What Factors Contribute to High Mechanical Strength of Tabia? Case Study of the Tabia from Coastal Forts Sites at Zhejiang, China

Cuisong Zhang
Zhejiang University

Bingjian Zhang (✉ zhangbiji@zju.edu.cn)
Zhejiang University  https://orcid.org/0000-0002-4591-0361

Biao Cui
Zhejiang Provincial Institute of Cultural Relics and Archaeology

Guocong Lin
Ningbo Institute of Cultural Relics and Archaeology

Research article

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Abstract

Tabia is one of the most widely used construction materials in ancient China. In this work, the tabia samples from three coastal defense fort sites at Zhejiang Province, China, we analyzed to determine their component composition and physiochemical properties. The results show that these tabia samples exhibited high compressive strength, which could be as high as 4–9 MPa. Furthermore, the systematic analysis demonstrated that the high compressive strength was related to the following factors: 1) a suitable mass ratio of sand, lime, and clay; 2) an appropriate sand particle size ratio; and 3) the formation of hydrated calcium silicate (C-S-H). Moreover, sticky rice was also detected in the tabia samples. These findings are fundamentally important, which could be beneficial to further study of the craftsmanship of the coastal defense forts and could further provide essential guidance for the protection and restoration of the tabia relics.

1. Introduction

Tabia, a mixture of clay, lime, and sand, was widely used in the urban wall construction (Liu et al. 2016; Shui 2012; Yao and Lv 2004), tombs (Cen et al. 2011; Pu 1994; Tie 2004), and water conservancy facilities (Zheng et al. 2016) in ancient China for its super mechanical properties. Zhang and co-workers have discovered starch in the mortar sample of a tomb in Eastern Han Dynasty (25 – 220 AD) in Xuzhou, Jiangsu, China (Li and Zhang 2019). About 1500 years ago, organic additives such as sticky rice, tung oil, egg white, sugar, blood, and plant vine juice have been widely applied to improve mechanical properties of the tabia (Zhang et al. 2014). After the Second Opium War (1856 – 1860 AD), the construction of the tabia coastal defense forts in China's coastal area began, and the sticky rice tabia coastal defense forts were also constructed (Feng 2015). Xu Jiagan's "Outline of Coastal Defense" recorded the craftsmanship of sticky rice tabia coastal defense forts. The proportion of lime: clay: sand of the tabia used in building the forts was 5 : 3 : 2. After being well mixed with sticky rice soup, it was pounded from eight inches to two inches thick. The finished material was said to be as hard as iron (Xu 1887). Due to long-term exposure to the natural environment, these tabia coastal defense forts were greatly subjected to water erosion, wind erosion, freezing and thawing erosion and temperature changes, which have caused some damages such as spalling and collapse. Therefore, it is in urgent to protect these tabia coastal defense forts (Chen et al. 2013; Chen et al. 2015; Pu et al. 2016; Qu et al. 2007; Shao et al. 2013). When the tabia coastal defense fort sites are to be subjected to the necessary in-situ replacement and repair work, the "original materials and original craftsmanship" needs to be done at the early stage. Therefore, understanding the relationship between the strength, raw material ratio, and construction methods is fundamentally important not only for studying historical of building materials, but also providing insights into the construction of tabia, and further severing for all purpose of restoring tabia coastal defense fort sites.

In recent years, researchers have investigated tabia coastal defense forts from Tianjin Dagukou (Li et al. 2008), Jiangsu Jiaoshan (Yuan et al. 2010), Huangshan Xiaoshiwan (Zhang and Wan 2010), Minjiangkou (Wu et al. 2018), and Guangzhou (Zhou et al. 2019). However, there are few reports on the
Tabia coastal defense forts in the coastal areas of Zhejiang Province, China. In this study, seven tabia samples were collected from Pinghu coastal defense forts sites, Ningbo coastal defense forts sites, and Wenzhou coastal defense forts sites in Zhejiang Province, China.

Jingyuan coastal defense fort, Pingyuan coastal defense fort, Zhenyuan coastal defense fort, and Hongyuan coastal defense fort are in Zhenhaikou, Ningbo City, Zhejiang Province, China. As a part of the Zhenhaikou Coastal Defense Site, the above four coastal defense forts have been listed as the national key cultural relics in China since 1996. Tianfeigong coastal defense fort and Nanwan coastal defense fort in Zhabu Town, Pinghu City, Zhejiang Province, China, have been listed as the national key cultural relics in China since 2013. Longwan coastal defense fort in Longwan District, Wenzhou City, Zhejiang Province, China, has been listed as a key cultural relic of Wenzhou City since 2002. All these forts were built during 1870s – 1890s, which have been listed in Table 1.

(Table 1)

2. Materials And Methods

2.1 Materials

The chemicals used in this work were as follows: calcium carbonate, hydrochloric acid, acetate, sodium carbonate anhydrous, sodium hydroxide, copper sulfate anhydrous, trisodium citrate dihydrate, iodine, potassium iodide, zinc powder, periodice acid, acetyl acetone, phenolphthalein, and Coomassie Brilliant Blue G-250 dye. All chemicals were procured from Sinopharm Chemical Reagent Co., Ltd., Shanghai.

2.2 Methods

The surface Leeb hardness of the tabia samples was tested using an Equotip 550 Portable Rockwell Leeb D Impact Device (Proceq SA). The compressive strength was assessed using a HANDPI electronic tensile testing machine (Yueqing Aidebao Instrument Co., Ltd.). The density and porosity were measured by a QL120C Density Tester (MatsuHaku, Inc.) based on the Archimedes’ principle.

The CaCO$_3$ content of tabia samples was calculated based on an acid dissolution method. First, 1.8 g well dried stone-free tabia was transferred to a conical flask, in which 20 mL 1 M HCl solution was added. Secondly, the flask was shaken for 15 min, to accelerate the chemical reaction: CaCO$_3$ + 2HCl = CaCl$_2$ + CO$_2$↑ + H$_2$O. Finally, the volume of CO$_2$ was recorded by a home-made CO$_2$ gas volume measuring instrument and the content Q$_1$ of CaCO$_3$ in tabia samples was calculated according to the aforementioned-chemical equation. This process was repeated three times to obtain the average for each tabia sample.

The sand and clay contents were also determined by the acid dissolution method. Briefly, 100 g well dried stone-free tabia was placed in a beaker with 1000 mL 1 M HCl solution. The excess HCl solution was removed after the reaction was completed. Then, the sand and clay were washed to pH = 7 and dried at
105 °C. After separated by a 200 mesh (0.075 mm) sieve, the sand with particle size > 0.075 mm was obtained, and the corresponding sand content $Q_2$ could be calculated. Finally, the content of clay (particle size < 0.075 mm) $Q_3$ was calculated by 1 - $Q_1$ - $Q_2$.

The sand of the tabia samples was sifted through a set of sieves in a sequence, including 10 mesh (2 mm), 14 mesh (1.4 mm), 20 mesh (0.85 mm), 30 mesh (0.6 mm), 40 mesh (0.425 mm), 60 mesh (0.25 mm), 80 mesh (0.18 mm), 100 mesh (15 mm), 120 mesh (0.125 mm), 150 mesh (0.1 mm), and 200 mesh (0.075 mm). The remains on each sieve were separately weighed and the weight fraction of sands within each size range was obtained. The particle size analysis of the clay in the tabia samples was performed using a BT-2002 laser particle size distribution analyzer (Dandong Bettersize Instrument Co., Ltd.).

The aging test of the tabia samples was performed after the samples were dried at 105 °C for 4 hours. The prepared tabia samples were subjected to aging test through the cycle steps as follows: (1) immersed in water for 1 hour; (2) frozen at -20 °C for 1 hour; (3) dried at 60 °C for 1 hour. The above steps were repeated until the samples were destroyed. The mass changes of the tabia samples were recorded after each cycle.

A variety of chemical analyses were implemented to detect the organic residues in the samples, including a Coomassie Blue staining test for protein, a Benedict's reagent test for reducing sugar, and a reducing phenolphthalein reagent test for blood, as well as a sodium periodate oxidation acetyl acetone test for fatty acid ester (i.e., oil). The relevant testing procedures have been documented in Fang et al. (2014). Additionally, an iodine–potassium iodide reagent was used to detect starch, and the detailed testing procedures have been documented in Zheng et al. (2016).

The capillary water absorption of the tabia samples was measured by a standardized method (ISO 15148: 2002). Firstly, the initial mass of the well-prepared tabia sample was weighed and then, the sample bottom was immersed in water. After a specific time period, the sample was taken out, wiped off to remove the water droplets absorbed on the bottom of the sample. Then the sample was weighed to obtain the mass increase of the sample. Finally, the capillary water absorption coefficient of the tabia samples was calculated.

3. Results And Discussion

3.1 The compressive strength, elastic modulus, and surface Leeb hardness of the tabia samples

Fig. 1 shows the compressive strength of the tabia samples. The samples NW, JY, and HY had higher compressive strength when compared with the other samples. The compressive strength of all these three samples surpassed 6.5 MPa. In this regard, a systematic investigation was performed to figure out why these three tabia samples had such high compressive strength.
Fig. 2 shows the strain-stress test results of the tabia samples, and the elastic modulus was calculated using the stress peak divided by the corresponding strain (listed in Table 2). The elastic moduli (over 350 Mpa) for the samples NW, JY, and HY were higher when compared with those of the other samples.

(Table 2)

The surface Leeb hardness of the tabia samples was among 270 – 360 HLD (shown in Fig. 3). Compared with the result elastic moduli of the tabia samples, the surface Leeb hardness increased with the elastic modulus. Thus, the portable Leeb hardness tester could be used as a nondestructive method for approximating the elastic modulus of the tabia samples.

(Fig. 3)

3.2 The density and porosity of the tabia samples

Fig. 4 shows the density and porosity analysis results of the tabia samples. The results show that the density and porosity of the tabia samples were similar. The density of the tabia samples ranged from 1.53 to 1.76 g/cm$^3$, and the porosity ranged from 41% to 49%. This might indicate that the craftsmanship of these coastal defense forts was alike.

(Fig. 4)

3.3 Determination of the contents of calcite, sand and clay in the tabia samples

The contents of calcite, sand and clay in the tabia samples are depicted in Fig. 5, which fluctuated markedly among different samples. The content of sand ranged from 23.1% to 58.5%, the content of calcite ranged from 18.7% to 39.3%, and the content of clay ranged from 22.3% to 53.5%. The differences among the tabia samples in the contents of calcite, sand, and clay indicated the variance in the craftsmanship. The ratio of calcite, sand, and clay in samples JY, NW, and HY (circled in red), was around 1 : 1 : 1. These results indicate that the appropriate ratio of sand, calcite, and clay could be an essential factor leading to the high compressive strength of tabia samples. In this regard, it is necessary to study the influence of the grain size distribution of sand on the high compressive strength of the tabia samples, because sand served as the aggregate and took up a large proportion of the tabia.

(Fig. 5)

3.4 Determination of the grain size distribution of sand and clay in the tabia samples.

Fig. 6 shows the grain size distribution of sand in the tabia samples. The grain size for each tabia sample could be categorized as: (1) small < 0.18 mm; (2) middle = 0.18 – 0.85 mm; and (3) large > 0.85 mm. The ratios of small size mass, middle size mass, and large size mass of sand in the tabia samples were donated as $R_s$, $R_m$, and $R_l$, respectively. The $R_s$, $R_m$, and $R_l$ of the tabia samples are listed in Table 3. It is
noted that all the $R_m$ values of samples NW, JY, and HY were below 50%. The $R_m/l$ and $R_m/s$ were calculated by dividing $R_m$ by $R_l$ and $R_s$, respectively. All the $R_m/l$ and $R_m/s$ values of samples NW, JY, and HY were below 2.0 (shown in Fig. 7). These results indicate the relatively disperse distribution of sand would enhance the mechanical strength of the tabia.

(Fig. 6)

(Fig. 7)

(Table 3)

The grain size distribution of clay had similarity among the tabia samples, which was mainly concentrated in 20 – 40 μm (Fig. 8). This might indicate that the clay used in these tabia coastal defense forts was processed by similar treatments.

(Fig. 8)

3.5 The detection of organic additives in the tabia samples

The detection was performed for the organic additives including oil, protein, blood, sugar, and starch in the tabia samples. Among these organic additives, oil, protein, blood, and sugar were not detected in any of the tabia samples. For the starch test, the absorbance at 533.4 nm of the obtained solution of tabia samples (shown in Fig. 9) is shown in Table 4. The absorbance of samples JY, PY, and ZY was 0.128, 0.198, and 0.172, respectively, while the limit of detection (LOD) for this method was 0.096, as reported in Zheng et al. (2016). This demonstrated that there was sticky rice in samples JY, PY, and ZY. The samples without starch might originally have it, but the starch was degraded. Herein, the detection of sticky rice in the tabia samples needs further clarification.

(Fig. 9)

(Table 4)

3.6 The morphology analysis of the tabia samples

Fig. 10 shows the morphology of tabia samples HY and NW. The hydraulic materials C-S-H fibers were found in samples NW (Fig. 10 a) and HY (Fig. 10 b). These C-S-H fibers might be generated by the chemical reaction between lime, quartz, and water: $\text{SiO}_2 + \text{CaO} + \text{H}_2\text{O} \rightarrow \text{C-S-H}$, and these hydraulic materials C-S-H fibers could lead to the hardness of the tabia.

(Fig. 10)

3.7 The aging test of the tabia samples
The mass ratio of the tabia samples after each aging cycle is shown in Fig. 11. The cycles of 100% residual mass ratio were taken as the aging resistance capability, and the aging resistance capability of the samples increased with the increase of the calcite content. Sample NW with the highest calcite content of 39.3% had the highest aging resistance capability (87 cycles). However, sample HY with the calcite content of 31.7% had a lower aging resistance capability (34 cycles), which is lower than that of sample JY (72 cycles with 23.6% calcite), PY (68 cycles with 23.2% calcite) and ZY (56 cycles with 19.2% calcite). This observation was due to the inhomogeneous distribution of lime in sample HY. The aging resistance test could be used as a method to evaluate the tabia’s craftsmanship of the tabia.

(Fig. 11)

3.8 The capillary water absorption test of the tabia samples

Fig. 12 shows the capillary water absorption quantity $\Delta m$ of tabia samples at different absorption time, $t$. The capillary water absorption coefficient could be calculated from the equation $\Delta m = C \ast A t^{0.5}$, where $C$ is the water absorption coefficient and $A$ is the bottom area of the tabia sample (Zhang et al. 2013). The results of capillary water absorption coefficient was divided into three parts. For sample TFG (with porosity 41.32%), the capillary water absorption coefficient is 0.024 g/cm$^2$ min$^{0.5}$. For samples JY, ZY, LW, and HY (with porosity from 43.72% to 46.34%), the corresponding capillary water absorption coefficients were from 0.044 to 0.059 g/cm$^2$ min$^{0.5}$, much higher than that of sample TFG. Samples NW and PY (with porosity from 48.72% to 48.95%) had a similar capillary water absorption coefficient 0.077 – 0.078 g/cm$^2$ min$^{0.5}$. These results show that the capillary water absorption coefficient of the tabia samples increase with the porosity.

(Fig. 12)

4. Conclusions

In this work, a comprehensive method was established for studying traditional tabia samples from the Coastal Defense Forts Sites in Zhejiang Province, China, which included evaluating surface hardness, compressive strength, density and porosity, component composition, distribution of sand and clay, organic additives, morphology, and aging resistant properties, and capillary water absorption. The superior strength in tabia samples NW, JY, and HY was determined to be largely related to the following factors: 1) a suitable mass ratio of sand : lime : clay, i.e., around 1 : 1 : 1; 2) an appropriate particle size ratio of sand; and 3) the formation of the hydraulic materials C-S-H. Pertaining to the craftsmanship of the tabia, the well distributed components could be beneficial to improve the performance of the tabia. The sticky rice components were detected in some of the tabia samples. However, whether sticky rice has been added to other tabia samples needs further study. These findings are fundamentally important for a better understanding of the craftsmanship of the Coastal Defense Forts Sites tabia, which could provide essential guidance for protection and restoration of the tabia relics.
Declarations

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate: This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication: The consent for the publication of details and images in the manuscript are obtained from all participants.

Competing interests: The authors declare that they have no competing interests.

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Authors’ contributions: CZ: Writing-Original Draft. BZ: Writing-Review & Editing, Supervision. BC: Resources, Writing-Review & Editing. GL: Resources, Writing-Review & Editing. All authors read and approved the final manuscript.

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References

Cen, D., Chen, X., & Wang, Z. (2011) Excavation report of Xinwuwan tomb in Xishui county. Jianghan Archaeology, S1, 66–73.

Chen, W., Guo, Z., Xu, Y., Chen, P., Zhang, S., & Ye, F. (2015) Laboratory tests on rammed earth samples of earthen sites instilled by reinforcement material SH. Chinese Journal of Geotechnical Engineering, 37(8), 1517–1523.

Chen, Y., Wang, X., Yang, S., & Guo, Q. (2013) A Preliminary Study of the Freeze-thaw Cycle on the Structure of Earthen Sites with Different Salts. Dunhuang Research, 01, 98–107+132.

Feng L. (2015) Research of Qing Dynasty Zhejiang coastal defense Fort. Master’s Thesis. Hebei Normal University.

ISO 15148: (2002) Preview Hygrothermal performance of building materials and products-Determination of water absorption coefficient by partial immersion.

Li, J., & Zhang, B. (2019) Why ancient Chinese people like to use organic-inorganic composite mortars? — Application history and reasons of organic - inorganic mortars in ancient Chinese buildings. Journal of Archaeological Method and Theory, 26(2), 502–536.
Li, N., Zhang, Z., & Wang, D. (2008) Primary study on the “Sanhe Tu” from the Haizi and Weizi Emplacements in Tianjing Dagu site. *Science of Conservation and Archaeology, 20*(2), 46–51.

Liu, X., Yang, S., & Zhang, B. (2016) Studies of rammed earthen foundations from the archaeological site of the Shang city at Zhengzhou. *Sciences of Conservation and Archaeology, 28*(4), 106–112.

Pu S. (1994) The Yuanzitai North Yan tomb in Chaoyang county Liaoning province. *Cultural Relics, 11*, 43–47.

Pu, T., Chen, W., Du, Y., Li, W., & Su, Na. (2016) Snowfall-related deterioration behavior of the Ming Great Wall in the eastern Qinghai-Tibet Plateau. *Natural Hazards, 84*(3), 1539–1550.

Qu, J., Cheng, G., Zhang, K., Wang, J., Zu, R., & Fang, H. (2007) An experimental study of the mechanisms of freeze/thaw and wind erosion of ancient adobe buildings in Northwest China. *Bulletin of Engineering Geology and the Environment, 66* (2), 153–159.

Shao, M., Li, L., Wang, S., Wang, E., & Li, Z. (2013) Deterioration mechanisms of building materials of Jiaohe ruins in China. *Journal of Cultural Heritage, 14*(1), 38–44.

Shui, B. (2012) Preliminary study on lime-soil in ancient rammed earth construction site in China. Master's Thesis, Northwest University.

Tie, F. (2004) Conservation and restoration of wall paintings of early Western Han Dynasty — Investigation of conservation history and actuality. *Sciences of Conservation and Archaeology, 16*(1), 47–51.

Wu, R., Bao, Q., & Ji, H. (2018) Research on Material and Manufacturing Process of Ancient Trinity of Coastal Defence Emplacements in the Minjiang River Estuary. *Industrial Construction, 48*(5), 127–133.

Xu J. (1887) Outline of Coastal Defense.

Yao, Q., & Lv, D. (2004) On Historical Evolution of the Ancient Tongwan City & Its Architecture. *Journal of Yan'an University (Social Science Edition), 26*(2), 126–128.

Yuan, R., Song, X., Li, J., & Ding C. (2010) Research on rammed earth composition and building craftsmanship in ancient emplacement at Jiaoshan. *Science of Conservation and Archaeology, 22*(2), 18–22.

Zhang, H., Shi, M., Shen, W., Li, Z., Zhang, B., Liu, R., & Zhang, R. (2013) Damage or protection? The role of smoked crust on sandstones from Yungang Grottoes. *Journal of Archaeological Science, 40*, 935–942.

Zhang, H., & Wan, L. (2010) Research on the optimal formula of “Lime-soil” for restoration of the Xiaoshi harbor fort site at Huangshan, Jiangyin. *Science of Conservation and Archaeology, 22*(2), 23–26.
Zhang, K., Zhang, H., Fang, S., Li, J., Zheng, Y., & Zhang, B. (2014) Textual and experimental studies on the compositions of traditional Chinese organic–inorganic mortars. *Archaeometry*, 56, 100–115.

Zheng, Y., Zhang, H., & Zhang, B. (2016) A new method in detecting the sticky rice component in traditional Chinese tabia. *Archaeometry*, 58(S1), 218–229.

Zhou, S., Chen, H., Li, S., Zhang, F., & Liu, X. (2019) Engineering Characteristics Analysis of Four Guangzhou Artillery Batteries of Qing Dynasty. *Heritage Observation*, 4(2):136–138.

**Tables**

Please see the supplementary files section to view the tables.

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![Figure 1](image)

**Figure 1**

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The capillary water absorption test results of the tabia samples.

Supplementary Files

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