Engineering Assessment and Recycling of Building Stones Produced from the Destroyed Buildings in Old Mosul City

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Abstract

Building stones have various mineralogical, textures, microstructures, and physical and mechanical properties. Limestone, dolomite, and gypsum stone samples were taken from the old city of Mosul, which was destroyed due to the liberation operation of the city. From the study of the rock segments, it appeared that there was a low percentage of the pores that were formed due to the dissolution process, as well as the effect of weathering was a few centimeters in depth. From the results of the physical tests of the samples, it appeared that the density of the limestone is low to high for the grey gypsum. The grey gypsum has zero porosity, while low in gypsum and medium to high in dolomite and limestone, respectively. The rate of forced water absorption varies, and the reason is the difference in the porosity as it increases with connected pores, which in turn leads to an increase in the amount of absorbed water. According to the results of the mechanical tests of the rocks, the compressive strength was low to medium, and the durability of the rocks was high, this confirms the validity of the rocks in the study area as unloading bearing stones. The economic feasibility results from not transporting the old rocks, but rather using them in the same site in the city. These huge quantities of stones, which took a great deal of work and money to bring to the city from the outskirts, cannot be wasted by transporting them outside the city because it will cause significant pollution and cost time and money, whereas they can be used in the reconstruction of the destroyed city, for instance, unloading bearing stones.

Keywords: Building stone; Mosul City; Demashed buildings; Recycling

1. Introduction

The city of Mosul is the largest governorate in Iraq, which has great historical and geographical importance, cited geomorphologically in the karst zone of Iraq (Sissakian et al., 2011) (Fig. 1). The destroyed old city of Mosul requires special legislation to ensure sustainability post-war reconstruction. Most countries around the world invented a modern urban planning system in the postwar period, which includes the enactment of urban and rural planning laws (Ratcliffe, 2009). Modern architectural studies confirm the destruction of historical centers and the disappearance of urban landmarks in the old city of Mosul after it was destroyed during the liberation operation in 2017. It is critical to construct a new center that encounters modern requirements, while also reviving the city and preserving its local character based on the old masterplan (Abdulla et al., 2021). The proximity of the quarries to the city

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was one of the most important factors that led to the use of stones in construction. The most common stones used in wall construction are limestone and dolomite, while white gypsum and grey gypsum were used to construct door and window frames (Al-Jawadi et al., 2022a). Usually, the thickness of the walls is large in the houses due to the weakness of the banding material (plaster) to bear the weights and ceilings, as well as for thermal insulation because the climate in Mosul city is very extreme. A previous study on rocks in Nineveh Governorate (Saleh, 2012) reveals a wide range of carbonate rock characteristics because of differences in weathering conditions (Arman et al., 2019).

Building stones are used for a variety of purposes, and global production is increasing as a result of ongoing research in several related fields (Swenson, and Chang, 2020). Building stone has provided readily available, natural building materials for thousands of years due to its superior strength, beauty, and longevity as well as in the long term, very cost-effective for almost all building applications. To propose the best building stone, detailed studies are required to assess the main factors controlling the physical-mechanical properties (PMP) and durability (Sousa et al., 2021). PMP of building stones, particularly porosity and compressive strength, reflect their variability (Siegesmund and Durrast, 2020). The data on carbonate rock strength demonstrates a wide range of variability, and the derived correlation equations of the rock strength parameters are proposed. The knowledge of (PMP) of stones used in heritage monuments is critical, both to understand the constraint factors dominating the evaluation under specific environmental conditions and to predict the durability and lifetime of the buildings. Stone structures appeal to us psychologically because they represent security and provide a sense of protection. Because the building stones have a wide variety, namely by differences in the process of formation, mineralogy composition, grain size, and texture, they are simple and elegant (Sousa et al., 2021). Good physical and mechanical engineering properties of building materials, including stones, are required for the design of safe and sustainable engineering structures such as homes and commercial buildings (Arman, 2023). The main factors governing stone behavior are texture and porosity, but weather conditions will accelerate the deterioration of highly porous rocks (Barnoos et al., 2020). The uniaxial compressive strength of limestone ranges from 4.4 MPa to 265 MPa when the porosity ranges from 20% to 1%, according to statistical analysis (Arman et al., 2021). Carbonate rocks with pure calcite, no dolomite, and no iron oxide as a cementing material are more susceptible to mechanical failure than other carbonate rocks (Arman et al., 2021). Gypsum is a building material that has been used since ancient times (Spina et al., 2015).

2. Geological Setting

The Fatha Formation (Middle Miocene) in the study area consists of a succession of clayey marl, green silt, white gypsum or grey gypsum rocks, and limestone in the form of cycles (Fig. 2). The thickness of this formation in the Mosul region varies between the 170-190 meters and gradually decreases towards the northeast (Al-Rawi, 1971). The total thickness of the formation around the city of
Mosul is 175 m according to the study that was implemented for the fifth bridge project in Mosul city (Al-Numan and Adeeb, 1995). With a few special cases that may be credited to the karstic solution of the gypsum beds, the beds in Mosul city commonly dip nearly 0.64 degrees to the east.

![Figure 2: Stratigraphic section of Fatha Formation and geological map of Mosul City](image)

**3. Materials and Methods**

Field surveys were carried out in Mosul's old city to characterize the effects of time on building stones. It was discovered that the presence of these stones in old buildings, some of which are over 100 years old, the weathering had little effect on them. Therefore, at the destroyed sites, stone samples of various types and positions were collected. Some samples were from the exposed outer walls, while others were from the inner walls. Cases of limestone used in the construction of monuments over sixty years old vary depending on the location of the building blocks and their impact on weather conditions and water activities (Saheb et al., 2016).

The Rock Laboratory at the College of Engineering and the Geological Laboratory at the Department of Geology at the University of Mosul was used to prepare rock samples for various tests. The general description of the building stones and the effect of weathering on the surface of the sample were directly tested, as well as the samples were cut to show the depth of weathering at the medium endoscopic scale. Moreover, the thin sections were prepared to show possible petrographic observations by using double staining of the pore network. Cubic samples with dimensions of 10 x 10 x 10 cm³ are used for physical and mechanical tests, which are density, porosity, water absorption, and uniaxial
compressive strength (Fig. 3). Lump samples for slake durability testing (Fig. 4), as well as thin sections for studying petro-physical properties, are used to determine the suitability of the rock as building stones. The tests are done according to (ASTM C97.618817-1, ASTM C170.618817-1, ASTM D2216.618817-1, ASTM C1721.618817-1, and ISRM, 1977).

**Fig. 3** Cubic samples with dimensions of 10 x 10 x 10 cm³ are used for physical and mechanical tests, which are density, porosity, water absorption, and uniaxial compressive strength.

**Fig. 4.** Samples for slake durability test.

4. Results and Discussion

From the petrographic study of limestone samples, it appeared that the rocks were not affected by military operations that took place in the city, it was also not affected by weathering, just a few millimeters depth from the surface (Fig. 5). Gypsum stones were affected by weathering, however, they can be used in reconstruction, as evidenced by the fact that this type of stone was previously used (Fig 6). The density, porosity, and absorption ratio of rock samples were measured with modern technology in the laboratories of the engineering college. The results showed that the density of the in-study site ranged from 1.682 gm/cm³ to 2.609 gm/cm³ and the porosity ranged from 3.03% to 22.6% and the
absorption ratio ranged between 1.4% and 12.09% and the corrosion test ranged between 91.93% and 98.56% (Table 1).

![Weathered zone](image)

**Fig. 5.** Thin section view shows the weathered zones on a microscopic scale, the radius of the sample is 3 mm.

From the results of laboratory tests of rock samples, the density of rocks is classified from low to very high density (Williamson, 1984). The lowest total density value was determined in limestone, while the highest density was encountered in grey gypsum rocks. Also, the results of measuring the porosity of rocks showed that they have low to high porosity (Rodrigues, 1988). In addition, the results of the absorption ratio range between (1.4-2.09%) and the reason is the difference in the percentage of connected pores. From the results of the mechanical tests of samples, the corrected uniaxial compressive strength ranged between (6.9-38.6) MPa, and therefore the rocks are classified as having weak to medium strength (Bieniawski, 1989). Physical tests and results of mechanical tests according to Iraqi and international specifications, deduce the suitability of rocks in the old city of Mosul to be recycled as building stones, decorations, and pillars (Fig. 6).

The limestone has the highest percentage of water absorption, exceeding 19% at a rate of more than 12%, while the dolomite has less than half, the gypsum has nearly one-tenth, and the grey gypsum stones have none (Table 1). The slake durability test was performed to determine the extent of resistance of these stones to weathering processes in the event of their use in reconstruction, and the results demonstrated the quality of these stones, particularly dolomite, limestone, and grey gypsum (Table 2). The porous materials, soil, stone, and even concrete have a physical property of porosity. However, this porosity property could be open porosity or closed porosity. Open porosity refers to the pores being interconnected, while, close porosity where the pores are isolated and not interconnected. In this study, the measured porosity is of the type of open porosity the Anhydrite stone has a closed porosity. Thus, the open porosity is zero, and the forced water absorption is also zero.
Table 1. Physical properties of building stones lumps

<table>
<thead>
<tr>
<th>sample number</th>
<th>Rock-type</th>
<th>dry wt. (g)</th>
<th>sat. wt. (g)</th>
<th>submerge d wt. (g)</th>
<th>total porosity (%)</th>
<th>Skeletal density (g/cm³)</th>
<th>apparent density (g/cm³)</th>
<th>forced water absorptio</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 1</td>
<td>Dolomite</td>
<td>165.8</td>
<td>174</td>
<td>102.1</td>
<td>12.380</td>
<td>2.603</td>
<td>2.281</td>
<td>5.43</td>
</tr>
<tr>
<td>D 2</td>
<td>Dolomite</td>
<td>156.4</td>
<td>165</td>
<td>96.7</td>
<td>12.645</td>
<td>2.609</td>
<td>2.279</td>
<td>5.55</td>
</tr>
<tr>
<td>D 3</td>
<td>Dolomite</td>
<td>166.2</td>
<td>176</td>
<td>102.1</td>
<td>13.881</td>
<td>2.598</td>
<td>2.237</td>
<td>6.20</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>12.969</td>
<td></td>
<td></td>
<td>2.603</td>
<td>2.266</td>
<td></td>
<td>5.73</td>
</tr>
<tr>
<td>L 1</td>
<td>Limestone</td>
<td>118.2</td>
<td>141</td>
<td>71.1</td>
<td>32.624</td>
<td>2.497</td>
<td>1.682</td>
<td>19.39</td>
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<tr>
<td>L 2</td>
<td>Limestone</td>
<td>153.2</td>
<td>169</td>
<td>94.4</td>
<td>20.240</td>
<td>2.569</td>
<td>2.049</td>
<td>9.88</td>
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<tr>
<td>L 3</td>
<td>Limestone</td>
<td>127.2</td>
<td>136</td>
<td>78.1</td>
<td>15.266</td>
<td>2.579</td>
<td>2.185</td>
<td>6.99</td>
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<tr>
<td>Average</td>
<td></td>
<td>22.710</td>
<td></td>
<td></td>
<td>2.548</td>
<td>1.972</td>
<td></td>
<td>12.09</td>
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<tr>
<td>G 1</td>
<td>White Gypsum</td>
<td>102.2</td>
<td>105</td>
<td>56.8</td>
<td>6.004</td>
<td>2.251</td>
<td>2.116</td>
<td>5.30</td>
</tr>
<tr>
<td>G 2</td>
<td>White Gypsum</td>
<td>116.2</td>
<td>117</td>
<td>65.4</td>
<td>0.581</td>
<td>2.275</td>
<td>2.262</td>
<td>0.26</td>
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<tr>
<td>G 3</td>
<td>White Gypsum</td>
<td>114.2</td>
<td>116</td>
<td>64.3</td>
<td>2.505</td>
<td>2.271</td>
<td>2.214</td>
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<tr>
<td>Average</td>
<td></td>
<td>3.030</td>
<td></td>
<td></td>
<td>2.266</td>
<td>2.197</td>
<td></td>
<td>1.41</td>
</tr>
<tr>
<td>A 1</td>
<td>Grey Gypsum</td>
<td>125.2</td>
<td>125</td>
<td>71.2</td>
<td>0.000</td>
<td>2.302</td>
<td>2.302</td>
<td>0.00</td>
</tr>
<tr>
<td>A 2</td>
<td>Grey Gypsum</td>
<td>129.2</td>
<td>129</td>
<td>72.9</td>
<td>0.000</td>
<td>2.295</td>
<td>2.295</td>
<td>0.00</td>
</tr>
<tr>
<td>A 3</td>
<td>Grey Gypsum</td>
<td>124.2</td>
<td>124</td>
<td>70.5</td>
<td>0.000</td>
<td>2.301</td>
<td>2.301</td>
<td>0.00</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.000</td>
<td></td>
<td></td>
<td>2.299</td>
<td>2.299</td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 2. Physical and mechanical characteristics of building stone cubes

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Dry Bulk Density gm/cm³</th>
<th>Dry U.C.S. MPa</th>
<th>Saturated U.C.S. MPa</th>
<th>Corrosion %</th>
<th>Durability %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomite</td>
<td>2.205</td>
<td>34.27</td>
<td>23.27</td>
<td>1.44</td>
<td>98.56</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.890</td>
<td>6.92</td>
<td>3.09</td>
<td>2.13</td>
<td>97.87</td>
</tr>
<tr>
<td>White Gypsum</td>
<td>2.110</td>
<td>14.74</td>
<td>4.84</td>
<td>8.07</td>
<td>91.93</td>
</tr>
<tr>
<td>Grey Gypsum</td>
<td>2.200</td>
<td>16.85</td>
<td>13.54</td>
<td>3.92</td>
<td>96.08</td>
</tr>
</tbody>
</table>
5. Conclusions

The use of stones in construction has numerous advantages due to their excellent physical and mechanical engineering specifications, as well as their thermal insulation. This use has structural disadvantages, such as increasing the thickness of stone walls, which reduces the building area. Stones are considered one of the best building materials for recycling, either by using them once or multiple times in reconstruction without significantly affecting their properties, or by recycling them with other uses, such as aggregate. The results of the study revealed a slight deterioration in the properties of building stones after decades of use as building materials. The reuse of these stones in the construction was previously present, as evidenced by a field survey of the old buildings, which revealed the use of some unloading bearing stones from older buildings.

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References


