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Study on constructive system of green cave dwelling in Loess Plateau—Interpretation with the "regional gene" theory*

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Abstract: This article reveals the inherent evolution adjusting mechanism of regional architecture by means of considering the concept and method of "regional gene" as the research approach of regional architecture construction system, and in the meanwhile establishes the "gene database" of regional architecture and optimum technology, on the basis of the principle of sustainable development and scientific evaluation system. In addition, this article chooses the planning of model villages of cave dwellings in Loess Plateau and the construction of ecological cave dwellings for case study to prove the feasibility of the research approach.

Key words: Regional architecture construction system, Regional gene, Primordial cave dwellings, Green cave dwelling, Sustainable development
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INTRODUCTION

Due to the impact of cultural convergence in the world, unique architectural culture traditions in various regions have suffered from irremediable damage during large-scale construction, traditional dwelling environment has not met the demand of modern life, and traditional social life network has disappeared, which resulted in the difficult situation of the redevelopment of regional architecture. Before industrial civilization, we can find from the settlement site selection of vernacular architecture in China that people made good use of natural benefit, avoided natural calamity, took full advantage of ecological rules and built their own dwellings in accordance with local conditions under the restriction of disadvantageous ecological environment. In addition, during the evolution of its formation and growth, ingenious construction system and technical means of regional architecture were formed, which ensured that it can adapt to local natural environment and resource status and expresses regional economic and social characteristics. Since the Industrial Revolution, people has relied on the architectural environment created by modern technology, and consumed enormous energy, which led to the increasing deterioration of the ecological environment and the aggravation of the energy crisis. This research is aimed at seeking primordial ecological principle contained in traditional architecture, and finding a way from traditional regional wisdom and current crisis according to the current real situation in China, exploring an architectural strategy that is suitable for the sustainable regional development and thus ensuring that the research can achieve advanced breakthrough by considering the concept and method of "regional gene" as the research approach of regional architecture construction system (Wang *et al.*, 2004).

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OBJECT

In order to avoid pure, empty theoretical research and express the research approach of limited scale and objectives, this research chooses dwelling form in the Loess Plateau in northwest China—cave dwellings as the object of case study for conducting theoretical and practical probe and proving the feasibility of the research idea. Cave dwellings are the most typical style of regional architecture in the Loess Plateau. Their simple and unsophisticated habitation form contains abundant local culture, and the energy-saving and land-saving construction pattern and the characteristic that it is warm in winter and cool in summer are considered as the model of simple ecological architecture. At present, there are still 40 million people living in cave dwellings. Although cave dwelling has various forms, it can be classified into three basic types in terms of the layout and structural forms, as shown in Fig.1: the lean cliff pattern, the subsidized pattern and the separated pattern.

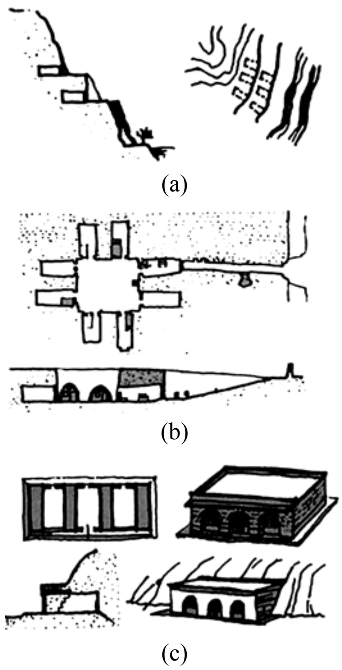


Fig.1 Three types of cave dwellings. (a) Lean cliff pattern; (b) Subsidized pattern; (c) Separated pattern

METHODS

Concept of "regional gene"

Gene is a basic factor that determines the vital phenomena of biological species. The biomass can adapt to the environmental change and make itself and other organisms survive and develop by means of its own gene adjustment and control system (Zhao, 1996).

From a comparison between a wide variety of biological species in China and dwelling forms in various regions, we can find that the responses of regional architecture to natural factors (such as climate, resources, geography, etc.) and human culture factors (such as economy, technology, society, folk custom, etc.), just like living things, reflect the trait of genetic information in a particular region. Such factors influence the formation and development of dwelling environment, gradually form their respective adjustment and control systems through subjective participation of people, and in the meanwhile establish different dwelling patterns in various regions (She, 1996). Additionally, there is a "same structure for different substances" phenomenon between its formation and growth rule and organism gene adjustment and control system.

Therefore, we determined our research idea according to (Wang *et al*., 2004): use the concept and method of gene for reference, identify and judge the regional gene in regional architecture construction system, find out the original model gene of regional architecture, control, regroup and combine the regional gene, establish the "regional gene database" (Wang *et al.*, 2004) of regional architecture; make use of scientific evaluation methods, determine the key point to be solved required for the realization of sustainable development of regional architecture; then carry out specific experiments and construction research, and finally seek a feasible development strategy of regional architecture.

Identification of and judgment on "regional gene"

In reasonable regional construction system, not all genes are protogenes: some still have their vitality in current construction activities; some can be transformed and regrouped into benign genes by some means; some are bad genes that cannot synchronize with social development and become the obstacle to the healthy development of new biomass. For this reason, we need to identify and judge correctly the "regional gene" (Wang *et al.*, 2004) in the construction system for clearly distinguishing good ones from bad ones. The correct identification of and judgment on regional gene shall be made all the time for the objective of sustainable development and based on the regional case study, which can result in the replacement of "ill" genes, activation of healthy genes, addition of new protogenes, and thus the benign development of the construction system in regional architecture.

Regrouping and combination of "regional gene"

The regrouping and combination of "regional gene" is based on the identification of and judgment on "regional gene" in order to seek feasible technology and measures, make various relevant genes in control by means of feasible measures, regroup and combine the "regional gene database" in the construction system, absorb continuously fresh genes, adjust and control actively regional gene database and thus achieve the objective of sustainable development.

A scientific evaluation system is needed for the evolution from components of construction system to "regional gene" that is in better conformity with the objective of sustainable development (AboulNaga and Elsheshtawy, 2001), which is directly related to the correctness of the judgment on "feasible" approach. The evaluation system of regional architecture construction determines the standard template (reference template for evaluating grades), establishes operating procedure and method for comprehensively evaluating its construction system, erects subitem indexes among a number of relevant genes, investigates and comprehensively analyzes typical cases, sets up case model library, conducts specialist investigation, finds comprehensive evaluation network model, and makes calculation and feedback (AboulNaga and Elsheshtawy, 2001) and improves the research (Herein, the designed evaluation procedure will not be described in detail) by means of the approach combining quantizing calculation and example inspection.

CASE STUDY

In 1997, the research team undertook a key topic research on "System of Green Architecture in Loess Plateau and Basic Inhabitation Unit Dwelling Pattern" sponsored by National Natural Science Foundation of China and chose the village with typical natural trait and landform in the Loess Plateau—Zao Yuan village of Yan'an City as the model area of research. From 1997 to 1998, the research team cooperated with the College of Science and Technology of Nihon University to conduct a series of tests for traditional cave dwellings in winter and summer, including several data on cave dwellings such as indoor sunlight and ventilation, indoor temperature distribution, ultraviolet radiation distribution, indoor and outdoor noise and indoor echo change, and indoor CO_2 concentration and dust distribution.

As shown in Fig.2, in temperature test plan, we chose the vertical section of elevation midpoint of cave dwellings as the testing surface to test temperature distribution curve of back walls of the entrances of cave dwellings (Ratti *et al*., 2003). From Fig.3, we can find that indoor temperature fluctuation in summer is within 5 °C, while that in winter is within 10 °C. Fig.4 shows indoor, outdoor and storage room's temperature fluctuation in winter and summer. Tests indicate that indoor daily temperature fluctuation is only 4~5 °C even if temperature difference between indoor and outdoor reaches 20 °C in winter and summer. Consisting of loess and bricks, the building envelope has high thermal insulation and heat accumulation performance, which can greatly reduce the influence of external environment change during the use process and make cave dwellings become a kind of natural, energy-saving building. In addition, both loess and bricks have high volumetric thermal capacity. When there is any intense change of outdoor temperature, the heat transfer between them and the building envelope will slow down, which causes time delay. In winter, the building envelope absorbs and accumulates heat in the daytime, and gives it off indoors in the evening to ensure a relatively stable indoor thermal environment. As we all know, this phenomenon is just the principle that makes cave dwellings warm in winter and cool in summer.

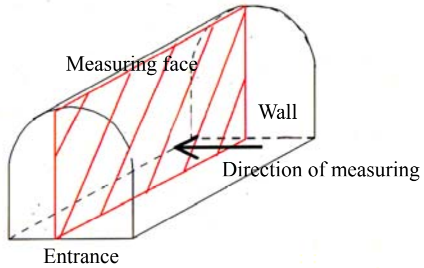
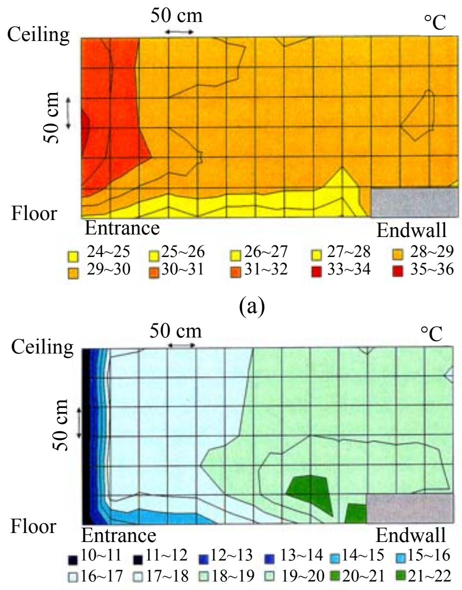
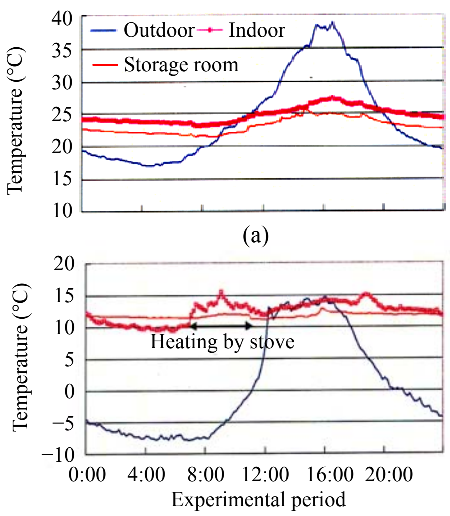


Fig.2 General idea of temperature distribution



(b)

Fig.3 Room temperature distribution in summer (a) and winter (b)



(b)

Fig.4 The changing pattern of air temperature in summer (a) and winter (b)

Diagnosing, identifying and judging "regional gene" in primordial cave dwellings

Loess Plateau has a complicated landform with vertical and horizontal ravines, scattered land, and rare vegetation. It is dry and cold in winter, and tepid and arid in summer. In addition, it has abundant sunlight which brings along sufficient solar energy resources. The formation and growth of cave dwellings is dependent on its "original model" gene all the time, which makes cave dwellings keep the adaptation to extreme climate and regional resources conditions in the Loess Plateau with an adjustment mechanism of drawing on its advantages and avoiding its disadvantages (Ratti *et al.*, 2003). We sum up the "regional gene" with vitality advantage in primordial cave dwellings construction as follows, as shown in Fig.5 (Wang *et al.*, 2004):

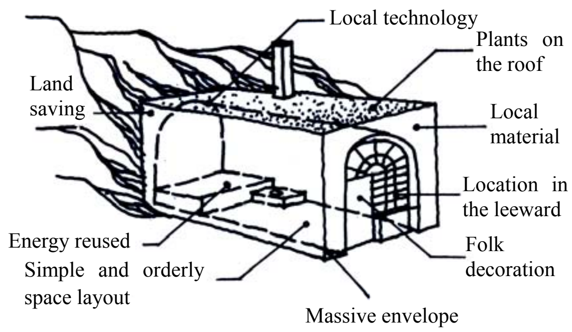


Fig.5 The original model of primordial cave dwelling

(1) Thick-and-heavy building envelope and stable indoor thermal environment.

(2) Simple and orderly space layout.

As for cave dwelling forms, there are no rough spaces, and multi-hole cave dwellings are arranged to form groups. Except windows facing the sun, they are all sealed thick-and-heavy structures with the smallest exposed areas, which thus help maintain indoor thermal balance.

(3) Optimized utilization of solar energy.

Cave dwellings are mostly built on the slopes facing south and their windows are mounted to the south. For this reason, sufficient ray and direct sunlight can be ensured, and they can be considered as the embryonic form of passive solar houses.

(4) Land-saving and courtyard economy.

Under land resources lack condition, land can be utilized fully without occupation of grain field, so as to ensure the harmony between production and life; vegetables and cash crops can be planted on the earth covering of cave dwelling's roof for increasing vegetation and adjusting microclimate. As a result, zero construction expenses for land combined with courtyard economy, which reaches win-win effects of land-saving and economy.

(5) Construction pattern of neighbor-to-neighbor help and using local materials.

Featuring even texture, great compressive strength and structural stability, local loess and stone are adopted for arch structure. In addition, they can also be reused following multi-level cycle principle of ecosystem substance if they are abandoned. No complicated techniques and mechanical equipments are needed for building them. Therefore, mutual help among neighbors will benefit good cooperation spirit and construction pattern.

(6) Multi-utilization of household energy consumption.

In most cave dwellings, heated kangs are connected with kitchen ranges. Dwellers can cook a meal and keep warm by utilizing radiant heat formed by remaining heat and smoke's heat quantity in the flue, kang's thermal storage capacity and its broad surface. Tests showed that: at an outdoor temperature of –24 °C in winter, cave dwelling only relies on thermal retardation of walls and radiant heat of heated kangs, while at about 18 °C, the energy for keeping warm can be saved effectively.

(7) Simple and natural visual image and folk decoration.

It is simple cave dwelling space and adoption of natural material that make cave dwellings feature simplicity. Additionally, cave dwelling communities are distributed in a natural manner; south elevations of cave dwellings are the visual focus of the whole buildings, and their carvings of masonry arch structure and woodcarving windows not only reflect the stress characteristic of arch structure, but also contain delicacy and simplicity.

With the change of modern life style and the demand for diversified culture, the development of traditional cave dwellings has faced a difficult situation. The disadvantageous "regional gene" of the disharmony between the survival of cave dwellings and social development is as follows:

(1) Unsatisfactory indoor space trait—poor privacy, poor ventilation, insufficient sunlight, wet and dark, poor safety, etc.;

(2) Poor precautionary measure against calamities—shortage of measures on earthquake resistance, landslip resistance and debris flow resistance;

(3) Village structure lacks overall planning—poor land use, shortage of necessary infrastructure such as drainage and traffic facilities;

(4) Low utilization efficiency of solar energy and renewable sources of energy;

(5) Absence of the treatment for changing waste into resources.

Establishing "regional gene database" in green cave dwelling construction system

As shown in Table 1, on the basis of analysis and understanding of the "original model" gene in primordial cave dwellings construction system and analysis of natural ecological condition, resources, social economy, production and life systems in the Loess Plateau, we make judgment on various kinds of components in cave dwellings construction system, absorb modern science and technology, develop clean, new-type energy (such as natural gas and marsh gas) and renewable energy (such as solar energy, ground energy and biomass energy), differentiate the structural relation between key genes and common genes, construct the "regional gene database" of green cave dwelling construction system (AboulNaga and Elsheshtawy, 2001), adjust and control key genes, specify the key point of solving sustainable development of green cave dwelling construction system, and thus realize the overall harmonious development among several systems, such as ecosystem, production system and architectural and life system.

From traditional settlement to sustainable development

1. The mode of land saving in typical topography of the Loess Plateau

We would popularize scientific farming in the plat field of ditch and plant the crops with high benefit. Meanwhile many measures would be taken to synthetically harness rivers and protect them from pollution. On the principle of land saving, we would do master planning to build cave dwellings on the slop and utilize the topography with different levels to compactly arrange the land use for inhabitation, road and infrastructure, so as to reduce the expense of traffic and infrastructure. The implementation of eco-agriculture on the top of the mountains could help to conserve water and soil, and comprehensively improve the eco-environment on the Loess Plateau (Lafortezza and Brown, 2004).

2. The mode of the residential unit

As shown in Fig.6, it is composed of 7 or 8 families to form a residential unit. In order to utilize

Table 1 A "gene database" of green cave dwelling

Factor sorting		Sufficient utilization of natural resources				Resistibility on disasters				Health and comfortable environment				Living and producing				Foundation planting				Material and construction strategy			
		Adjusting measures to local conditions	Natural air-condition	Active and passive solar energy utilization	Earth energy, Biology resource	Multi-utilization of water resource	Appropriate location selection	Aseismatic design	Enhanced waterproof and dampproof	Favorable lighting and ventilation	High-quality heat environment	Dispelling the dampness and coldness	Enough public space	Dwelling group	Courtyard economy	Green enterprise	Traffic system	Drainage system	Rubbish-recycle system	Utilization of local stone	Dynamic design technique	Multi-floor cave dwelling design	Additional solar house design	Heat-accumulated wall and remaining function	Tunnel design
Natural condition	Topography	●					○							○			○								
	High daylight			○																			○		
	Hot and dry in summer		●		○																				○
	Cold in winter		●	●	○						○													●	○
	Lack of water					●												○							
	Enough solar energy			●							○												○	●	
	Local stone																							○	
Disasters	Drought					●	○											○							
	Flood						○		○									○							
Environment	Serious air pollution	●								○													●		○
	Water pollution				○													○							
	Life and producing rubbish				●														○						
	Disposal of waste				●														○						
	Structure of energy utilization		○	●	○																		●	○	○
Economy and society	Lowly-developed economy				○	○									○	○								○	○
	Poor foundation planting					○								○			●	●	○						
	Ecological agriculture														○			○							
	Well-to-do village standard															○	○	●							
	Ecological village standard														●	●			●				○	○	○
	Environment construction												○	○			○		●			○	○		
Living system	Community solidarity												●	●											
	Need for modern life	○		○	○	○				○	○	○	●	○			○	○			○	○			●
Design and construction	Regeneration of traditional building			○				○												○		○	○	○	○
	Easy-to-update method																				○				
	Usage of permanent materials							●												○		○			
	Life cycle							○	○											○	○	○			
	New materials and techniques	●	●					○	○									○	○		○	○	○	○	○
Modern technology	Planning and architecture	●		●	●		●	○				○	○		●					○	●	○		●	
	Ecology	●	○	●	●	●	○				○				○	○									
	Economics			○		○		○							○	●									
Participation of the public	Discussion of the villagers						○				○	○			○						●	●	●	○	○
	Participation of local craftsmen							○	○											○					○

● Important factor solved especially; ○ Secondly factor established the relation the topography with different levels, diversified yard configuration and places would be constructed to define different spatial fields for family privacy and public traffic, moreover providing convenient places for neighborhood connection and mutual aid, and rebuilding the indigenous living atmosphere. Various places in a residential unit are as follows:

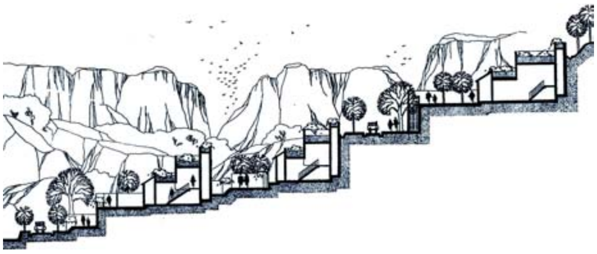


Fig.6 Land utilization mode

(1) Neighborhood center: improving the physical and social living environment; providing space for communication and folk activity.

(2) The public leisure space: offering space for social communication among neighbors;

(3) Cave dwelling: as the cell of the community and the minimum unit of life and production;

(4) Courtyard economy: planting vegetables, raising livestock and poultry, building methane gas pool near lavatory and stockyard to offer cooking and electricity; water cellar for storage, etc.;

(5) Public pedestrian roads: connecting every household with the neighborhood center conveniently;

(6) The overlapping space for saving land and utilizing slope fully.

3. The "green model" of cave dwelling

In terms of ecological principles included in primitive model (Wang *et al*., 2004), we would adopt measures including passive and active design to synthetically improve the air quality, as well as thermal and optical environment. Instead of using mechanical equipment, passive designing measures emphasize regulating the micro-climate of cave dwelling only by three means as follows: rational cave configuration and layout; cave's component structure including roof, wall, windows, ventilation shaft and underground tunnel; environmental elements such as tree, water and yard, etc. Active one lies in using solar energy system to provide heat and electricity with the aid of mechanical equipment. These measures of green cave dwelling above listed in Fig.7, could help to reduce the energy consumption caused by equipment's operation. Moreover, synthetically reform lighting, warming proof, heating, natural air-condition and dehumidification indoors on the basis of maintaining their characteristics of being warm in winter and cool in summer (Nahar *et al*., 2003).

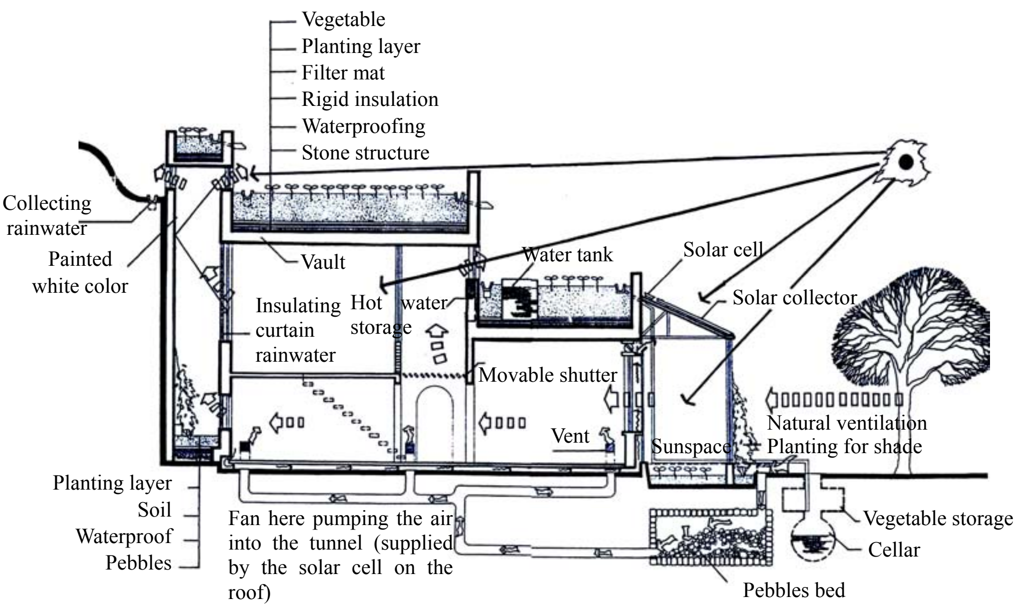


Fig.7 The ideal model of green cave dwelling

(1) To utilize the floor level difference between upper and lower storey to solve the problem of day lighting and divide the space of different functions;

(2) The ventilation shaft in the rear improves the day lighting, ventilation and dehumidifying (Leslie, 2003);

(3) Solar energy system regulates and keeps the indoor heat environment, and provides hot water (Nahar *et al.*, 1999);

(4) To adopt underground tunnel to separate pollutants and regulate ventilation to improve indoor air quality;

(5) Double glass windows and curtain can maintain stable indoor heat environment and avoid the loss of heat (Knowles, 2003);

(6) Planting on cave dwelling's roof can strengthen the ability of preservation and insulation, regulate the micro-climate and promote courtyard economy.

CONCLUSION

By means of theoretical and practical research on model areas, we re-renovated village environment and built a batch of new ecological cave dwellings, which resulted in great improvement in dwelling quality and life environment of residents. New cave dwellings, built as a result of joint participation of architectural designer, specialists in environmental science, ecology and sociology, and local residents, adopted a series of regional technologies and feasible technology system with optimized combination of current technologies, which improved local material and cave dwelling technology, combined and made use of local material and modern material (for example, partial concrete constructional elements are adopted for improving the integrity and earthquake-proof performance of multi-storied cave dwellings), and reformed the earth base treatment, bricklaying, arched film manufacture, and roof vegetation recovery technology of cave dwellings. This kind of new cave dwelling has been widely adopted by and popularized for local residents.

Although the research case we chose is applicable to a particular region, the research idea and method are considerably beneficial for researches on the construction system of other regional architecture. With respect to researches on other regional architectures, we can also select typical cases for a breakthrough in research, and seek a construction system strategy that is suitable for this region.

References

AboulNaga, M.M., Elsheshtawy, Y.H., 2001. Environmental sustainability assessment of buildings in hot climates: the case of the UAE. *Renewable Energy*, **24**(3-4):553-563. [doi:10.1016/S0960-1481(01)00041-6]

Knowles, R.L., 2003. The solar envelope: its meaning for energy and buildings. *Energy and Buildings*, **35**(1):15-25. [doi:10.1016/S0378-7788(02)00076-2]

Lafortezza, R., Brown, R.D., 2004. A framework for landscape ecological design of new patches in the rural landscape. *Environmental Management*, **34**(4):461-473, [doi:10.1007/s00267-002-2009-z]

Leslie, R.P., 2003. Capturing the daylight dividend in buildings: why and how? *Building and Environment*, **38**(2):381-385. [doi:10.1016/S0360-1323(02)00118-X]

Nahar, N.M., Sharma, P., Purohit, M.M., 1999. Studies on solar passive cooling techniques for arid areas. *Energy Conversion and Management*, **40**(1):89-95. [doi:10.1016/S0196-8904(98)00039-9]

Nahar, N.M., Sharma, P., Purohit, M.M., 2003. Performance of different passive techniques for cooling of buildings in arid regions. *Building and Environment*, **38**(1):109-116. [doi:10.1016/S0360-1323(02)00029-X]

Ratti, C., Raydan, D., Steemers, K., 2003. Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and Buildings*, **35**(1):49-59. [doi:10.1016/S0378-7788(02)00079-8]

She, Z.R., 1996. The Discussion of Ecological Wisdom. Social Science Press, Beijing (in Chinese).

Wang, Z., Wei, Q., He, Y., 2004. Stepping to sustainable development from traditional settlement: analyzing the Loess Plateau green cave dwelling in terms of regional architecture. *Architectural Journal, Beijing*, **427**(3):34-37 (in Chinese).

Zhao, G.M., 1996. The Conception of Gene. Social Science Press, Beijing (in Chinese).