Physical characterization of heritage mortars for restoration interventions

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***Abstract*—The analysis of old mortars is performed for either conservation, repair or the compatible restoration of heritage buildings. It includes experimental analysis of original materials from historic buildings using the non-destructive methods. The methods such as visual investigation, color test, cohesion test and microscopic analysis are considered the most cost-effective methods for determining the composition of heritage mortars. The paper reports the results of an experimental investigation into the physical properties of the cementing materials from the oldest colonial building in South Africa; *Castle of Good Hope*. The original materials from the Castle were made of lime as a binder, fragments of seashells as aggregates and soil mortars without a binder. The physical characterization of original heritage mortars gives details of the binder type and the aggregate type. It may help to achieve the sustainable restoration of ancient buildings.**

Keywords—physical characterization, heritage mortars, compatible restoration, sustainability

I. INTRODUCTION

The use of lime as binder dates as far back as the first millennium BC [1]. This type of binder was used for the construction of various structure types such as temples, churches, castles, cathedrals, monuments and museumswa among others. As a result, all structures that were constructed before the mid-eighteenth century are neither Portland cement nor ordinary Portland cement based. Such structures were constructed using lime-based or soil mortars [2]. This is because natural cement was only introduced to the construction industry towards the end of the nineteenth century [3, 4].

According to research, the use of Portland cement for restoring heritage buildings does not only provide unfavorable results but, also accelerates deterioration on original masonry surfaces. Nonetheless, a majority of heritage restoration projects are still executed using Portland cement materials even though the structures were built with lime-based mortars. The application of the modern materials for repair of historic buildings is indeed found to be a common application practice [5, 6]. This approach often fails as lime-based mortars have different properties to the cement-based mortars; hence, merging the old material with the modern Portland cement materials warrant careful attention [7]. For example, lime mortars have low mechanical strength, slow setting behavior, low modulus of elasticity, high permeability and low resistance to the freeze-thaw cycles, as opposed to Portland cement-based materials which have high mechanical strength, less permeability, heat of hydration and possible shrinkage caused by a decrease in volume during hydration [8]. The differences are in most cases the basis for incompatibility when the two materials merged.

Even though most historic buildings last for decades, even more than some of the modern constructions [9], they face deterioration with time. This is the case on the Castle as it shows some signs of deterioration on its masonry. When this happens, the primary concern is authenticity as far as heritage restoration is concerned [10]. It becomes a challenge to source the best fit repair materials from the modern construction materials whose properties differ from the original historic materials. This is due to little knowledge of the concept of original heritage material analysis prior to restoration works. It could lead to the loss of structural integrity over the years caused by repeated repairs using generally incompatible repair materials. Moreover, this is a significant threat to historic buildings as their existence is, to some extent threatened by this.

Considering the problems associated with heritage masonry restoration, material analysis is proposed as an intervention measure before restoration [11]. The analysis involves analyzing material samples collected from heritage buildings using the procedure in Fig 1. It encompasses the survey of original materials on site, conducting the non-destructive, minor destructive and destructive laboratory testing. The analysis could be referred to as the reverse engineering process which seeks to determine the original mortar components (aggregates, binder and additives).

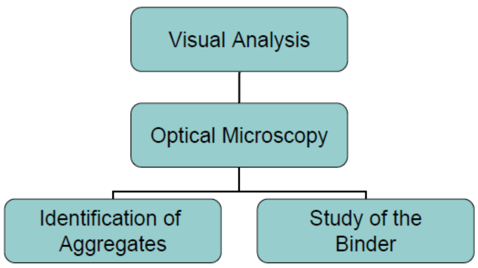

Figure 1. Mortar characterization procedure [12]

In this study, only non-destructive testing was performed to investigate the physical properties of the materials at the Castle. The analysis provided necessary details on the mortar components; however, it is advised to carry out confirmatory tests to verify the results of the physical characterization. Further, the analysis could be either chemical (aggregates type, cementation and hydraulicity indices for determination of binder type) or the mechanical analysis (mortar strength).

II. STUDY AREA

A. Location

The study was carried out at the Castle of Good Hope, which is located at Cape Town, in the Western Cape Province, South Africa as shown in Fig. 2. The castle was originally built on the Table Bay coastline, but due to land reclamation, it is now inland [13]. The samples were collected from the kitchen (oldest area of the castle) and physically analysed.

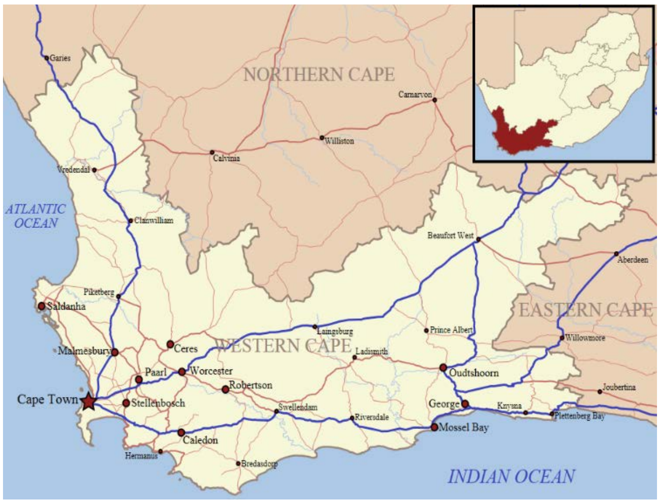

Figure 2. Western Cape, South Africa [14]

B. History

The Castle is the second fort at the Cape which dates back from 1666 to 1679. It is considered the oldest existing colonial building in South Africa [15]. This historic building has a pentagon shape and is made of stone and block masonry, as shown in Fig. 3. At present, the Castle houses the administration and organization elements of the military (Headquarters of Western Cape Command). The structure is open for tourists.

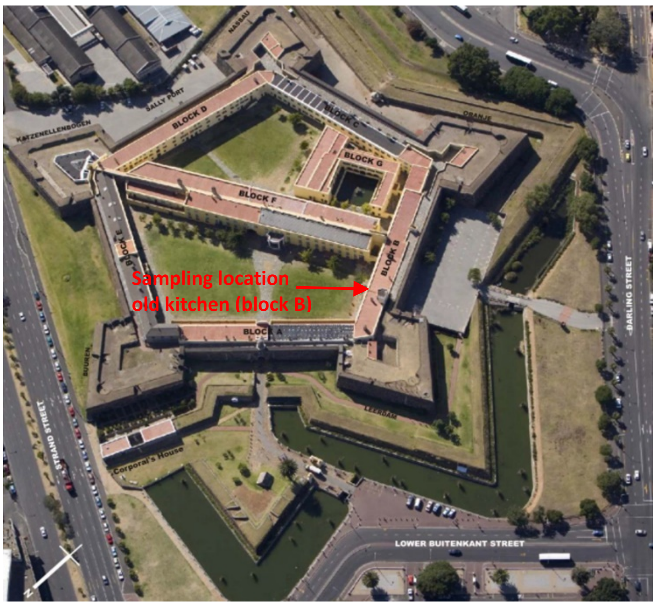

Figure 3. Castle of Good Hope, South Africa [13]

The Castle, like many other old buildings, deteriorated over to such an extent that some parts became unsafe to use. This resulted in a repair and restoration project, which started around mid to late 1960s [16]. However, this building is still experiencing materials failure and deterioration in some areas. Some of the deteriorations are caused by natural factors such as aging and weathering. Additionally, the use of incompatible materials for repair of old areas seems to be a challenge not only for this structure but a majority of other historic buildings, worldwide.

III. METHODOLOGY

The samples were collected from Block B - old kitchen and taken to the laboratory for analysis. Prior to laboratory testing, a thorough on-site visual investigation was carried out. The analysis was investigating the aspects of mortar used, such as the degree of deterioration and the condition of the surface material (original or repairs). Fig. 4 indicates the location where the samples were collected.

Figure 4. Internal masonry, Castle of Good Hope-South Africa

A. Materials

A total of nine representative samples were collected for analysis using a small hammer and a chisel. Where possible, 1 kg of materials were collected from the floor, plaster and the bedding materials. Areas targeted were those who were already damaged, to avoid causing disturbance to the structure. All the samples were named and described according to their appearance in terms of color, texture and location in accordance with the sampling data sheet [17]. The data sheet shows information such as the sample location (wall, foundation, exterior or interior), the function of the sample being either render, plaster or jointing/bedding among the essential details. Fig. 5 shows some of the samples during collection before they were physically analysed and the prepared materials awaiting analysis.

Figure 5. Test samples

After collection of the intact materials as indicated above, the samples were prepared for further analysis through gentle crushing using a mortar and pestle. It was done to avoid breaking the respective particle sizes of aggregates that would have an impact on the gradation curve.

B. Methods

- **Visual investigation:** was carried out following a procedure outlined by [18]. The physical, analytical method helps distinguish between the original and the recent repair materials. The behavior of the two materials from different eras is assessed through this characterisation technique. The materials are assessed on site prior to collection for laboratory sampling. The color of the material, the binder and aggregate types are predicted right at this stage. It gives relevant data to dismiss the use of any mismatching materials on the spot.

- **Cohesion test:** The texture of the material was tested in alignment to [19]. The procedure involves the use of human hands to gently rub and break the material between the fingers to determine its texture. This analytical technique helps identify the texture of the aggregate used for the production of the material. The technique does not require any use of equipment or apparatus. The sample roughness denotes the high content of aggregates in the mortar while the smooth mortar surface indicates high binder content [19].

- **Microscopic analysis**: The mortar chip is placed under an optical microscope (see Fig. 6) to evaluate the particle distribution and the particle sizes. From this characterization method, the size of the particles of additives is determined to lead the restorer in search of replica repair materials. The microscopic images display magnified details of the sample that were missed by the naked eye. A procedure by [18] was referenced in this study.

Figure 6. Microscopic analysis set-up

- **Sieve analysis**: The experiment was the determination of the particle distribution curve. It is considered a critical factor in defining the quality of a mortar mix [20]. The pattern at which the soil is distributed in a mortar mix determines its engineering properties even though the properties do not depend only on the gradation properties [21]. Hence, it is considered necessary to determine the distribution pattern. It can only be performed on material samples greater than 200 g. The reason for the use of a large amount of materials is to get the best representation of particles retained on all the different sieve sizes.

  The non-standard dry method aligning to [18] was followed for this study. The method involves passing 300 g of mortar in a powder form though a set of sieves and weighing the materials retained on each sieve. The useful soil parameters were computed from the logarithmic plot of particle distribution curves. The parameters included the uniformity coefficient (C_u) and coefficient of curvature (C_c), which are computed from the extrapolation of the 10%, 30% and 60% materials passing the corresponding sieve sizes.

Coefficient of uniformity

The coefficient of uniformity is a parameter that evaluates the consistency in the particle size in accordance with (1) [22, 23].

$$\mathbf{C_u = \frac{D_{60}}{D_{10}}} \tag{1}$$

Coefficient of curvature

The coefficient of curvature (C_c) evaluates the variation in size of soil particles, and, therefore, the gradation of different particle size ranges. It is calculated using (2). The C_u of 1 indicates the grain sizes, which are all the same (poorly graded material), $C_u > 1$ indicates the uniform material. For the soil to be classified as well-graded, it must meet the criteria: $C_u > 1 < C_c < 3$ [22, 23].

$$C_c = \frac{D_{30}^{\ 2}}{D_{10} \times D_{60}} \quad (2)$$

Where:

D_{10} – the sieve size when 10% of the particles are still being retained

D_{30} – the sieve size when 30% of the particles are still being retained

D_{60} – the sieve size when 60% of the particles are still being retained

IV. RESULTS

The majority of the samples from the castle were whitish in color with traces of seashell fragments, as indicated in Table I. The friable materials showed no signs of binder present. It could be the reason for the loose particles as there is no binder to hold the aggregates together.

TABLE I. VISUAL & COHESION PROPERTIES

ID	Type	Color	Cohesion	Binder	Additive
SK1	Plaster	Whitish	Tough	Lime	Shell
SK2	Platser	Whitish grey	Tough	Lime	Shell
SK3	Platser	Whitish yellow	Tough	Lime	Shell
SK4	Floor	Whitish grey	V. Tough	Lime	Shell
SK5	Joints	Whitish	Tough	Lime	Shell
SK6	Joints	Cream white	Tough	Lime	Shell
SK7	Joints	Light yellowish	Friable	None	Soil
SK8	Joints	Reddish brown	Friable	None	Soil
SK9	Joints	Yellowish orange	Friable	None	Soil

*The binder and aggregate types are based on a visual investigation

The microscopic images of the mortars indicated the shell particles to range between 0.5 and 25 mm. This range was different for different samples. Fig. 7 illustrates the magnified mortar samples as were seen under a microscope.

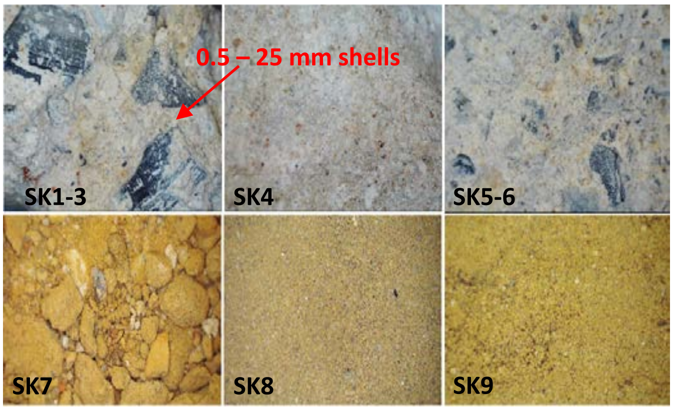

Figure 7. Microscopic images

The gradation curves for the samples weighing 200 g are shown in Fig. 8. The mortars indicated the presence of well graded aggregates. According to [21], a well-graded aggregate has some effect on the porosity and retraction of mortars. The binder results in homogenous and consistent mortars.

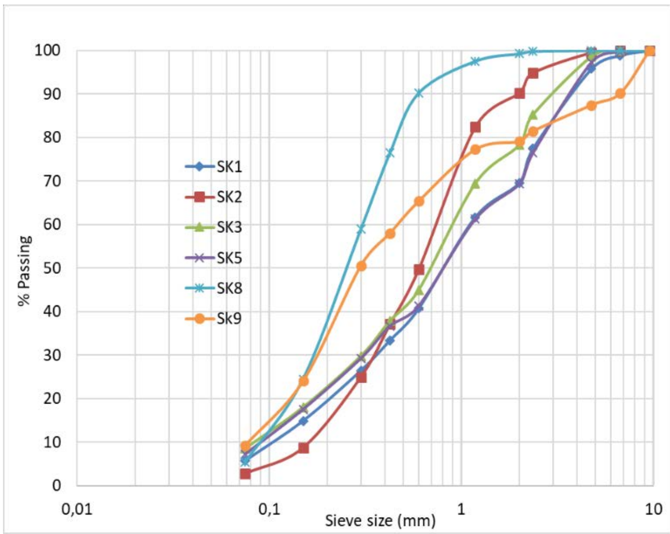

Figure 8. Sieve analysis

The values of D_{10}, D_{30} and D_{60} were determined by extrapolation on the sieve analysis logarithm plot. The results for the soil parameters used for classification of mortar samples are presented in Table II for each mortar sample. Looking at the values for the coefficients of uniformity and curvature, it can be concluded that the mortars were made of uniform soils except for sample 8, which was well graded.

TABLE II. SOIL CLASSIFICATION PARAMETERS

ID	D_{10}	D_{30}	D_{60}	C_u	C_c	Gradation
SK1	0.075	0.170	1.100	14.7	0.4	Uniform
SK2	0.075	0.170	0.730	9.7	0.5	Uniform
SK3	0.075	0.170	0.900	12.0	0.4	Uniform
SK5	0.075	0.170	1.100	14.7	0.4	Uniform
SK8	0.075	0.170	0.300	4.0	1.3	Well-graded
SK9	0.075	0.170	0.460	6.1	0.8	Uniform

V. CONCLUSION

It is vital to investigate and understand the physical properties of the original mortar before carrying out any restoration on heritage buildings. It gives valuable information on the material composition which would work as a guide for searching for replica materials. However, the concept of historic material characterization is yet to be explored in detail on the African continent. Only a few studies have analysed the properties of heritage material properties for restoration interventions in Africa.

The analysis of not only the physical but, also the chemical, mineralogical and mechanical properties of historic mortars would provide detailed results on mortar composition, hence, compatible restoration. The study in such area would be a worthwhile investment as it will help augment the life span of historic buildings through compatible and sustainable restoration.

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