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## Performance of Stones Under Different Conditions: A Study of Metro Stations

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**Abstract.** The study of stone alterations in the Lisbon Metro stations allowed the discussion of the influence in the development of these alterations of stones characteristics and the actual conditions to which the stones are subjected. Alterations occur under what can be considered the usual conditions of use but also under abnormal situations that must be taken into account given its frequency. The diverse situations identified are considered in the discussion of possible recommendations bearing in mind the actual situations found at the stations.

## Introduction

Stone is one of the main natural materials used on building works around the world. After emplacement in the built environment, stone can suffer diverse alteration processes [1,2,3] that result in features that can be recognized macroscopically. Besides the characteristics of the stones and their variability, stone selection for building works needs also to consider the conditions under which the stone would be placed.

Railway transport stations constitute promising case studies of stone decay and durability since they are reasonable dated and several situations can be found under variable conditions of use and spanning diverse exposition times. Partial studies of alteration of stones in the Lisbon Metro (subway system) have been previously published in [4] regarding decay features associated with exogenous decay agents and in [5] regarding the influence of the characteristics of the materials.

In the present work it is made a synthesis of the results of studies regarding the alterations that diverse types of stones suffer after emplacement in stations of the Lisbon Metro with the view of discussing possible implications for recommendations regarding guidelines for materials selection for these kinds of applications under the conditions of use actually found.

## Materials and methods

The Lisbon Metro is a subway network with stations inaugurated between 1959 and 2009 where a large diversity of building materials (including sedimentary, igneous and metamorphic rocks) can be found in diverse architectural elements under varied conditions of use in outside and inside areas. Information regarding the general history of the stations can be found at [6] and [7] (more information about each station, in Portuguese, can be found at [8]).

The study presented here consists of an extensive study, based on strictly non-invasive and non-destructive macroscopic visual inspection of the types of decay features affecting stones in all the stations. While sometimes being belittled, the importance of visual inspection in general and especially for the assessment of engineering structures has been highlighted, among others, by [9]. This visual inspection approach implies, however, limitations in the knowledge of the characteristics of stones and decay features. In the present study are also lacking data regarding the environmental conditions (temperature, moisture) in the stations. It is admitted that in inside areas, temperature variations will be mild since there is not direct sunlight incidence on the surfaces and considering the general environmental characteristics of Lisbon (in [10] are reported monthly average temperatures between 11.3 °C and 23 °C for the 1971-2000 period). It is proposed that the study of the patterns of distribution of decay features might minimize, by comparison of different situations, the impact of these limitations.

## Results and discussion

The visual inspection of the stations shows a great diversity of alteration features that will be discussed in relation to conditions of use and the characteristics of the stones (and its susceptibility to the exogenous agents).

Stains that can be related to absorption of solutions by the stones pore system are observed at the upper and lower portions of walls, at pavements and at other locals near pathways of solutions (infiltrations and capillary rising). Some stains seem to be simply a darkening related to moisture permanence and are observed in recent stations (Fig. 1a), even at the time of its opening. In some limestones are observed brownish stains similar to those observed in limestones in other modern constructions (Fig. 1b). It has been proposed that limestones can be susceptible to staining by alkaline solutions due to reactions with organic matter and to precipitation of compounds [11,12]. Colour alterations might also involve addition of matter to the surface of the stones by biological growth, particles deposition and inorganic neoformations. While biological growth is generally limited to outside zones, particles deposition and inorganic neoformations can be observed in inside areas. Soluble salts could contribute to white stains thorough the formation of efflorescences (Fig. 1b), that are generally extremely rare considering the whole set of stations but that in the Cais do Sodré station (near the Tagus river) can cover wide areas. Infiltration of salt solutions also seems to be associated with some occurrences of reddish stains that would result from the oxidation of iron containing materials. Whitish coatings (Fig. 1b,c), presumably carbonate-rich, have a noticeable frequency and might cover wide areas, being found in both outside and inside areas of the stations, in walls and stairs, as has been generally observed in other recent constructions [13]. Since they are very stable after formation they are good markers of the circulation of free flowing solutions. In walls the distribution of these coatings seems to be linked to heterogeneities such as joints between blocks and cracks. These carbonate coatings are frequent in stairs, even in those inside the stations, presenting often a distribution that suggests that the contact between treads and risers acts as preferential pathway for the circulation of solutions (Fig. 1c). Particle deposition can be observed in several outside and inside related to particle settling and can be also promote by biological growth and mineral neoformations (such as carbonate coatings). In some cases, it seems that there could be an initial process of formation of black crusts, which might indicate reactions of the stones with atmospheric agents. There are also, in the Cais do Sodré station, stains related to bird excreta in a freestanding wall (Fig. 1d) and at the base of this wall are observed stains with capillary rising type distribution patterns (Fig. 1e), suggesting a possible influence of the excreta (that might evolve to surface erosion in the future).

There are occurrences of erosive features that cause loss of material from the stone. Patterns of occurrence of these erosive features can be discussed mainly in relation to what can be considered customary conditions of use (pavements and stair steps) and in relation to the circulation of solutions (that inside the stations will be considered unexpected conditions).

Erosive decay in pavements (described and illustrated in more detail in [5]) can result in the loss of polishing and the thinning of steps (in limestones) with a distribution pattern that seem related to pedestrian pathways. One can also observe erosive patterns in pavements that seem related to joints between slabs on both limestones and igneous rocks.

Erosive features (resulting in marked differential relief) with a more erratic distribution are observed in some limestone slabs (e.g. Fig. 2a) suggesting the effect of the initial heterogeneities of the stones [5]. These are observed on pavement and walls but are more widespread on the pavements (they are also frequent in walls where the stone was

not polished). It has been proposed for these pavement stones that heterogeneities present from the beginning of their application could develop irregularities that would be exacerbated by the more aggressive conditions of use of the pavements [5]. Indeed one can observe in some recent applications fissures with an orientation that could facilitate the erosion of the fragments. Polishing of the stones would minimize the initial irregularities of the surface of the stones (certainly so it is hoped by the polishers!) and this could explain by the unpolished blocks on the walls seem to present greater irregularities than polished stones in walls and recent pavements. The role of the initial characteristics and the interest of petrographical studies been referred for similar limestone types [14,15].

In other elements (walls, freestanding elements) erosion of stones is observed in places that seem affected by solutions absorption and in this way their distribution also serves to mark the circulation of solutions (Fig. 2b). The most marked case was observed inside the station of Cais do Sodré where evidences of salt contamination (salt efflorescences) are observed associated with these erosive feature (Fig. 2c) and where erosion can affect inscriptions and cause surface recessions of several millimeters in limestones blocks. This is a particularly interesting case since these marked erosive features occur in areas sheltered from direct sunlight exposition. Field observations (Fig. 2d) suggest that the stones had a surface treatment that could contribute to the intense erosive decay of these limestones by avoiding solutions circulation from inside to outside and, hence, promote salt crystallisation inside the pore system of the stone. Erosive features in other locals where decay patterns suggest the absorption of solutions are much less marked. These features could also be related to salt presence, even if no efflorescences are observed. Additionally, it is speculated that stone surfaces treatments could contributed to this erosive decay.

There are also some observations of cracks, some of which seem to be related to the limestone structures and were described in [5]. There are also cracks on the massif limestone types classically used in Portuguese pavements that seem to be related to the application conditions (it is admitted that at least in some cases these cracks could have been formed at the moment of application). Erosion features associated with these cracks occurrences are of limited significance.

## Concluding remarks and recommendations

In these concluding remarks, the observations presented in the previous section will be discussed in a perspective of possible implications for guidelines of materials selection bearing in mind the actual conditions found at the stations.

Occurrences of surface irregularities in stones applied in pavement and stair steps under the customary conditions of use have been observed and are discussed in relation to the stone characteristics. There are erosive patterns in limestones applied in stair steps that seemed related to pedestrian pathways. The choice of stones with higher abrasion resistance should be pondered for this kind of applications. For example, data on abrasion tests from the database of Portuguese ornamental rocks [16] indicates for the limestones and marble types values equal or above 0.9 mm (generally higher than this value) while there are other rock types with better values (for example for granite types in [16] are reported values below or equal to 0.6 mm). In some pavements, the erratic distribution of the erosive features suggests the role of stone heterogeneities in the decay process. In a previous work was referred the interest for the definition of stone selection criteria of the study of petrographical features that promote decay in these stones [5]. The observed patterns of distribution of the decay features suggest that the assessment of the effect of the heterogeneities would require specimens of a significative size (ideally similar to the slabs that are being applied).

There are situations where decay features are related to what can be considered abnormal conditions of use resulting from solutions infiltration. Our extensive study of all the subway stations indicate that solutions infiltrations seem to be an unavoidable problem and that it could be worthwhile to consider this risk in materials selection given its rather frequent occurrence. In that sense, it would be advisable to select for places where there is a higher foreseeable risk of infiltration stones less susceptible to erosive processes or to staining (or, in this last case, stones where the foreseeable stains would have a lesser visual impact). Of particular scientific interest are the erosive decay features related to infiltrations that were observed in inside walls. However, in the assessment of the susceptibility of the wall stones to these erosive processes it is necessary to consider the possible effects of suspected surface treatment that could increase decay by hindering the circulation of solutions to the surface (surface treatments that must, therefore, be avoided).

Some features of soiling seem to indicate reactions between the stones and the atmospheric pollutants. In that sense, it could be considered, for the stations in the most polluted regions of the Metro network, to select stones that are less susceptible to reactions with atmospheric contamination.

Carbonate coatings occur regardless of the material considered and its presence in the inside areas of the stations is also valuable as indicator of circulation of free-flowing solutions (registering the occurrence of these undesirable situations).

Still in relation to pollution sources, the question of the birds excreta, even if very localized, must be considered given its high visual impact (and even possible related environmental concerns) and its potential contribution to the future development of erosive decay.

It was shown that visual inspection studies can help to discuss the effects of the materials characteristics and the conditions of use in the development of alterations features of stones, contributing to the discussion of recommendations for the selection of materials for the actually expectable conditions. Additionally, some of these features can be useful as visible evidences of situations that could be related to defects in the structure.

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