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# Engineering Properties of Building Materials in Historic Buildings in Bagamoyo (Tanzania)

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***ABSTRACT:-The paper investigates the physical, mechanical, mineralogical and chemical properties of building materials in historic buildings in Bagamoyo and exposes the causes of deterioration in the materials in order to identify the effective treatment to repair the damages with the replacements that match the original in composition, colour, texture, and design. Because the deterioration of historic buildings is mainly in masonry material mainly due to salt crystallization, this paper focuses on walling materials (limestone and conglomerates, coral stones and mortar) widely used as building materials in the historic buildings in Bagamoyo. Uniaxial compressive strength, dry unit weight and water absorption were carried out to determine the geomechanical properties of masonry materials. The results revealed that average compressive strength of limestone, coral stone and mortar was 20.8 N/mm$^2$, 10.3 N/mm$^2$ and 0.75N/mm$^2$ respectively. Likewise, the total absorption capacity of the limestone ranged from 5% to 8% while that of coral stones ranged from 28% to 34%. On the other hand, the average bulk density of limestone was found to be 2,311 kg/m$^3$ while that of coral stone was found to be 1,189 kg/m$^3$. The results of XRD show mainly the presence of calcite followed by quartz, small quantity of feldspar and lack of clay mineral in mortars. The main destructive elements behind the deterioration of historic buildings were weak mortar quality and to a smaller extent absorption capacity, salt transport and contamination. Lastly, the study ascertained the effect of marine salt crystallization on the physical and mechanical properties of building materials in historic building by carrying out salt-loading tests. The damaging salts identified in friable mortar included chlorides, nitrates and sulphates These salts are believed to have influenced the disintegration processes of masonry units in historic buildings in Bagamoyo.***

***Index Terms**: Chemical Composition, Compressive Strength; Absorption Capacity; and the X-Ray Diffraction (XRD).*

## I. INTRODUCTION

Many historic buildings in Bagamoyo, Tanzania are experiencing rapid deterioration of building materials mainly caused by lack of maintenance, climatic conditions, ageing of materials, use of incorrect or faulty incorrect materials for repair, poor workmanship and inherent structural design defects. Inadequate maintenance is mainly a result of shear negligence by public and government concern of historic buildings whereby most citizens attach them to slave trade and colonialism. The climatic factors include rain, temperature, wind and atmospheric pollutants acting singly or in combination with other agents of deterioration. Rainwater in combination with atmospheric gases result in acid rain which causes salt crystallization in porous network of mortars and limestone commonly found in historic buildings. Temperature on the other hand can worsen the rates of deterioration by assisting the patterns of salt migration within the network of mortars and limestone. Likewise wind combined with high rainfall, places a lot of stress on structural behaviour of historic buildings in terms of keeping them dry as well as causing erosion and unnecessary movement. Other deteriorations affecting the structural behaviour of historic buildings which are caused by climatic factors include staining, blistering, crumbling, chipping, cracking, crazing, detachment, efflorescence, flaking, friability, peeling, sugaring, exfoliation, delamination, surface crust, rising damp and spalling. All these defects have a large effect on physical, mechanical and chemical properties of masonry units. The physical, mechanical strength and durability properties and chemical compositions play significant roles in structural behaviour of historic buildings. Accurate understanding of masonry physico–mechanical properties, which are mainly uniaxial compressive strength, water absorption and unit volume weight helps in finding better solutions for restoration interventions [7] and [22]. Although the determination of built-in material properties proves difficult, many authors have spearheaded the tests mainly compressive strength tests [10], [14], [15] and [17]. The compressive strength tests are usually conducted to determine the ability of a material to resist deformation under load. Similarly, water absorption is a characteristic of masonry materials that indeed paints a true picture of moisture movement and storage which play a key role in the durability of building [6]. Likewise, density often relates to the strength, toughness and stiffness of masonry material. It is from the above facts that masonry properties such as compressive strength, absorption and density (hardness) indicate the suitability for selection of building materials. Aside, chemical properties of materials like structure, composition, reactions, resistance against environmental effect like salt attack also affect the selection of engineering building materials for restoration purpose. This calls an investigation on chemical properties of masonry units as well as chemical and physical impact of salts. Salt which is widely transported by moisture in porous network of mortars and stones of historic buildings is the major cause of deterioration of the masonry walls [11], [21] and [25]. The restoration of historic building may call for removal and replacement of materials heavily disintegrated or deteriorated and affected by soluble salts. During restoration, every attempt should be made to retain or restore as much of the original building fabric as possible so that the building continues to carry its original history. Any material to be replaced should match the original in its mineral composition and physico–mechanical properties. It is from this fact that the basic properties of materials used in the building are therefore investigated as guide towards restoration of the building.

## II. BACKGROUND TO BAGAMOYO HISTORIC BUILDINGS

Bagamoyo boasts as one of the East Africa's largest assembly of 18th century architecture. It was at one time the most important city of mainland Tanganyika and the most important harbour in East Africa. When the colony of German East Africa was established in 1888, Bagamoyo was chosen as the capital [24]. However, over time the importance of Bagamoyo has declined due to both historical and economic reasons [12]. To the end of the 19th C and throughout the 19th C Bagamoyo prominence has significantly deteriorated to the verge of collapse. The town of Bagamoyo is a home to many spacious and beautiful historic buildings dating back to the early contacts between East Africa, the Middle and Far East. Some of the outstanding testimonies of the built heritage are the Old Fort built in 1860, Customs House built in 1895 and the Old Boma Building built in 1897 [18]. These historic buildings are important for our future to constantly remind us the physical materials, ideas, skills, knowledge and the flow of our culture over the past. In order to create a more sustainable future**,** it is important to preserve, enhance and enjoy significant historic buildings [19].

## III. METHODOLOGY AND EXPERIMENTAL APPROACH

To gather useful information of the important historic buildings in Bagamoyo, this study employed interpretive historic research based on literature review and case study approach. To tackle this complex challenge, much effort was directed to a comprehensive review of existing literature, on-site examination of the property, extensive photographic documentation of the material features and condition of the building, mapping the building layout and landscape features of the property, in-depth archival research to reveal the history of the property and informant interviews and written narrative, and laboratory tests. The literature review was mostly acquired from published books, research papers, seminar papers and journals mainly from the archival records of the Department of Antiquitie. The literature review was supplemented with the in-depth physical investigation of the building in question to go on with the building's history. The in-depth physical observations were carried out through site survey/pilot survey where data was obtained from a visual inspection of defects at its exact location or based on building elements. Measurements, construction details, foundation survey, identification of major alterations and documentation of condition of the building elements were detailed step-by-step with sketches and digital photographs where necessary. Laboratory experimental tests included bulk density, basic mechanical strength (uniaxial compressive strength), absorption tests, chemical composition, XRD and salt-loading test. Stone specimens and mortar samples were taken from sections of walls that had fallen from the buildings in accordance with obtained permit and tested in the laboratories at the University of Dar es Salaam and SEAMIC for geomechanical and chemical properties respectively. The limestone and coral stones specimens were taken from the walls by using a cutting machine. Most mortars were too soft to withstand conditioning stress, so no mortar specimens were retrieved for this test. Compressive strength, density and water absorption were three major properties tested. The compressive strength was tested according to [2] on samples size 60×60×60mm dried for 24 hours in oven at 60ºC and the absorption and bulk density was carried out according to [4]. Observation of mortar samples under a petrographic microscope according to [1] permitted an extra insight into the mortars composition. On the other hand, X-Ray Diffraction (XRD) technique following the method of [8] was employed to identify and quantify the minerals and the chemical composition were determined by performing Scan Electron Microscope (SEM) on both lime stones and coral stones. For salt-loading tests, samples dried overnight at $40^{o}C$ were used for testing. Thereafter 5 g of dried powder sample placed in a glass bottle with 100 ml distilled water and boiled for 30 minutes and allowed to cool (covered) overnight. Prior to the detection of ionic concentration, the solution was filtered to remove possible interference from suspended particles. The anion contents (mg/l) was analyzed using a spectrophotometer as well as by wet chemical analysis using standardized reagents for $Cl^-$, $SO_4^{2-}$ and $NO_3$. The tests to determine physical and mechanical properties of materials were conducted so that the repair should strive to use only similar materials which were used originally or materials with comparable physical characteristics to the original materials so as to preserve the authenticity of the property as a historic resource.

## IV. STRUCTURAL CONDITION OF HISTORIC BUILDINGS IN BAGAMOYO

In order to identify the appropriate preservation for historic buildings in Bagamoyo, it is important to identify the form and detailing of architectural materials and construction details that are important in defining the character or historical significance of the building that are to be retained and preserved. The historic buildings in Bagamoyo are predominantly detached or semi-detached with one or two floors that were constructed in the late $19^{th}$ century. Most of the buildings are designed in the

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blend of Swahili- Arabic style architectural design. The Swahili culture is depicted in the corridors, the verandahs and the U form that opens in the backyard. The Arabic style is in the decorations of pillars, towers, walls and some of the doors and windows. For most historic houses the design and construction of foundations comprises a strip of stone in lime mortar supporting floors and load-bearing walls. A thick layer of coral stones bonded with clay-lime mortar is provided below floor finish. The main gravity load-bearing structure consists of massive stone masonry walls made up of limestone and coral stones bonded with clay or clay-lime mortar and rendered with lime mortar and finished with lime-wash, creating flat and white façades. The walls act as lateral as well as gravity load-bearing elements. The windows in many historic buildings are solid wooden shutters and doors are wide and mostly ornately paneled. In these historic buildings in Bagamoyo there was no standardization for openings (doors and windows), thus not possible to generalize the number or size of these elements. The roofs are mainly pitched with a high gable covered with full-length sheets of corrugated iron sheets.

## V. DAMAGE IDENTIFICATION

The identification of damages and technical condition of historic buildings is very important prior to identifying and undertaking appropriate preservation measures. The buildings were looked for evidence of condensation and black mould staining, peeling of rendering and plaster, disintegrating mortar, Most of the Bagamoyo buildings have born too much stamp of wear and tear because of dearth of serious maintenance for centuries. Some buildings are completely falling beyond economic repair (Figures 1). The dilapidation survey or revealed that the lime washed plastered walls have eroded and lost their outer skins in some areas due to the action of climate mainly wind, temperature and rain (Figure 2). In certain cases the friable mortar has completely disintegrated into dust leaving the lime-stones and coral stones completely exposed. Close examination revealed that the cause of the disintegration in the masonry elements is rooted in the deteriorated mortar leaving the limestone and coral stone firmly intact. It is from this fact that most physical and chemical tests were mostly directed at the mortars and little allusion was paid to the walling materials. Further examination revealed some roof leakages in some historic buildings to the extent that damp patches an condensations are penetrating the ceiling (Figure 3). In the efforts to restore the some buildings, incompatible materials (e.g. cement sand blocks instead of limestone) were used (Figure 4). The use of different materials is likely to cause differential expansion.

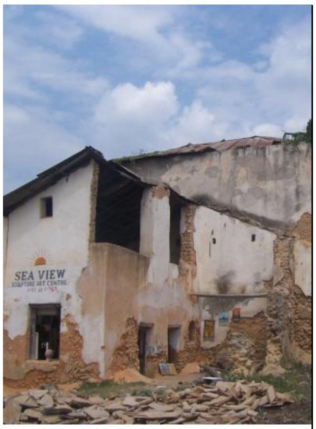


**Fig 1: Incurably deteriorated historic building falling apart inside and out in Bagamoyo, Tanzania**

**Fig 2: Lime plaster falling off the external wall of the Old Fort in Bagamoyo, Tanzania**

**Fig 3: Condensation, dampness and mould growth on the slab of the Old Boma**

**Fig 4: Use of cement sand blocks not similar to the original limestone on German Customs House in Bagamoyo, Tanzania**

## VI. RESULTS AND DISCUSSION

The results of chemical composition are presented in Table 1. Both stones composed of high amount of calcium oxide (CaO) with an approximate proportion of more than 50%, high amount of MgO as well as active compounds of calcium silicates and aluminates. Thus, the stones used in this building are more likely to yield hydraulic limes [9]. The mortar on the other hand contains low percentage of Calcium Oxide (CaO) indicating that it is not pure hydraulic lime but hydrated lime (air-hardening lime), also known as quicklime. These mortars were probably made by mixing both hydraulic and non-hydraulic or feebly-hydraulic lime aggregates such as marine deposits, sand and crushed sedimentary rocks found in the neighborhood of the historic buildings. It is reported that the non-hydraulic conglomerate were burned using open heap kilns, with the alternating layers of limestone and woods laying on

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top of each other followed by a long-term storage of slaked lime (Ca(OH)2) under water. The results of water absorption are shown in Table 1. Coral stones have higher rates of water absorption than lime stones. The higher water absorption in coral stones indicates that they allow water to pass through them easily which may induce physico-chemical reactions (dissolution, crystallization) leading to textural changes and deterioration. Likewise the results of the bulk density are found in Table 1. The average bulk density of limestone was found to be 2,311 $kg/m^3$ while that of coral stone was found to be 1,189 $kg/m^3$. According to [4], limestone is Class II (Medium-density) while coral stone is Class I (Low-density). Figure 5 indicates the main crystalline compounds identified by XRD in the mortar. In the figure calcite appeared to be the most abundant compound followed by quartz, feldspar in small quantity and additional presence of beidellite clay mineral. The results of XRD indicate lack of clay mineral which is the main source of expandable minerals. Further tests to examine the presence of expandable chemicals in the soft and friable mortar showed no significant shifts in the peaks after glycolation (Figure 6). It can be concluded from the results of the XRD after glycolation that the clay mineral in the mortar is a non-swelling. The assessment of the salt distribution in the dry lime mortar powder showed more accumulation of salts at the surface that decreased with height (Table 3 and Figures 7 and 8). $Cl^-$ emerged as the major ions present in all samples. The concentration of chloride decreased with both height and depth. $NO_3^-$ on the other hand increased with both depth and height. $SO_4^{2-}$ decreased with height but slightly increased towards the interior of the wall. This behavior is due to the fact that sulphates are less soluble salts than nitrates and chloride and therefore difficult to be easily transported to higher level. Because the historic buildings in Bagamoyo are very close to the Indian Ocean, the salts from the ocean easily affect the mortars. A sacrificial plaster is a good solution to preserve exposed mortar and protect it from the penetration of sea salt.

**Table 1: Chemical Composition of Coral and Lime Stones**

| | Content, % (weight in percent) | | |
|---|---|---|---|
| Component | Lime | Coral Stone | Lime Stone |
| CaO | 42.19 | 52.98 | 53.83 |
| $SiO_2$ | 17.2 | 2.93 | 0.51 |
| $Al_2O_3$ | 4.5 | 0.91 | 0.14 |
| $Fe_2O_3$ | 0.07 | 0.03 | 0.95 |
| MgO | 0.52 | 0.35 | 0.41 |
| $Na_2O$ | 0.39 | 0.33 | <0.01 |
| $K_2O$ | 0.89 | 0.1 | <0.01 |
| $SO_3$ | 0.54 | 0.41 | 0.11 |
| $P_2O_5$ | 0.15 | 0.07 | 0.09 |
| SrO | nd | 0.95 | 0.25 |
| Cl | 0.25 | nd | nd |
| $Cr_2O_3$ | 0.04 | nd | nd |
| MnO | 0.02 | nd | nd |
| $TiO_2$ | 0.19 | 0.06 | 0.03 |
| $ZrO_2$ | nd | 0.18 | <0.01 |
| LOI | 32.83 | 40.7 | 43.68 |

**Table 2: Compressive strength, bulk density and water absorption of Lime and Coral stones**

| Category | Compressive strength ($N/mm^2$) | Bulk density $kg/m^3$ | Total water absorption, % (weight percent) |
|---|---|---|---|
| Lime stone 1 | 17.1 | 2,481 | 5 |
| Lime stone 2 | 20.2 | 2,354 | 6 |
| Lime stone 3 | 25.1 | 2,100 | 8 |
| Coral stone 1 | 9.5 | 1,350 | 28 |
| Coral stone 2 | 9.2 | 1,015 | 32 |
| Coral stone 3 | 12.1 | 1,204 | 34 |

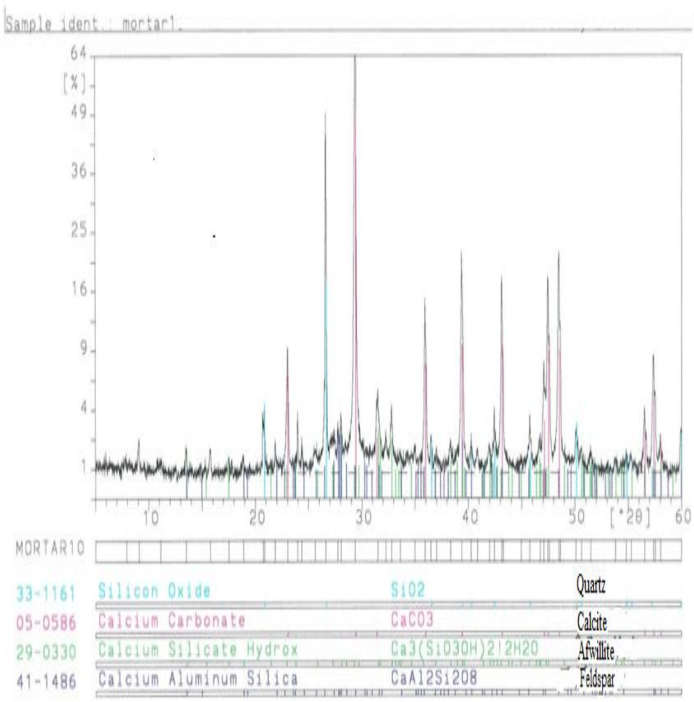


**Fig 1: X-ray diffracts gram patterns attributed to the calcite, quartz and feldspar.**

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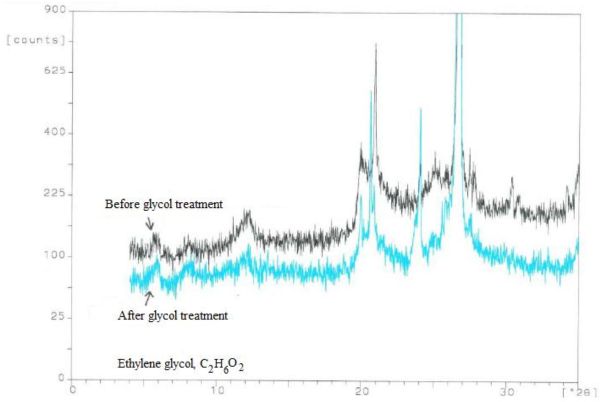


**Fig 6: X-ray diffractogram showing peaks before and after treatment with ethylene glycol**

**Table 3: Anion Content (%w/w) of powdered mortar sample**

| Sample | Sample category | Height (m) | Depth (cm) | $Cl^-$ | $N0_3^-$ | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|
| A | 1 | 0.5 | 0.5 | 1.85 | 0.59 | 0.07 |
| | 2 | 0.5 | 1.0 - 2.0 | 1.13 | 0.51 | 0.12 |
| | 3 | 0.5 | 3.0 - 4.0 | 1.75 | 0.67 | 0.16 |
| B | 1 | 1.5 | 0.5 | 1.84 | 0.67 | 0.06 |
| | 2 | 1.5 | 1.0 - 2.0 | 1.15 | 0.71 | 0.08 |
| | 3 | 1.5 | 3.0 - 4.0 | 1.17 | 0.6 | 0.11 |

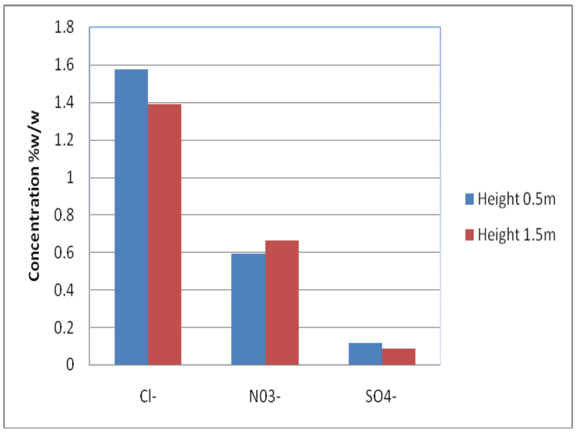


**Fig 7: Types of Soluble Salts with Heights**

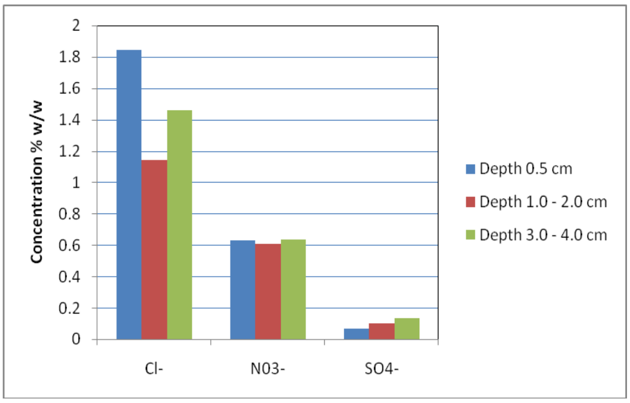


**Fig 8: Types of Soluble Salts with Widths**

## VII. CONCLUSION

Many historic buildings in Bagamoyo, Tanzania have fallen into a state of disrepair because of a lack of continuing and effective maintenance plan. The cause of the problem is mainly revolving around badly deteriorated mortar joints caused by different chemical, physical, mechanical and biological processes. The chemical analysis carried out on both stones and mortar indicated that the mortar contained low percentage of Calcium Oxide (CaO) exhibiting poor cementing and hydraulic properties. Likewise, the X-Ray Diffraction (XRD) measurement indicated the presence of quartz, feldspars and calcite in the mortars implying that they have indeed practically lost their binding ability due to presence of weak zone at the interface of the particles. Luckily, X-Ray Diffraction patterns of glycolated samples indicated that mortars were free of expandable clay minerals. Furthermore, the deteriorated mortars mainly due to excessive water infiltration proved to be rich in crystallized soluble salts. The concentration of total soluble salts decreased with both depth and height. This behaviour suggests that the most likely sources of the salts are due to both groundwater and prevailing winds carrying ocean salt and depositing it on the wall. This was proved from the assessment of the salt distribution analyzed by carrying out a number of chemical analyses. The high pressure generated during the crystallization of salts inside the mortar indeed triggered serious structural failure and total collapse of various historic buildings in Bagamoyo, Tanzania. Based on water absorption and density tests, limestones were favoured over coral stones because porous coral stones might obvious be sensitive to deteriorating weather influence. However, the fact that mortar proved to be relatively friable and disintegrated when soaked in water; it was not tested for water absorption. Dilapidation surveys and accurate laboratory tests of samples are vital steps in the conservation of historic buildings. The conservation should as much as possible preserve most of the values of the building [5], [6], [13], [20], [23] and [26]. Both physical and chemical properties of the existing materials should be maintained during restoration. As such, the friable, dusting and salt affected mortar should be removed and replaced with the stabilizing mortar based on pure hydraulic lime (by mixing slaked pure lime with clay and calcining the mixture) that will ensure long term performance of mortar. Where stones need replacement, limestone rather than coral stones should be used because they have higher strength and less water absorption. Stones like limestone with high strength are generally more durable than coral stones and those with low strength (coral stones) are more susceptible to breaking and fracture. Likewise, stones with low absorption provide some indication of the stones' performance in service, particularly their strength and stain resistance while those with high water absorption will be more susceptible to the presence of deleterious inclusions and staining from liquids. Finally, the masonry units (mortar and stones) should be protected from the effect of salts by applying lime plasters on them.

## VIII. ACKNOWLEDGEMENT

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## PERSONAL PROFILE

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(KTH) in Sweden in 2006 and 2008 respectively. He has widely published and presented various peer reviewed technical engineering papers in international journals and conferences.