunnels [30,31]. These elongated voids contain cross sections that are round, oval, or flat oval, and their long axis is normally inclined from perpendicular by 20° to 70° (rarely 90°). They are modular structures from which new axes may extend an already existing structure [32]. These distinctive topological traits of ant nests are also influenced by the life cycle and development of the colony. With growth of the community, nest excavation rates and final nest size rise. Ant nests are known to be built underground so that they can withstand loads accidentally imposed by other organisms on the surface or forces caused by natural events. The majority of current study on ant nest construction has concentrated on the nest's intricacy, namely basements, shaft nodes, and tunnels [33,34]. However, little attention has been paid to the role of structural morphology in improving the mechanical robustness of ant nest constructions. With the introduction of 3D printing (3DP) technology, academics are increasingly using it to mimic nature-inspired buildings [35,36]. We can complete the complicated building of an ant nest with great precision using 3DP technology, making it easily accessible, inexpensive, and ecologically beneficial [37]. Since 3DP technology allows for flexibility in design, complicated structures may be easily manufactured. Topological optimisation methods, which produce the greatest results by optimising the design in the appropriate constraint space, can be used to enhance the design of complicated structures [38]. In 2022, Kushwaha et al. [39] investigated the mechanical robustness of 3D-printed anthill constructions, which is currently unique in the literature. The team extracted four distinct nest types using cement casting. Three-dimensional micro-computed tomography (CT) scans were used to digitise the cement structures. A finite element method (FEM) was used to simulate the digitised structures under different loading conditions. The digital architecture was 3D printed and evaluated under uniaxial loading conditions. Following that, an innovative biomimetic solution was demonstrated using a blending of computational and experimental analysis to define the structural topology and material contributions to the strength and deformation resistance of the ant nest structure. The results showed that the abnormal mechanical robustness of ant scaffolds was caused by two distinct architectural components, namely, the main spine (core) and the secondary arms, that grew for long periods of time. The primary spines of ant nests seemed to develop in a funnel-like structure from the top to the bottom, and afterwards expanded as the surface area increases. This provided the base with the typical hourglass shape. These constructions were capable of withstanding high stress levels without suffering considerable deformation and retained their original shape. The mound branches and branch structure could endure increasing stress and deformation due to volume pressure as the surface area increased, making it a sacrificial unit for major calamities like floods and earthquakes. A robust design was demonstrated by 3DP technology and FEM simulations, and, as a result, tree-trunk geometry may be used to create civil structures.

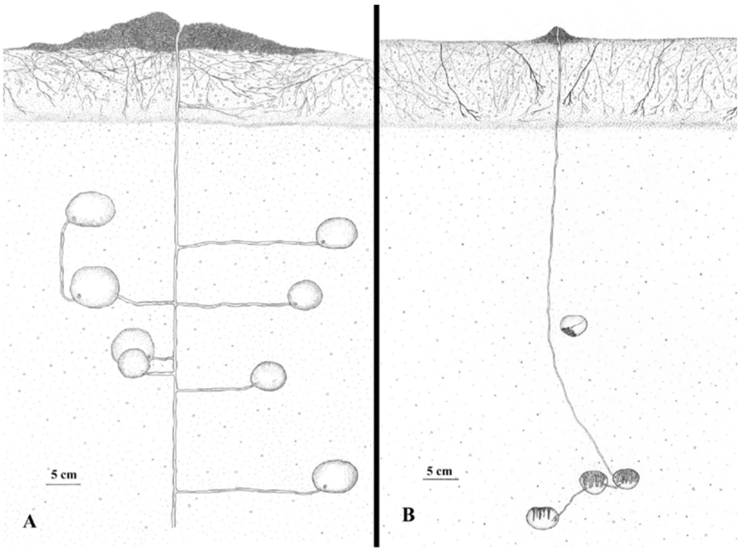


Figure 5. Two nest architectures found in Mycocepurus nests. (**A**) A Mycocepurus goeldii nest; (**B**) A Mycocepurus smithii nest.

3.2. Internal Environmental Characteristics of Underground Ant Nest

Numerous social insect species also control the microclimate within their nests to ensure constant living circumstances that are unaffected by changes in the outside environment [40]. Some leafcutter ant nests exhibit a similar phenomenon, controlling the oxygen/carbon dioxide balance by passive air movement. Kleineidam et al. [41] studied the mechanisms driving nest ventilation in a nest of Atta vollenweideri. Their research found that wind-induced nest ventilation, which drew air from central entrances, was extremely effective during the summer. However, in the fall, A. vollenweideri colonies shut the majority (approximately 90%) of the nest openings, reducing wind-induced nest ventilation. Bollazzi et al. demonstrated that leafcutter ant colonies, of several Acromyrmex species, built thatch nests at temperatures that were more stable than ambient temperatures, just like many other ants that lived in temperate climates. By changing thatch structures, such as by lowering thatch thickness or penetrating the thatch with apertures to enable heat exchange with the external world, workers could balance temporary variations in nest microclimate [42]. In addition, Bollazzi indicated that workers of Acromyrmex Heyeri created more openings in the thatch of the nest at higher temperatures in the range of 20–30 °C. When the air around the nest was dried at a constant temperature during the experiment, worker ants were observed to open holes. This suggested that A. Heyeri's workers exchanged responses related to thermoregulation in order to maintain humidity in the internal nest [43]. To keep the nest close to its ideal developmental temperature, worker ants of many ant species that dig their nests into the earth periodically shifted the nests away from, or toward, the surface when the surface warmed up or cooled down [44,45].

3.3. Ventilation Analysis of the Ant Nest

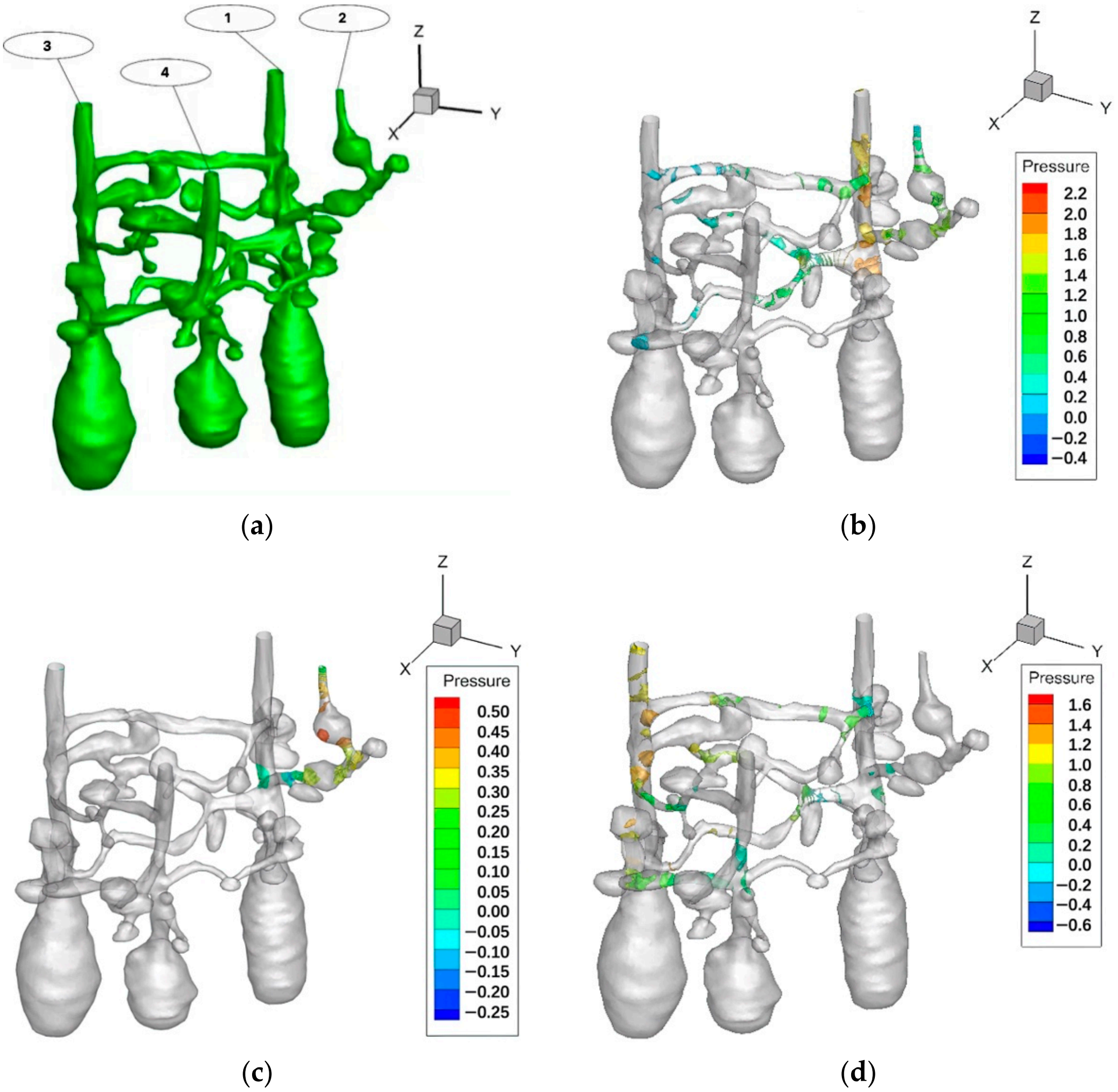
Subterranean nests of Iridomyrmex anceps were collected from different collection sites, manually cut and exposed to frozen computer numerical control (CNC) milling of the nests in the laboratory, and, then, 2D and 3D digital structural models of the nests of Iridomyrmex anceps were established (Figure 6a). Ventilation simulations of the underground nest structure were carried out using finite element analysis software (FLUENT) and the ventilation characteristics of the nest were discussed. The results revealed that the ventilation environment inside the underground nest was stable and the airflow from outside had little effect on the life of ants inside the nest. The simulation assumed that the air inside the nest was not exchanged with the surrounding soil and that air could only be circulated within the nest, with air entering through one entrance and exiting through other exits.

When inlet 1 was used as the fluid inlet, the pressure distribution inside the underground nest is shown in Figure 6b. It can be seen that after the air entered inlet 1, it mainly flowed out through inlet 2 and inlet 3, which were adjacent to inlet 1. Inlet 4 was arranged diagonally with inlet 1 and was far away, and the air basically did not flow out from inlet 4. After entering the interior of the nest through inlet 1, the air flowed mainly in the first and second layers of the nest structure and did not go deeper into the third layer of the queen chamber, and the air flowed out through the upper channels.

When inlet 2 was used as the fluid inlet, the pressure distribution inside the underground nest is shown in Figure 6c. It can be seen that, due to the small geometry of inlet 2, the air entering through inlet 2 flowed mainly to inlet 1, which was closer, and out of inlet 1, without flowing to inlets 3 and 4, which were farther away. The air flow was mainly concentrated in the first nest chamber and channel connected to inlet 1 and inlet 2, and the air did not flow to the second and third nest chambers and channels, which were farther away from the surface.

When inlet 3 was used as the fluid inlet, the pressure distribution inside the subterranean nest is shown in Figure 6d. It can be seen that the gas flowing through inlet 3 mainly flowed out of inlet 1 and inlet 4 and not out of inlet 2, as inlet 1 and inlet 4 were adjacent to inlet 3. The gas flow was mainly concentrated in the nest chambers and channels of the first and second layers, which were closer to the ground, and the gas did not flow to the deeper third layer of the structure.

The above analysis showed that when gas entered the underground colony nest from any entrance or exit, the internal gas flow mainly concentrated in the first and the second layer of nest chambers and channels which were closer to the ground, and the gas did not flow to the deeper third layer of the structure. Gases flowing in from one of the entrances and exits of the nest would preferentially flow out through the entrance and exit closer to it. When there was no exchange of air between the interior of the nest and the surrounding soil, natural winds and other gases generally did not reach the third level of the structure, the queen's chamber.



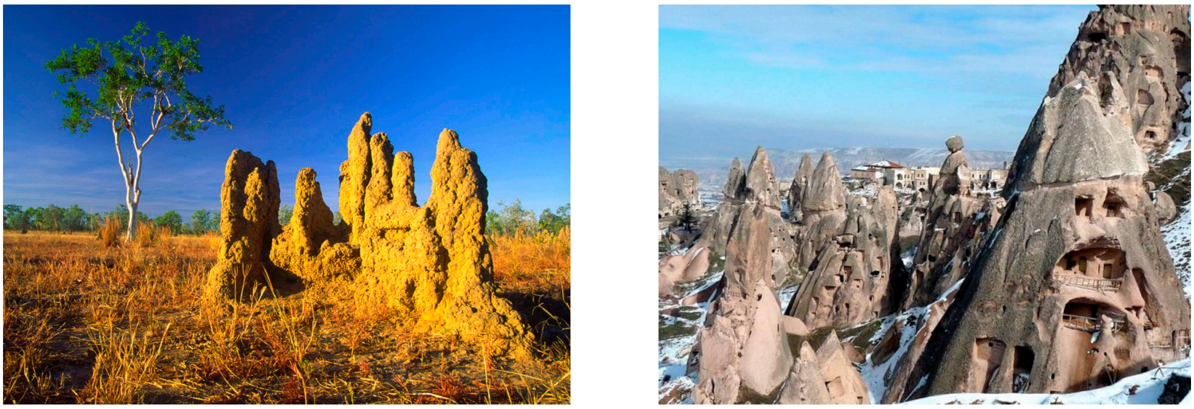
(**a**) (**b**)

(**c**) (**d**)

Figure 6. (**a**) 3D model of ant nest structure with inlets 1, 2, 3 and 4; pressure distribution inside the underground ant nest using (**b**) inlet 1, (**c**) inlet 2 and (**d**) inlet 3 as a fluid inlet, respectively.

3.4. Morphological Bionics of Underground Ant Nest Structures

In terms of morphological bionics, the underground city of Cappadocia in Turkey is a masterpiece of ant nest bionics. With churches, schools, warehouses, breweries, kitchens, wells, toilets and other amenities, each Cappadocian underground city is like an underground network of anthills that could house and provide for thousands or even tens of thousands of people for long periods of time. Two of the largest underground cities are found in Cappadocia, the Derinkuyu and the Kaymakli, which is a much smaller city than the Derinkuyu. There were eight levels of underground caves, with bedrooms, kitchens, dining rooms, wineries, stables, churches, schools and a water reservoir at the bottom of each level. From the ground level to the bottom, many ventilation holes were excavated so that the air could circulate smoothly through the underground city, even when descending to the lowest level, without any auxiliary air supply. There were not only stone staircases, but also shafts and secret passages between the various levels, and the surface exits were covered by houses and mountains, and there was even a secret passage dug between the underground city of Kaymakli and the Derinkuyu, which is ten kilometres away (Figure 7).



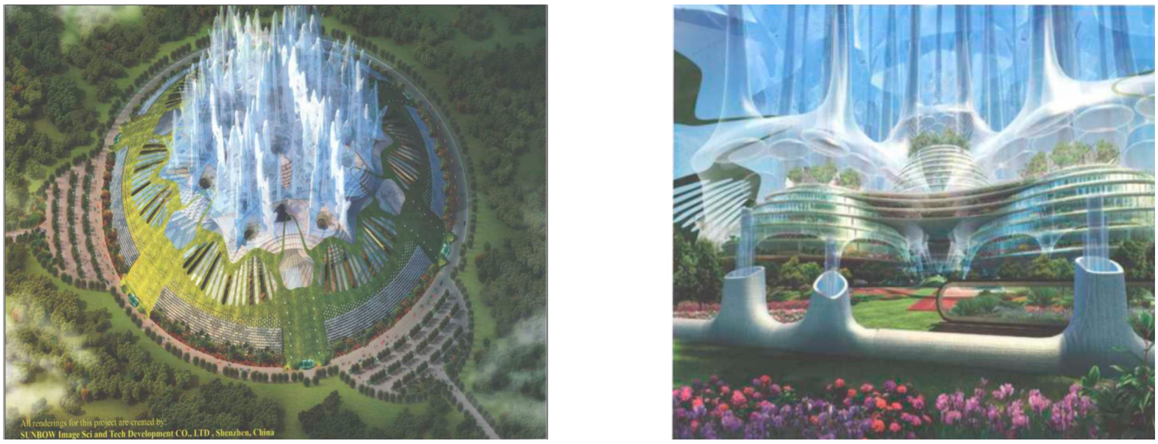
(**a**) (**b**)

Figure 7. Comparison of the morphology of (**a**) the anthill and (**b**) the rock house in Cappadocia, Turkey.

3.5. Functional Bionics of Underground Ant Nest Structures

Through an in-depth study of underground ant nests, it was found that ant nests have obvious characteristics and advantages in terms of environmental functions, such as constant temperature, moisture retention and ventilation, which are worth studying and exploring in depth.

The concept of the Global Health Centre (as shown in Figure 8), developed by the State Key Laboratory of Subtropical Building Science at the South China University of Technology in Guangzhou, China, aimed to mimic an underground ant colony nest in building a cave environment that is well insulated, hydrated and ventilated. With a diameter of 500 metres and a height of 120 metres, the cave is an apartment complex for 2000 people. The building's temperature is maintained at 18 to 22 °C all year round, based on the principle of the passive water-cooling design of an ant nest. Ants dig deeper into the underground, creating linear shafts that become the water table at the source of the underground, often forming an aquifer where the pressure of the groundwater from the aquifer collects water in the burrows dug by the ants. These water-storage burrows then become a source of cooling for the whole nest, with cool air rising when it encounters the warm bodies of the ants and other warmer nests. A series of concentric circular walls suspended from the ceiling inside the room act as cooling heat sinks, able to collect moist air and concentrate it into cooler air. In this way, the heat generated inside is allowed to rise and escape through the ventilation chimney at the top of the nest [46].



(**a**) (**b**)

Figure 8. (**a**,**b**) Global Health Centre in Guangzhou.

4. Civil Engineering Perspective

4.1. The Effect of Underground Ant Nest on Soil Geotechnical Properties

The latest studies start from the material properties of the soil itself, and provide a new approach for the comprehensive study of underground ant colony nests. Ant nest soil makes up the majority of the subterranean ant nest material. From the perspective of agriculture, scholars at home and abroad have studied the effects of ant nests or ant nesting activities on the chemical and physical properties of soil materials and their fertility. It is widely assumed that ant nesting or ant life activities alter the chemical and physical features of soil [47], which improves soil fertility. In a few cases, from the perspective of civil engineering, the research on underground soil of ant colony nests also showed that the physical, hydraulic and mechanical soil properties of ant nest soil were different from those of non-ant nest soil, and the ants' nesting or living activities changed the soil geotechnical properties. Physical and hydraulic geotechnical tests were conducted on the underground ant nest soil of Iridomyrmex anceps, commonly found in Shanghai, and the non-nest soil around the nest. The data were analysed mathematically and statistically, using one-way ANOVA and the least significant difference method to compare the differences between the two groups of data. The Shapiro–Wilk test was applied to test whether the differences between the physical and hydraulic geotechnical parameters of the ant nest soil and the non-nest soil reached a significant level, so as to illustrate the extent to which the nesting or ant life activities affected the physical and hydraulic geotechnical properties of the soil.

4.1.1. Physical Properties

The density ρ of ant nest soil was smaller than that of non-ant nest soil in the same environment and geographical location conditions, which did not reach a significant level ($p = 0.184 > 0.05$). The difference between in situ ant nest soil and non-ant nest soil was not significant. Ant nesting or living activities had an effect on soil density, but the effect was small. Ant nesting activities reduced the density of the soil because the number of dead plants in the nest soil was larger than in the non-nest soil because the nest soil was mixed with ant food, carcasses and other materials less dense than the soil, and there were holes, such as nest chambers and channels, in the nest soil.

The dry density of ant nest soil ρ_d was smaller than that of non-ant nest soil in the same environment and geographical conditions, reaching a significant level ($0.01 < p = 0.012 < 0.05$), so the difference between in situ ant nest soil and non-ant nest soil was significant, with ant nesting or living activities having a greater effect on soil dry density. Soil dry density is often used to evaluate the degree of compactness of the soil. Ant nest soils are less compact than non-nest soils due to the loosening effect of ant activity.

The water content of the ant nest soil ω was about 10% smaller than that of the non-ant nest soil in the same environment and geographical location, reaching a significant level ($0.01 < p = 0.015 < 0.05$). The difference between in situ ant nest soil and non-ant nest soil was significant, as the nesting or living activities of ants had a greater influence on the water content of the soil. Iridomyrmex anceps nests had a large volume of grass clippings and other dead plant material, which prevented quick water infiltration, meaning that water was poorly retained in the nest and channel, etc. The soil adjacent to the nest was relatively compact, and the soil infiltrated more slowly but held water well. The effect of these factors led to lower water content in the nest soil than in the adjacent soil.

4.1.2. Hydraulic Properties

The liquid limit w_L and plastic limit w_P of ant nest soils were smaller than those of non-ant nest soils in the same environment and geographical location, both reaching a highly significant level ($p < 0.01$). The difference between in situ ant nest soils and non-ant nest soils was very significant, with ant nesting or living activities having a great influence on the liquid limit and plastic limit of the soil. Ant nest soils had a larger porosity and pore ratio, larger soil particles and smaller specific surface area, which facilitated the passage of water, and gave rise to poorer soil water storage properties. Ant nest soils were looser than dry soils, and their soil clay content less, making the soil less viscous and less swollen when exposed to water, so capillary water did not rise as high, and the soil liquid–plastic limit was reduced. Soil clay content could effectively change the distribution of soil particles and water, and clay particles could influence the plasticity of soil by affecting the arrangement of soil particles. At higher clay content, coarse particles were more evenly distributed in the clay matrix, and the soil was filled with clay particles. Coarse particles were separated and favoured the orientation of the particles, and the weakly bound water content rose, thus increasing the liquid limit of the soil [48].

The liquidity index I_L was greater than that of non-nest soils in the same environment and geographic location, but did not reach a significant level ($p = 0.510 > 0.05$). The plasticity index I_P was smaller than that of non-nest soils in the same environment and geographic location, but did not reach a significant level ($p = 0.183 > 0.05$), and the difference between in situ and non-nest soils was not significant. Ant nesting or living activities had an effect on the soil liquidity index and the plasticity index, but the effect was small. The nesting and living activities of the ants had a loosening effect on the soil, and the nest chamber and channel itself softened the soil texture and increased the liquidity index. The ant nest soil had larger soil particles, smaller specific surface area and lower bound water content due to the mixing of ant secretions and soil, and the activity of the ants pushed the clay minerals in the soil to the surface, which reduced the hydration of the soil below the ground and decreased the bound water content, and, therefore, the plasticity index of the ant nest soil was lower.

4.2. CANCP

According to the current research situation, ants, through nest-building activities, change the physical and chemical properties of soil [49], which leads to redistribution of the nutrients in the soil profile [50], increases soil porosity, improves the conductivity and permeability of soil water, increases soil water retention [51], changes the bulk density of soils [52], enhances the conductivity of the soil, the nutrient content of the soil and the potential for higher yields of crops [53]. Underground ant nests also have an impact on soil chemistry, increasing the concentration of organic matter, P, N, and K [54], as well as the content of Na^+, K^+, Ca^{2+} and Mg^{2+} in the ant nests [55] and changing the pH [56]. Ant activity can enhance the release of N from plant residues, the breakdown of organic matter and the recycling of minerals and nutrients through the decomposition of plant residues [57]. The above activities can also enhance soil organic matter, particularly that of stable humic acid, which is advantageous to soil structure stability and fertility [58]. Such activities can also boost CO_2 generation [59], organic N mineralization in the soil and soil denitrification [60]. Ants can provide N contribution to their habitat by fixing nitrogen [61]. As a result, the chemical and physical characteristics of the subterranean ant nest material are significantly altered in comparison to the surrounding ordinary clay.

This series of changes provides the possibility of application of ant nest soil in engineering building materials. Elinwa et al. proposed the concept of calcined soldier-ant mound clay (CSAMC) in their 2006 study [62], which showed that replacing cement with 40% CSAMC, which is pozzolanic, reduced the heat of hydration by about 17% and sped up the setting time of concrete. When cured for more than 60 days, the mortar compressive strength of the mixture containing 10% CSAMC exceeded that of the reference mixture, and the splitting tensile strength to bending strength ratio was around 0.33. Since termites and ants do not belong to the same classification class, this study is not discussed in this review. However, the concept of CSAMC provides new enlightenment for the study of underground ant nest soil.

Ants have certain standards for the earth they need to build their nests, including weight, particle size, gloss, and colour. Underground ant nests are typically comprised of gravel and soil combined with organic materials, like dead plant remains and ant secretions, with a high clay content. The clay of subterranean ant nests is a firm, brick-like substance composed of soil particles bonded together. Natural clays often contain mixtures of nonclay minerals associated with clay minerals. The majority of natural volcanic ash exerts its activity by means of clay minerals e.g., illite, montmorillonite, and kaolinite. For every type of clay, there is an optimum range of calcination temperatures leading to the destruction of the crystal structure of the clay and the formation of alumina and amorphous silica [63]. A number of pozzolar-like active materials are appropriate for partial substitution of cement. These materials can be natural products like pozzolanic ash [63,64], solid waste and zeolite, industrial by-products like, fly ash, slag, waste glass, rice husk ash [65], broken ceramic [66] and clay brick [67], or low-energy products, like calcined termite clay [62] and calcined clay [68].

In 2019, Zhou et al. carried out a thorough investigation on the fundamental material characteristics, and associated utilisation of calcined ant nest clay powder (CANCP) [69]. Their research team calcined and ground subterranean ant nest material of the common ant Iridomyrmex anceps in Shanghai, China, and analysed it in terms of specific gravity, chemical composition, specific surface area, particle morphology, particle size distribution and volcanic ash activity index (the volcanic ash activity of CANCP was assessed by the intensity contribution of volcanic ash activity), revealing that CANCP facilitated the strength formation of mortar systems. The effect of CANCP on concrete compressive strength was investigated from three perspectives: dosage, calcination temperature and curing age. The following conclusions summarise the range of testing and evaluation methods:

1. The chemical composition analysis results showed that SiO_2, Fe_2O_3 and Al_2O_3 at 600 °C and 800 °C CANCP reached 83.37% and 88.76%, respectively, which were higher than the 70% standard stipulated by ASTM.

2. CANCP had volcanic ash activity, according to two methodologies (strength index and lime absorption).

3. The mortar CANCP intensity contribution to the pozzolanic impact was positive and increased as it aged. CANCP had a positive effect on the strength of the mortar system from early on in the process.

4. When the CANCP content was 10%, the compressive strength of concrete achieved its maximum due to the pozzolanic activity [70], and this early strength grew more rapidly. Concrete with 20% CANCP had a compressive strength that was comparable to reference concrete without CANCP. The concrete's compressive strength started to decline when the CANCP concentration exceeded 20%, whereas the decline in early strength was less pronounced.

5. Concrete containing CANCP that was calcined at 800 °C had better compressive strength than concrete that was calcined at 600 °C. At 800 °C, CANCP had superior pozzolanic activity.

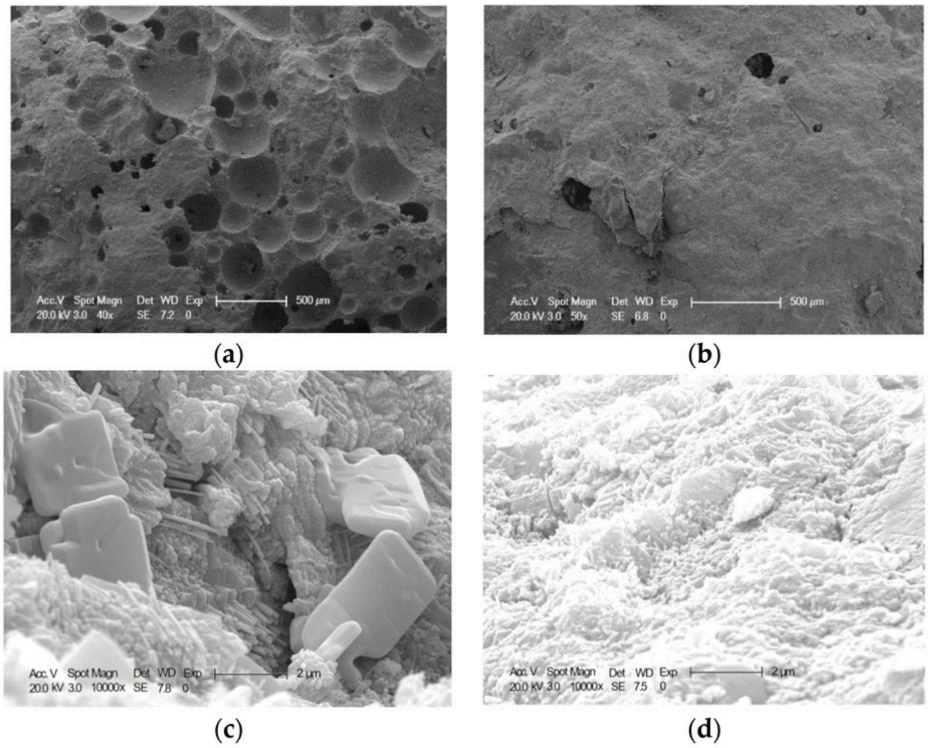
6. CANCP could speed up cement hydration and had a hardening and filling effect, so it could enhance the strength of concrete and mortar. To further strengthen the strength of concrete and mortar, it was crucial to speed up cement hydration and the pozzolanic effect. The fill effects also worked in minor ways (Figure 9).

In 2020, Zhou et al., took a closer look at CANCP [71]. Under standard curing conditions, the effect of calcined ant nest clay powder (CANCP) on concrete durability was evaluated by chloride permeability resistance, carbonisation resistance and freezing–thawing resistance, and the effect of powder content on concrete durability was also investigated. The impact of calcined ant nest clay powder (CANCP) on concrete durability was assessed under standard curing circumstances using tests for carbonisation resistance, chloride permeability resistance, and freezing–thawing resistance. The impact of powder content on concrete durability was also examined. It was demonstrated that CANCP could be applied to concrete as a mineral additive to promote its durability. The following conclusions could be drawn in light of the experimental evaluations and data analysis:

1. When the CANCP content was lower than 10%, increasing the CANCP content caused the initial current value and chloride penetration depth of the concrete to decline, which significantly boosted the concrete's resistance to chloride penetration.

2. The inclusion of CANCP could hasten the carbonation of concrete. The concrete carbonation resistance grade was unaffected if the CANCP content did not exceed 20%.

3. Even when the CANCP concentration was lower than 10%, the concrete mixed with CANCP could maintain dense internal structure under the effect of freeze–thaw, thus, improving freeze–thaw concrete resistance.



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

Figure 9. (**a**,**c**) 40×, 10,000× ordinary concrete (28 days curing) and (**b**,**d**) 50×, 10,000× 10% CANCP concrete (28 days curing) SEM micrographs.

In conclusion, CANCP has excellent material properties, which can be used as biomimetic materials and green concrete admixtures to improve concrete properties. A series of studies provided good evidence of the feasibility of CANCP as an ecological building material.

4.3. Material Bionics of Underground Ant Nest Structures

The material of the underground ant nest has excellent performance, saves energy and is free from environmental pollution. It also has good mechanical properties, is strong and durable, heat insulating and heat preserving, waterproof and moisture absorbent, and it reduces sound and noise, etc. Therefore, modern technology could be used to transplant the material properties of the ant nest into the ecosystem of building and develop bionic building materials according to living requirements.

Termite mound clay, for example, is a very hard, weather-resistant building material. Scientists proved that termite mound clay had a stabilising effect on soil, and when used in Portland cement, termite mound clay was found to be volcanically active and to reduce the heat of hydration of the cement, improving its compressive strength and increasing its compatibility. According to Jiang [72], Zhao and Xu [73], the Eastgate Centre project in Zimbabwe used eco-concrete that mimicked termite mound material, and had excellent thermal storage capacity and a very positive effect on regulating indoor temperature fluctuations and reducing building energy consumption. As shown in Figure 10a, the floor of each office floor was made of specially prefabricated concrete blocks, which were flat on the front side and acted as a floor, while the reverse side had a toothed structure that hollowed out the floor. At night cold air was exchanged with the concrete through the toothed structure, cooling the structure and removing heat and during the day the cold radiation prevented the rooms from reaching a high temperature. In this way, the concrete raised floor became a natural heat exchanger. This use of the material's heat storage properties was similar to that of termites using anthill material. The eco-concrete floor slab had a constant temperature of around 20 °C in both summer and winter, and, as the air passed through the precast eco-concrete floor slabs, heat was exchanged between the two and the air became pre-cooled or pre-heated before entering the office space. In addition, the vaulted concrete ceilings of the offices reflected light and absorbed its heat, as shown in Figure 10b.

(**a**) (**b**)

Figure 10. (**a**) Ecological concrete ventilated floor slabs and (**b**) vaulted ceilings.

5. Conclusions

It is obvious that ant colonies can build complex and dynamic structures. The mechanisms behind these phenomena deserve further study by scientists. In ant colonies, individual-to-individual and individual-to-structure interactions lead to complex and co-ordinated behaviours, and we are eager to apply this understanding to human-related problems. The similarities between ant colony nesting and other biological processes and human architectural design can serve as a good reference for practical human architectural engineering, as summarised below:

1. From the point of view of bionics, underground ant nests have bionic form, material, structure, function and construction and in-depth and detailed study to explore the underground ant nest bionic characteristics in application to civil structures is advocated. Researching new applications of bionic origin, strengthening the new field of architectural bionics, and, especially, the construction organisation and the construction process of underground ant nest bionic research, offers a good reference role for actual human construction engineering.

2. From the perspective of structural engineering, the mechanical and ventilation characteristics of ant nest structure are viable, and the bionic advantages of ant nest structure explored. According to the special robustness brought by the unique structure of the ant nest, civil buildings with tree-trunk geometry could be constructed.

3. From the perspective of civil engineering materials, studies on the basic material properties of calcined and ground ant nest clay powder and its impact on the durability and compressive strength of concrete provide strong evidence for the possibility of calcined ant nest clay powder as an ecological biomimetic construction material.

Although biology has long influenced architecture, architects and biologists have just recently begun to collaborate. As pointed out in this paper, integrating civil engineering, architecture and biology, inspires architects and biologists to converge their thinking, provides new ideas for underground ant colony nests, and provides references for human long-term residences. This combination presents inherent challenges, as each discipline has its own way of viewing the same problem. The purpose of this review was to establish a framework that could facilitate collaboration between different disciplines in the study of buildings built by organisms, such as ants, that have important value to human society.

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