Chapter 1
Impact Response of Coquina

S.G. Subhash, P. Jannotti, and G. Subhash

Abstract The Castillo de San Marcos Fort in St. Augustine, FL was built over 330 years ago and has endured numerous wars between the Spanish and the British. During these wars, cannonballs were fired at the fort walls and became embedded in the walls. The walls did not shatter, nor did large cracks form. The fort was constructed from a native rock called coquina, found on the east coast of Florida and the west coast of Australia. Coquina is a highly porous sedimentary rock, consisting of crushed shells, fossils, limestone, sand, minerals, and clay. There are no scientific studies illustrating coquina's ability to withstand cannonball impacts. This research focused on testing coquina and a similar material (a commercial cellular foam) in uniaxial compression. The compression experiments revealed that coquina had two times the specific energy compared to a structural foam. The research revealed that the microstructure of coquina allows impact to be absorbed by progressive failure and hence possesses a high energy absorption capability.

Keywords Coquina • Rock • Energy absorption • Impact • Castillo de San Marcos

1.1 Introduction

The Castillo de San Marcos fort in St. Augustine, Florida, has been standing for 330 years [1–3]. It has endured numerous wars between the Spanish and British, and several hurricane. During the wars, cannon balls were fired and the impact impressions can still be seen in the fort walls. The fort is built from the native rock called coquina which is was quarried along the east coast of Florida. Coquina rock is mainly formed of crushed shell, fragmented fossils and coral, limestone, sand, minerals and clay [4, 5]. It contains many pores and is relatively soft when quarried and it hardens over the years from surface exposure [6].

Currently, little scientific information is available which details the mechanical response of coquina which can be used to rationalize its historical significance as a structural material. To the authors' knowledge, only one study by Knab and Clifton [7] has been conducted to examine the physical properties of coquina such as static compressive and flexural strength, dry density, and water absorption; however, beyond determining these properties there is a lack of experimental investigation of the energy absorbing capacity of the coquina. The current study seeks to identify the specific energy of coquina compared to a modern day structural foam which has a similar cellular structure (albeit man-made).

The Castillo de San Marcos Fort was built by Spanish and each wall of the fort is 12 ft thick and the wall facing the harbor is 19 ft thick. Seven years after the fort was built, the British attacked the fort [1]. However, when the cannon balls hit, the coquina absorbed the impact without causing large cracks in the wall. The cannon balls became stuck a few inches deep into the wall. The walls did not crack or fragments from the wall did not eject off. Surprisingly, to date, no systematic studies have been performed to understand this behavior. More than a million visitors and students visit each year but no detailed scientific explanation is available to these visitors. With this motivation, the current study was conducted to understand the behavior of Coquina under quasistatic compression (Figs. 1.1, 1.2, and 1.3).

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B. Song et al. (eds.), *Dynamic Behavior of Materials, Volume 1*,
Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-22452-7_1

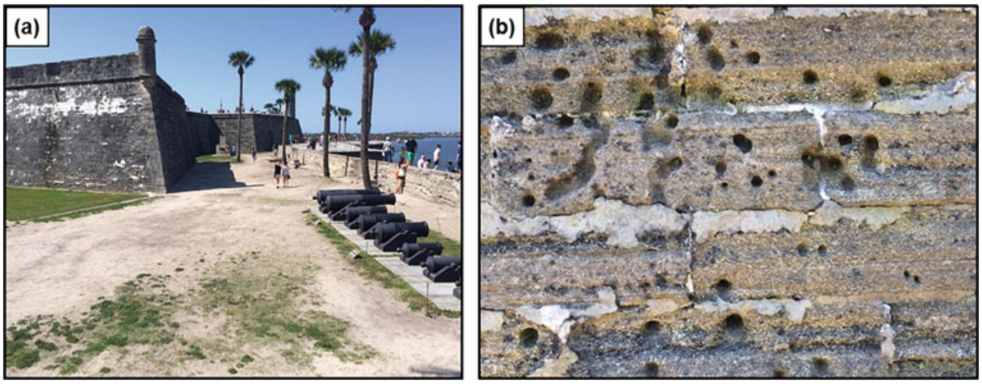

Fig. 1.1 Image of the Castillo de San Marcos fort in St. Augustine, FL and (**a**) residual impressions left in the fort walls due to projectile impacts. Notice in (**b**) that no significant cracking extends beyond the impact craters

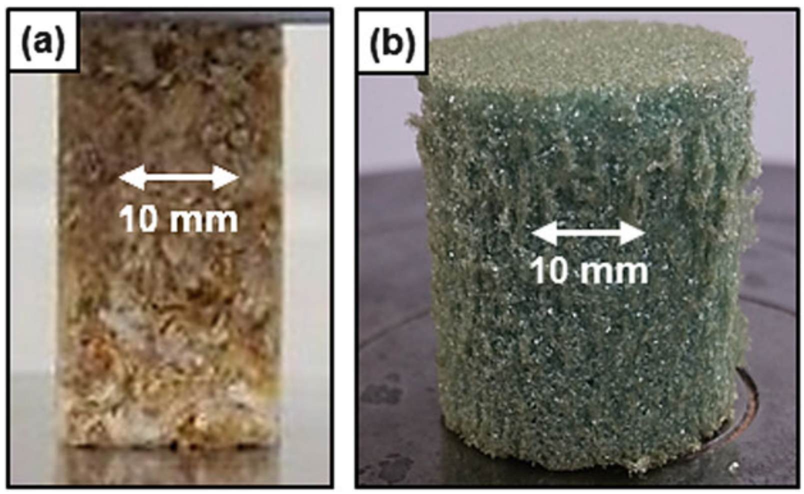

Fig. 1.2 Images of the (**a**) coquina and (**b**) foam samples used for testing

Fig. 1.3 Image of the servo-hydraulic testing machine used to perform quasi-static compression experiments

1.2 Materials

Coquina is a sedimentary rock made up primarily of small clam, oyster, and mollusk shells as well as fossils, sands, and calcite [4, 5]. Samples of approximately 100 mm × 100 mm × 25 mm were purchased from the Castillo de San Marcos Fort Gift Shop and cut into appropriate size and shape for various tests. This coquina was quarried from Summer Haven, FL. To gain better insight into its deformation behavior another material with similar microstructure, i.e., a commercial foam, was also obtained and cut into the appropriate size and shape for testing. The commercial foam, trade named Divinicell® H-60, was selected due to its uniformity in porosity and cellular structure. This material is expected to provide the response of an ideal cellular material with uniform porosity and will act as a reference to understand the response of natural materials (Table 1.1).

1.3 Experimental

Quasi-static uniaxial compression studies were conducted using a servo-hydraulic testing machine (MTS model 309.2, Eden Prairie, MN USA). The force-displacement data from quasistatic tests were plotted for each material and the area under the curves, which represents the energy absorbed during deformation, was calculated and compared. The surfaces in contact with the test specimens were lightly lubricated prior to experimentation to minimize friction between the loading surfaces and the specimens. Using displacement control, specimens were tested at a nominal strain rate of 10^{-4} s^{-1}.

1.4 Results and Discussion

The compression tests revealed interesting differences in the behaviors of coquina and foam. The force-displacement curves, shown in Fig. 1.4, revealed that for coquina, the applied force increased initially and reached a maximum. At this stage, the load dropped rapidly as is typical for brittle materials, but rather than experiencing catastrophic failure the load stabilized to around 20 % of the peak load. This behavior was marked by intermittent increase and decrease (load oscillation) until the

Table 1.1 Selected properties of coquina and foam

Material	Density(g/cc)	Compressive strength (MPa)
Coquina	1.4–1.6 [7]	1.0–1.9 [7]
Foam	0.06 [8]	0.9 [8]

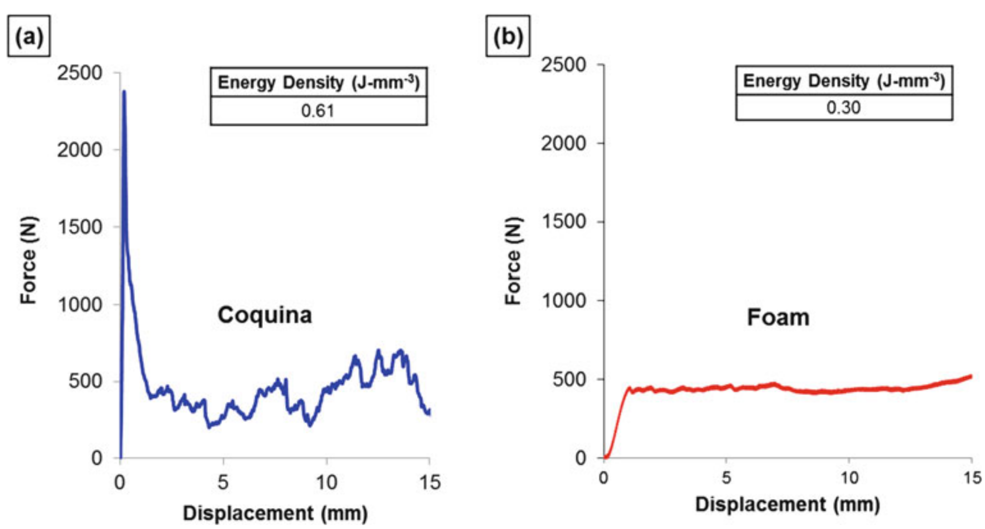

Fig. 1.4 Representative load-displacement curves for (**a**) coquina and (**b**) foam

coquina was fully crushed. In this way, coquina exhibits a progressive failure as it is crushed beyond is elastic limit. It can be inferred that such crushing in coquina occurs by particle debonding due to weak interparticle bonding. On the other hand, the commercial foam revealed an initial peak in applied load followed by continuous crushing behavior at the peak stress. Unlike the brittle coquina, the foam had a nearly constant load bearing capacity beyond its peak load. Here, crushing relates to the buckling of cell walls, resulting in pore closure and crushing.

The area under each force-displacement curve represents the energy consumed in the deformation process for that specimen. For the coquina and foam approximately 0.61 and 0.30 J-mm^{-3} was absorbed over ~15 mm of displacement. It is noted that coquina has around two times the energy absorption capability compared to foam. Despite being a brittle material, the coquina exhibits an ability to retain load after its initial load drop, which contributed to the excellent dissipation of energy due to the cannon ball impacts during the wars.

1.5 Conclusions

The energy absorbed per unit volume of coquina is significantly higher than that of the foam with similar cellular/porous structure. As the cannon ball impacted the coquina, these mechanisms came into play immediately and hence cracks did not propagate long distances and no large fragments ejected from the fort wall. The energy of the impact was absorbed locally. These mechanisms contributed to the ability of the fort to withstand the impacts of cannon balls and the effects of hurricanes.

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