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Microstructural Analysis of Failure in Building Materials

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ABSTRACT

Scanning Electron Microscopy "SEM" provide valuable tools to identify microstructural differences in materials due to ageing, aggressive environmental exposures and loading. Image processing technique has been applied on several SEM micrographs to provide information on the extent of damage in the surfaces of the microstructure; it measures the area of micro-voids on the surface. Analysis has shown that lime mortar materials were the main building materials used in many heritage buildings due to the ease of production and application. However due to long exposure the lime mortar develop failure in the mode of cracks, crumbling and erosion of the materials. Steel sections were also deteriorated due to environmental exposure combined with loading. Therefore, to understand how various materials degraded with time, it is important to analyze the microstructural changes supplemented with measurement of the area of damages in the form of micro-voids. SEM micrographs revealed loose microstructures in damaged lime mortar materials and uniform and dense microstructures in protected and durable materials. The void fraction of the damaged steel section due to load and exposure was found to be 0.0003.

Keywords: *SEM, Lime Mortar, Microstructure, Steel, Micro-Voids, Image Processing.*

1. INTRODUCTION

Scanning Electron Microscopy "SEM" combined with X-Ray analysis has been used in characterization of various types of materials that are used in cultural and historical buildings. It can be used for concrete, bricks, steel, bronze and wood materials. Mortar materials removed from historical cultural sites were investigated to determine its mineralogical compositions in order to define and produce new mortar materials that are compatible with the original old mortar and make it easy to repair. Transitions between such areas of high and low-density binder appear to be sharp[1] as shown in Figure 1.

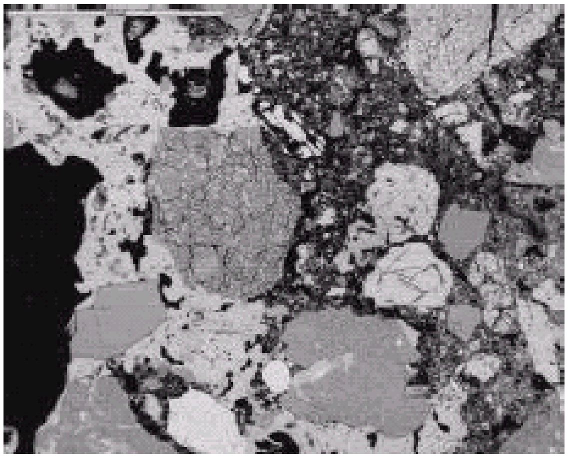


Figure 1: Mortar removed from old cultural building[1]

Hughes and Cuthbert used SEM to study sections taken from historical castles. The SEM revealed many components contain numerous dense, brown particles that have a fine-grained texture and are commonly of a size 10-200 microns[1] as appeared in Figure 2. Their interpretation was based on the absence of aggregate within these particles and their similarity in appearance to the surrounding lime binder [1].

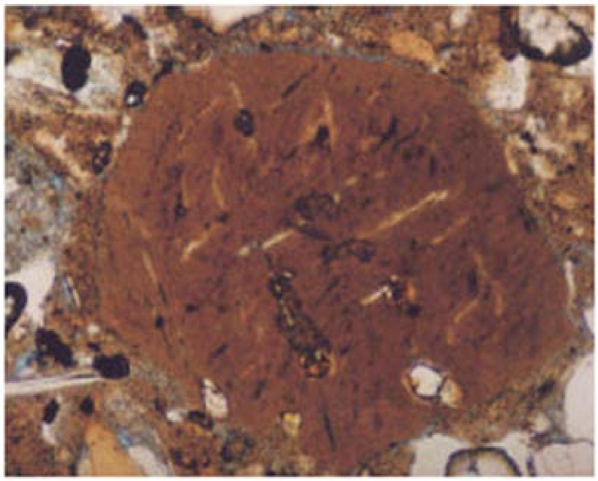


Figure 2: Lime binder [1]

They prepared thin sections and studied them under the microscope, it showed evidence of voids uniformly distributed in the samples [1] as shown on Figures 3 and 4.

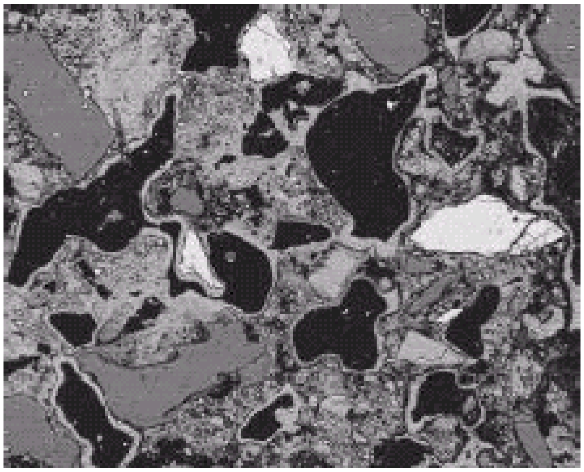


Figure 3: Voids in thin sections [1]

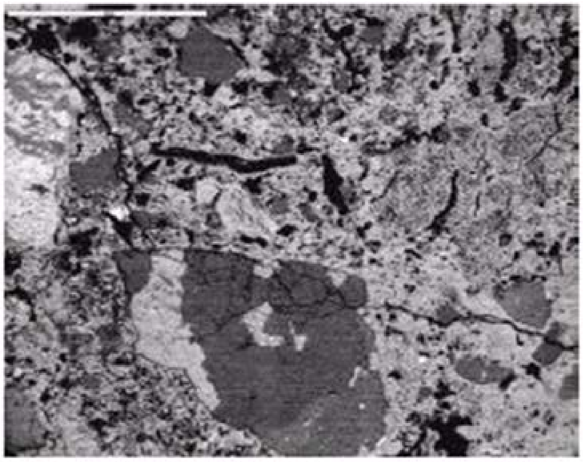


Figure 4: Voids in thin sections [1]

The adoption of the fraction area of voids and cracks measurement method was due to the fact that the original definition of damage is related to the effective area concept. Modern image analysis tools have heightened the use of this approach to measure damaged areas [2]. The Scanning Electron Microscope (SEM) is utilized in this study due to its great incorporated features. It produces easily interpreted micro-graphs and provides diverse information that can be employed for qualitative and quantitative analysis. The SEM is being used as a successful tool for material characterization since it reveals two or three dimensional information about the microstructure, the chemistry, and crystallography of the tested material. SEM images have a large field depth that displays spatial variations, high quality of resolution and a wide range of magnification from 20X to almost 30000X. The SEM also can focus on specific points for analysis. SEMs are relatively easy to work with and they require few sample preparation steps. Generation of images takes time approximately less than five minutes. Additionally, these images can be converted to any suitable format. Some limitations include the sample size which can be a maximum of 10 cm horizontally and 40 mm vertically. SEM analysis does not lead to volume loss of the sample, so it is possible to analyze the same materials repeatedly [3].

2. SAMPLING AND METHODOGY

SEM has also been used to investigate damages in steel cross sections. Round type specimens of length 200 mm and diameter of 12 mm were used in the tests. Figure 5 shows the SEM used in this research. The experimental specimens were manufactured according to ASTM E9 standards [4] with the only modification of a shorter gauge length to enable the higher strain rates and prevent buckling due to high compression straining. The geometry of the chosen specimen has been widely employed in the literature due to the following main reasons; (1) pre-determined location of failure, (2) assumed proportional loading conditions along the minimum section; (3) the stress triaxiality is considered to be constant during the whole deformation process with the plastic strain as approximately uniform along the gauge length [5].

Figure 5: Scanning Electron Microscope – The Petroleum Institute (Philips-FEI Quanta 200)

Table 1: Mechanical properties of the steel

Yield Stress σ_y (MPa)	Ultimate Stress σ_u (MPa)	Ultimate Strain ε_u (%)	Young's Modulus E (GPa)	Poisson's Ratio v	Hardening coefficient B (MPa)	Hardening power n
460	600	9.3	200	0.3	710	0.5

3. SAMPLE SPECIFICATION

Table 1 shows the mechanical properties of the steel bar used in the research. The measured yield and ultimate stresses of the material are 460 MPa and 600 MPa, respectively.

4. RESULTS AND DISCUSSIONS

Damage in materials can be divided into several types according to the prevailing macroscopic behavior, as mentioned by [6-7], and others in the literature. These types include brittle, ductile, creep and fatigue damages. In brittle damage, micro-defects are initiated without significant plastic strains unlike ductile damage in which micro-defects are caused by large plastic strains. Creep damage is related to high temperature loadings while fatigue damage is formed due to cyclic loadings. A damage parameter φ is introduced, which represents the damage evolution. Voyiadjis and Kattan [8] defined the damage variable φ for the case of isotropic damage using the effective stress concept as the following:

$$\varphi = \frac{\mathbf{A}-\bar{\mathbf{A}}}{\mathbf{A}}$$

Where $\bar{\mathbf{A}}$ is the effective net area and A is the damaged area as shown in Figure 3. The net area can be calculated by subtracting the areas of the micro-defects. The previous expression shows that when φ=0, the material is undamaged (the damaged area and effective undamaged area are the same). On the other hand, when φ=1 the effective area is zero and material is totally damaged with a complete loss of material's structural integrity (i.e., fracture of the Representative Volume Element (RVE)) as shown on Figure 6.

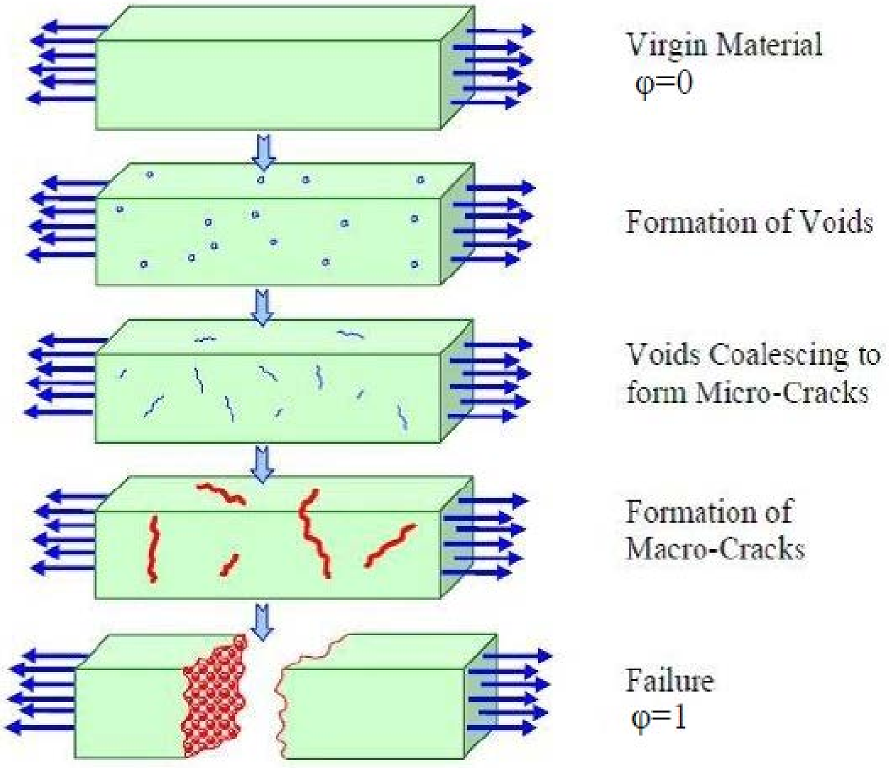


Figure 6: Damage in terms of crack evolution [8].

The theoretical value of φ is between $0 \leq \varphi \leq 1$ while in reality Lemaitre [9] set the critical value of the damage variable to be between $0.2 \leq \varphi_{cr} \leq 0.8$ for metals.

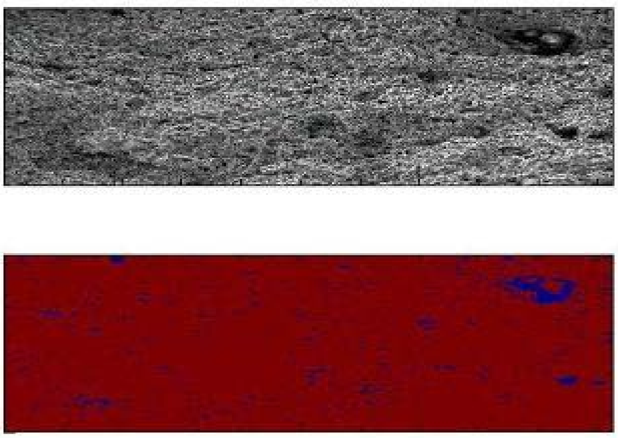
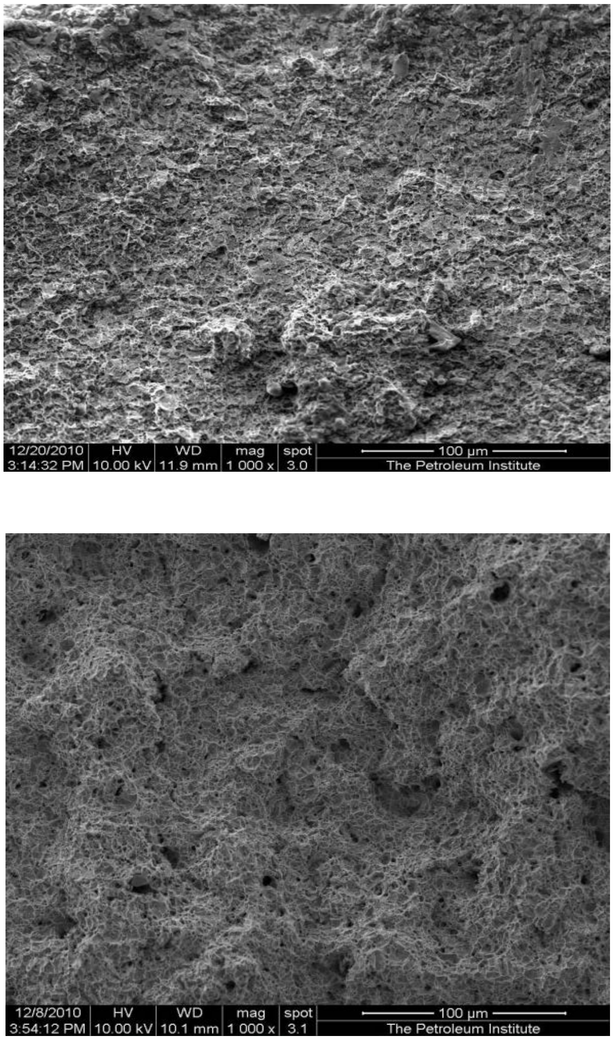


Figure 7: Image obtained by SEM and Binary Image



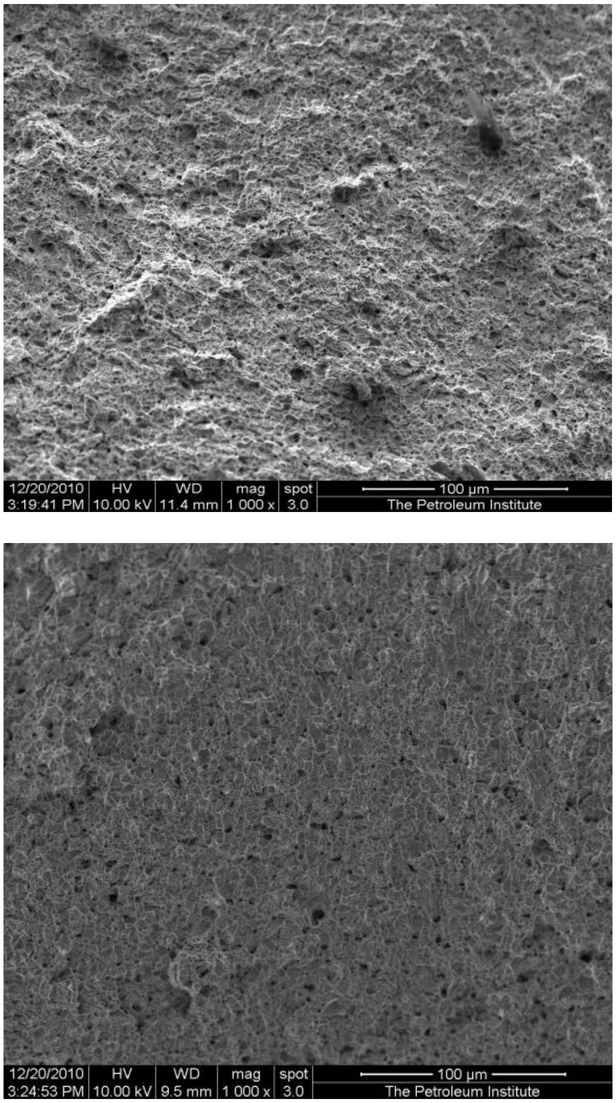


Figure 8: SEM samples at 1000X magnification

Damage is characterized by void nucleation, growth and coalescence and it is concentrated in regions near the fracture surface where plastic strains and the associated stresses are the highest. The void fractions were found using image processing techniques. The software that was used to handle images is called XL Docu. This program provides enhancements in image handling and manipulation, expanded measurement and annotation capabilities and flexible database image storage and retrieval. Thresholds were set to identify varying gray areas in the images to obtain binary images (Refer to Figure 7), such that everything below it in pixel numerical value is assumed to belong to an air void and everything above that threshold value is assumed to belong to solid surface. The ratio is then computed to obtain some kind of a density measure which could be highly correlated with the actual object density. Images at 1000X were taken in which damage measurements showed very close results as shown on Figure 8. The whole sample is shown but the micro voids are not visible. SEM micrographs reveal different microstructures; however they are not enough to reach solid conclusion without extra analyzes such as measuring the area of voids using image processing technique. The initial void fraction of the present steel was found to be 0.0003. Therefore, combination of SEM and image processing are useful tools to provide qualitative and quantitative results for the damages in artifacts materials used in historical buildings.

5. CONCLUSIONS

a. Harsh environment combined with long term ageing are the main factors of deterioration of materials used in historical buildings.

b. It is crucial to understand the characteristics and behavior of old materials used in historical building before restoration begins.

c. Durability plays significant role in the service life of materials; deterioration of any materials depends mainly on its durability. Materials will undergo chemical and physical changes though ageing. Therefore, comparability between deteriorated and new materials should be evaluated before repair commences.

d. Scanning Electron Microscopy and X-Ray Analysis have been used successfully in evaluating the characteristics of the materials taken from historical building and study their mineralogical compositions.

e. SEM micrographs showed loose microstructure at higher plastic strain which resulted in a complete state of fracture.

f. Combination of SEM and image processing provide both qualitative and quantitative measurements to assess damages artifacts.

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