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Material characteristics of ancient Chinese lime binder and experimental reproductions with organic admixtures

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HIGHLIGHTS

- Organic-inorganic binders were widely used in ancient Chinese construction.
- Representative samples from four important ancient Chinese walls were investigated with diverse analytical methods.
- Three series of lime binder reproductions with sticky rice, tung oil and pig blood were fabricated and investigated with similar methods.

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ABSTRACT

The application of traditional construction materials, such as lime binders containing organic additives, has attracted a great deal of attention in recent years for the sustainable conservation and restoration of ancient buildings. Here, representative samples from four important Chinese city walls from Hebei, Jiangsu, and Gansu provinces, constructed from 563 to 1381 CE, are comprehensively investigated with micro- and macro-scale analytical techniques. Traces of organic additives were detected, and according to the Song Yingxing text (1637 CE), these should be sticky rice, tung oil or pig blood. To clarify the potential influences of additives on the physical properties of ancient lime binders, reproductions of the lime paste binders were fabricated according to the Song Yingxing formulas with sticky rice slurry, tung oil and fresh pig blood, and evaluated with standard engineering testing experiments. Continuous observation of the early stage of microstructure formation used an innovative ultrasonic monitoring apparatus. Interactions between the lime and organic additives, analyzed via powder X-ray diffraction and environmental scanning electron microscopy, show gains in specific performance capabilities. Sticky rice slurry at 5 wt% accelerates setting and hardening and increases compressive strength and bonding capability, although unit weight and water resistance are slightly reduced. Tung oil at 5 wt% strongly improves water resistance through dramatically reducing water sorption. Pig blood at 1 wt% accelerates setting and hardening, and improves water resistance. The archeological record and Song Yingxing text indicate that Chinese builders recognized these influences and selected the specific organic additive for lime binders in wall constructions, caulking, wall facings, and groundwork foundations.

1. Introduction

The Great Wall, a massive 21,196 km structure constructed between 221 BCE and 1644 CE, is one of the most impressive, imperial era monuments of ancient China [1]. Remarkably, hundreds of similar historical wall relicts can be seen today, from the Hushan wall near the Yalu River of Liaoning province in eastern China to the Tiemen wall of Korla county of the Xinjiang Uygur Autonomous Region in the west (Fig. 1). These ancient walls were mainly constructed with local dimension stone or clay–fired bricks bonded with lime binders [2,3]. Throughout China, the ancient bricks are large rectangular blocks, on the order of 48 cm × 24 cm × 120 cm. The lime binders do not generally contain sand- to gravel-sized aggregate but rather are composed of hydrated quicklime paste that develops a rather homogeneous fabric of calcite crystals. There are only occasional particles of gravel sized rock or brick fragments. In sieving the ancient binders, <5 wt% fraction is sand sized quartz grains >1 mm. This likely comes from sand inclusions in the host limestone that was processed for calcination.

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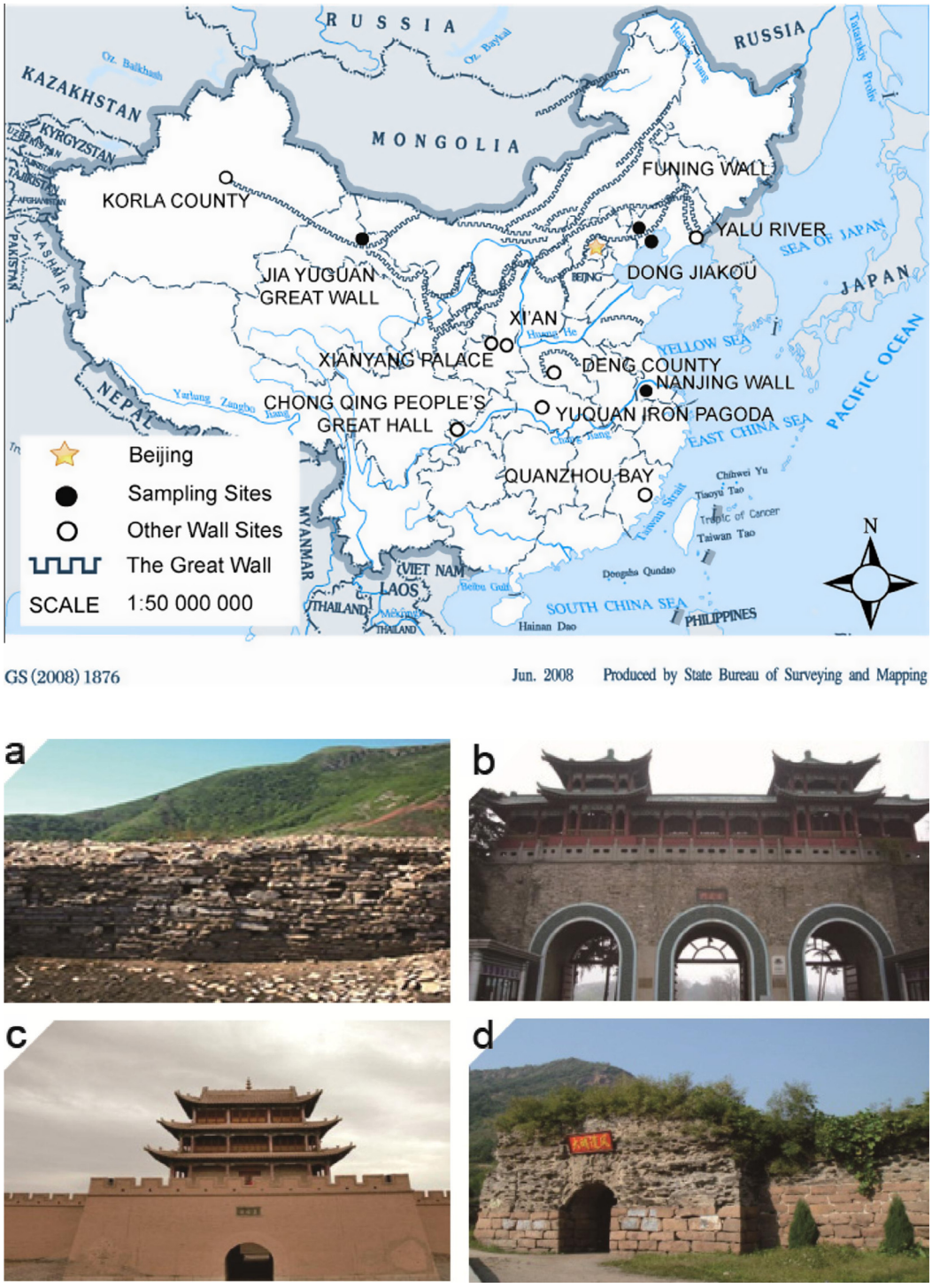

Fig. 1. Map of China showing the geographical distribution of Great Wall structures (Dong, 1988), and sampling sites. (a) Funing city wall (563 CE), (b) Nanjing city wall (1368 CE), (c) Jia Yuguan Great Wall (1372 CE) and (d) Dong Jiakou city wall (1381 CE).

By as early as 221 BCE, in the Xian Yang palace of Shanxi province, Chinese builders had developed an empirical knowledge of the role of certain organic additives in enhancing specific properties of the lime binders [4]. These are the extraordinarily resilient binding component of highly developed rubble concrete technologies developed by Chinese builders over many centuries. They are of great significance to ensuring the durability and long service life of the ancient walls. Although the walls have suffered from hundreds of years of direct exposure to weathering agents such as rain, freeze–thaw cycles, thermal cycles associated with solar heating, and daily variations in relative humidity, most remain cohesive and intact [5] (Fig. 1). They are a testament to builders' empirical expertise and advanced building technologies [6–9] that were apparently disseminated throughout China. Archeological studies indicate that calcination of limestone and application of lime technologies [10] began by the middle to late West Zhou dynasty (1046–771 BCE). Lime was broadly used in the reinforcement of groundwork foundations, supporting pillars, and roofs. Ancient