SSRG International Journal of Civil Engineering
ISSN: 2348-8352 / https://doi.org/10.14445/23488352/IJCE-V9I11P106

Volume 9 Issue 11, 43-49, November, 2022


*Original Article*

# Ageing Behavior Analysis of Concrete Tunnel Lining

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Received: 03 October 2022    Revised: 06 Novemer 2022    Accepted: 18 November 2022    Published: 30 November 2022

***Abstract*** - *Tunnel lining may be exposed to a range of deterioration and instability phenomena, such as aging. In the present paper, the ageing behavior of concrete lining has been examined by factorial experiments for three mechanical properties of the concrete lining material (cohesion, angle of internal friction and tensile strength). Badama railway tunnel in Syria has been demonstrated as a case study. Complete factorial experiments were performed using the software Universal Distinct Element Code (UDEC), and further, a correlation between the three studied mechanical properties of the concrete lining was examined using statistical regression analysis. The results showed that the coefficient of concrete cohesion has the most significant effect on the other studied properties.*

***Keywords*** - *Tunnel, Concrete Lining, Ageing behavior, Infrastructure, UDEC.*

## 1. Introduction

Hilly terrain conditions while planning a railway and highway alignment compel the designer to opt for tunnel insertion to optimize the route length and also on cost considerations. Tunnels constitute a critical part of the construction, and they consume the significant capital cost of the project. The safety and durability of tunnels must be ensured during their operations and maintenance of their lifetime due to the high construction cost. Therefore, the long-term performance of the used construction materials has to be studied to determine the structural parameters playing a significant role in lining deterioration of its strength over time. In the long run, many types of structural defects are likely to be developed due to the ageing process, which would be affected significantly by the mechanical properties change in the concrete lining.

Many researchers examined the ageing of concrete for many types of structures.[19],[20],[21], [22],[5], [15],[14],[23],[17],[24],[11],[25]. Many other researchers have studied the ageing behavior of old masonry structures.[18],[9],[13],[2],[10],[7],[6],[8],[3],[16],[4]. Nevertheless, the publication focuses on the analysis of old deep concrete tunnels is very limited.

## 2. Concrete Ageing Phenomena

The strength characteristics of cement concrete change with time and depend on the environmental conditions of the area where the structure is located. The tunnel's concrete lining is a material that directly interacts with the soil, subsoil water and moisture and temperature fluctuations, surcharge loads, lateral forces acting on the soil, etc. Thus, the dynamic factors influence the concrete's structural and behavioral characteristics over time, leading to the development of many types of deteriorations that can appear and develop in this lining, such as cracks and sometimes partial deterioration in the lining. The phenomenon of aging is a complex phenomenon and has many effects on the structural properties of the tunnel lining material.

Environmental factors and the surrounding soil affect the properties of the lining, especially if an effective waterproofing system is not available or damaged where groundwater can easily penetrate discontinuities and breaks. With time, some physical, chemical and biological changes occur in the concrete tunnel lining. This phenomenon and its effects are called the phenomenon of aging.

## 3. Badama Tunnel

The Badama Tunnel is one of eight tunnels located on the axis of the Aleppo-Lattakia railway (Figure 1). The tunnel is surrounded by soil with a stable rocky structure of limestone and marl; therefore, the tunnel was excavated without placing temporary support except in a few parts. The length of the tunnel is 1885.8 meters, and the maximum depth of the tunnel with the mountain is 114 m, as shown in (Figure 2). The tunnel was built in 1971-1972, and the lining was made of ordinary concrete M-200 without reinforcement.[26]. The thickness of the concrete lining is about 60 cm at the wall and 40 cm at the arc (Figure 3).

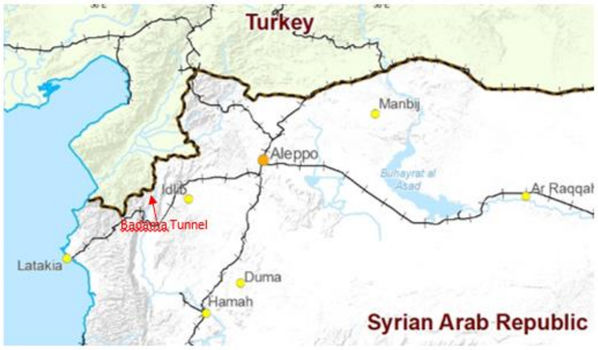


**Fig. 1 Badama Tunnel**

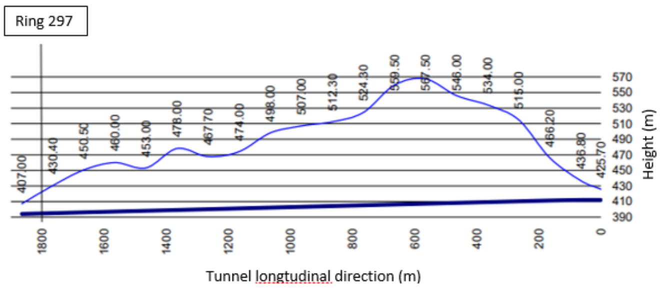


**Fig. 2 Longitudinal section, Badama Tunnel**

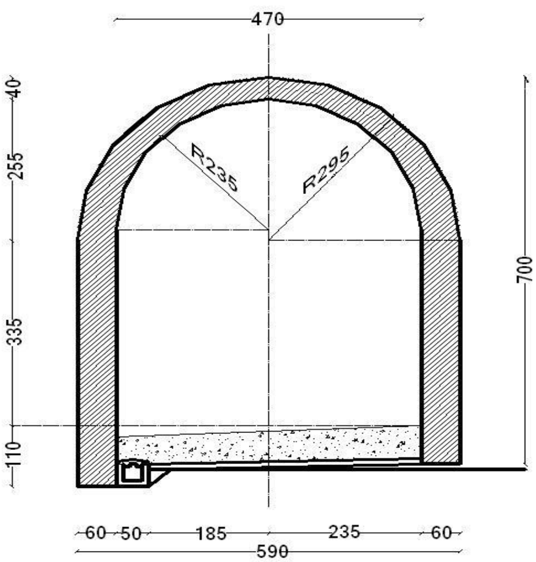


**Fig. 3 Cross section, Badama Tunnel**

## 4. Numerical Model

The 297th ring of the Badama tunnel was modeled at a depth of 23 m (Figure 2) and had the section shown in (Figure 4). At this tunnel ring, many visible structural defects were observed on the cement concrete lining surface in the form of cracks or water seepage. The mechanical properties of the soil, the lining concrete and the discontinuities are given in (Table 1). The analysis state is a plane strain case, and the tunnel lining with the surrounding soil follows Mohr-Coulomb collapse criteria and has an elasto-plastic behavior.[26]. Two stages carried out the calculation, the first one is before tunneling, where the model consolidates in the initial soil stresses, and the second stage is the tunneling stage (Excavation and lining construction).

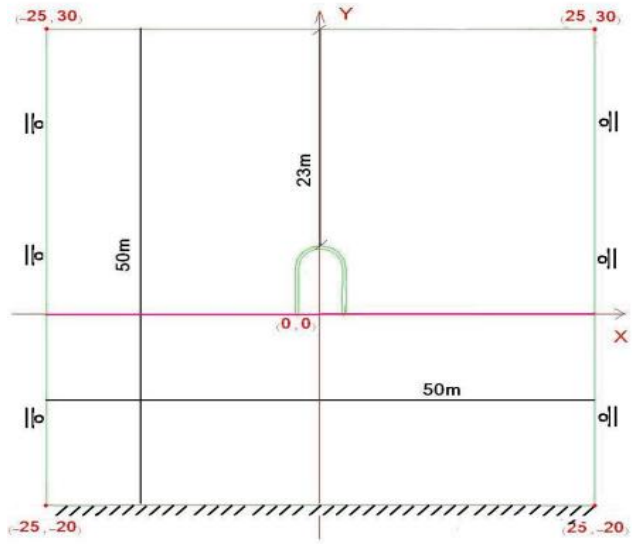


**Fig. 4 Numerical model**

## 5. Modelling  Concrete Ageing Behavior

To understand the structural behavior of the cement concrete lining in tunnels over time, the selected mechanical properties of the concrete lining have been changed alternately to determine the effect of these properties on the structural behavior of this lining and to determine which of these properties have the most significant impact on changing the long+ term behavior of the lining.

The model shown in (Figure 4) was analyzed to study the primary state of the tunnel stability, and the principal, maximum and minimum stresses affecting the lining were calculated. Accordingly, Mohr circles have been drawn that determine the approved collapse criteria for all the elements of the divided network of the lining, as in (Figure 5), which shows that the stresses are affecting the network elements of the tunnel lining fall entirely below the Mohr-Coulomb collapse line indicating that the behavior of this concrete lining material is quite elastic.

The figure also shows the limiting values of cohesion, tensile strength and friction angle of the concrete lining at which the behavior of the lining can be changed from elastic to plastic. Thus, the researchers can determine the minimum and maximum limits for changing the property values.

**Table 1. Behavior of concrete Lining and surrounding soil specifications (Koehne RVP 2004)**

| Strength parameter | Concrete Lining | Surrounding soil |
|---|---|---|
| E(MPa) | 23E3 | 15E3 |
| υ | 0.3 | 0.35 |
| K(MPa) | 19166.7 | 16666.7 |
| G(MPa) | 8846.2 | 5555.6 |

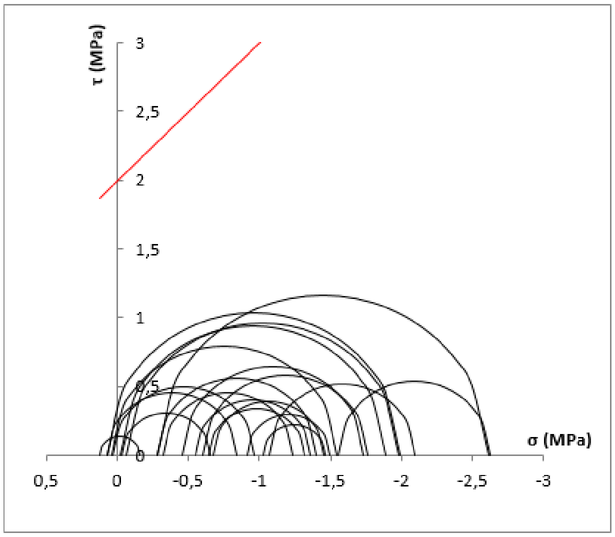


**Fig. 3 Mohr circles for the studies section**

## 6. Studied Mechanical Properties

The Three mechanical properties of the concrete lining have been chosen as variables to study their effect on the structural behavior of the tunnel. These properties are concrete cohesion, tensile strength, and internal friction angle.

To examine and evaluate the effect of changing each of these three factors on the behavior of the tunnel, it is necessary to monitor some essential changes in the model's behavior that occur after changing the value of this factor. So, the change in the number of network elements that change their behavior from elastic to plastic will be monitored (Figure 6).

The values of cohesion, tensile strength and internal friction angle of the concrete lining were changed in three stages within the appropriate range of the studied model, and 27 cases have been obtained as in (Table 2). Where appropriate analysis and calculations were performed, the number of plastic elements produced for each studied case was monitored.

**Table 2. studied values of concrete aging**

| Ex. Number | Cohesion C[MPa] | Tensile Strength t[MPa] | Internal Friction Angle ϕ[Deg] | Plastic Elements Number (PE) |
|---|---|---|---|---|
| 1 | 1.8 | 1 | 45 | 0 |
| 2 | 1.8 | 1 | 20 | 1 |
| 3 | 1.8 | 1 | 0 | 39 |
| 4 | 1.8 | 0,5 | 45 | 12 |
| 5 | 1.8 | 0,5 | 20 | 13 |
| 6 | 1.8 | 0,5 | 0 | 52 |
| 7 | 1.8 | 0 | 45 | 292 |
| 8 | 1.8 | 0 | 20 | 292 |
| 9 | 1.8 | 0 | 0 | 297 |
| 10 | 0.9 | 1 | 45 | 34 |
| 11 | 0.9 | 1 | 20 | 149 |
| 12 | 0.9 | 1 | 0 | 322 |
| 13 | 0.9 | 0,5 | 45 | 43 |
| 14 | 0.9 | 0,5 | 20 | 154 |
| 15 | 0.9 | 0,5 | 0 | 320 |
| 16 | 0.9 | 0 | 45 | 292 |
| 17 | 0.9 | 0 | 20 | 304 |
| 18 | 0.9 | 0 | 0 | 358 |
| 19 | 0.3 | 1 | 45 | 334 |
| 20 | 0.3 | 1 | 20 | 369 |
| 21 | 0.3 | 1 | 0 | 370 |
| 22 | 0.3 | 0,5 | 45 | 334 |
| 23 | 0.3 | 0,5 | 20 | 370 |
| 24 | 0.3 | 0,5 | 0 | 370 |
| 25 | 0.3 | 0 | 45 | 335 |
| 26 | 0.3 | 0 | 20 | 370 |
| 27 | 0.3 | 0 | 0 | 370 |

## 7. Results and Discussion

### *7.1. 2D Relations Analysis*

The analysis results were plotted as graphs in Figure (7). Where the change of cohesion with the number of plastic elements is plotted, this figure shows that changing the cohesion coefficient has an apparent effect on the structural behavior of the lining concrete, and its effect is greater than the effect of the tensile strength on the behavior of the tunnel lining, as shown in Figure (8) because decreasing the cohesion values rapidly increases the number of plastic elements in the lining. Figure (9) shows that the effect of changing the angle of friction is also important, but to a lesser extent than the effect of changing the cohesion. However, it is difficult to accurately compare the effect of the internal friction angle with the effect of the other two coefficients through these two-dimensional diagrams. Due to these limitations, these values should be presented in 3D response surfaces to compare these results well.

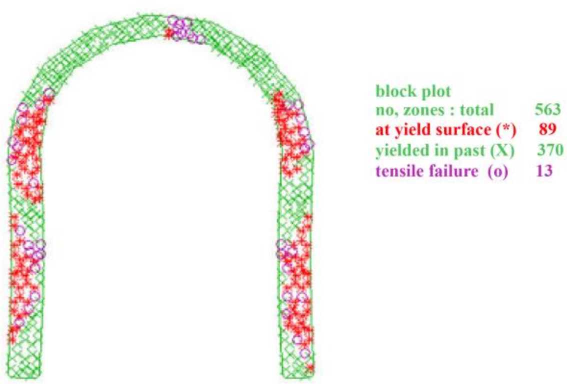


**Fig. 6 Network elements behavior**

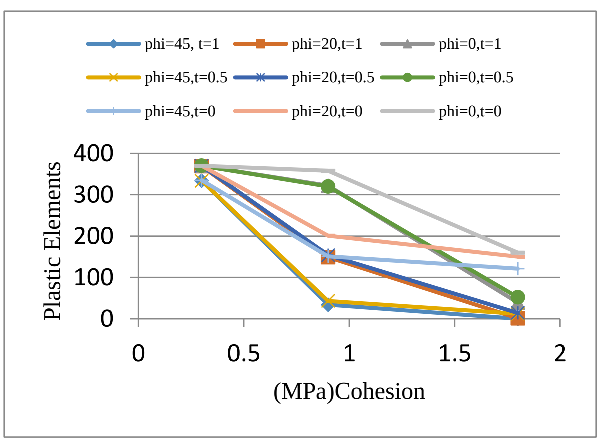


**Fig. 7 Relation between C and PE**

### *7.2. Response surface analysis*:

3D response surfaces have been generated to preview the results. The height of the plane surface was adopted to represent the number of plastic elements related to the change of the other two parameters. Thus, it is possible to study the effect of these two factors and know the possible overlapping effect between them.

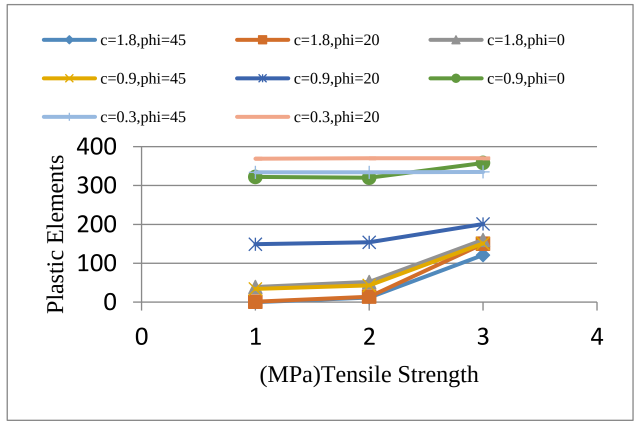


**Fig. 8 Relation between T and PE**

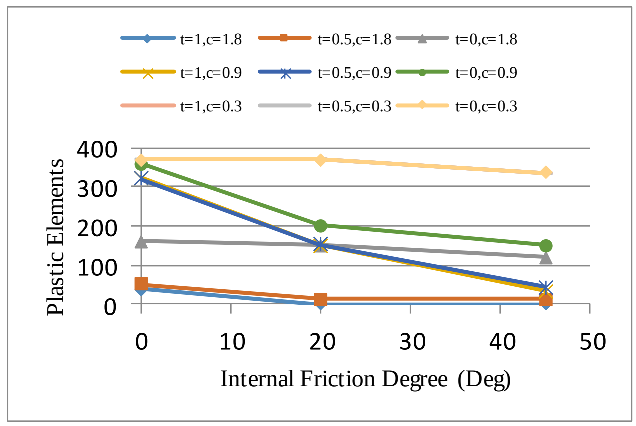


**Fig. 9 Relation between φ and PE**

The response surfaces, as shown in Figure (10), show that there are two essential factors whose change clearly affects the structural behavior of the lining. These factors are the cohesion coefficient (C) and the angle of internal friction(Ø). At the same time, there does not appear to be a noticeable effect of the change in the tensile strength of the concrete lining.

Also, it is difficult to compare the effect of the coefficient of cohesion and the angle of internal friction on the structural behavior of the lining from the 3D graphic surface. There appears to be an essential potential overlap between these two parameters, where this overlap depends on the values of stresses where:

$$\tau = \sigma_n \tan(Ø) + C \quad (1)$$

The lower the value of $\sigma_n$, the greater the effect of C will be than that of Ø. In order to study the effect of these two coefficients, a multiple regression analysis will be used.

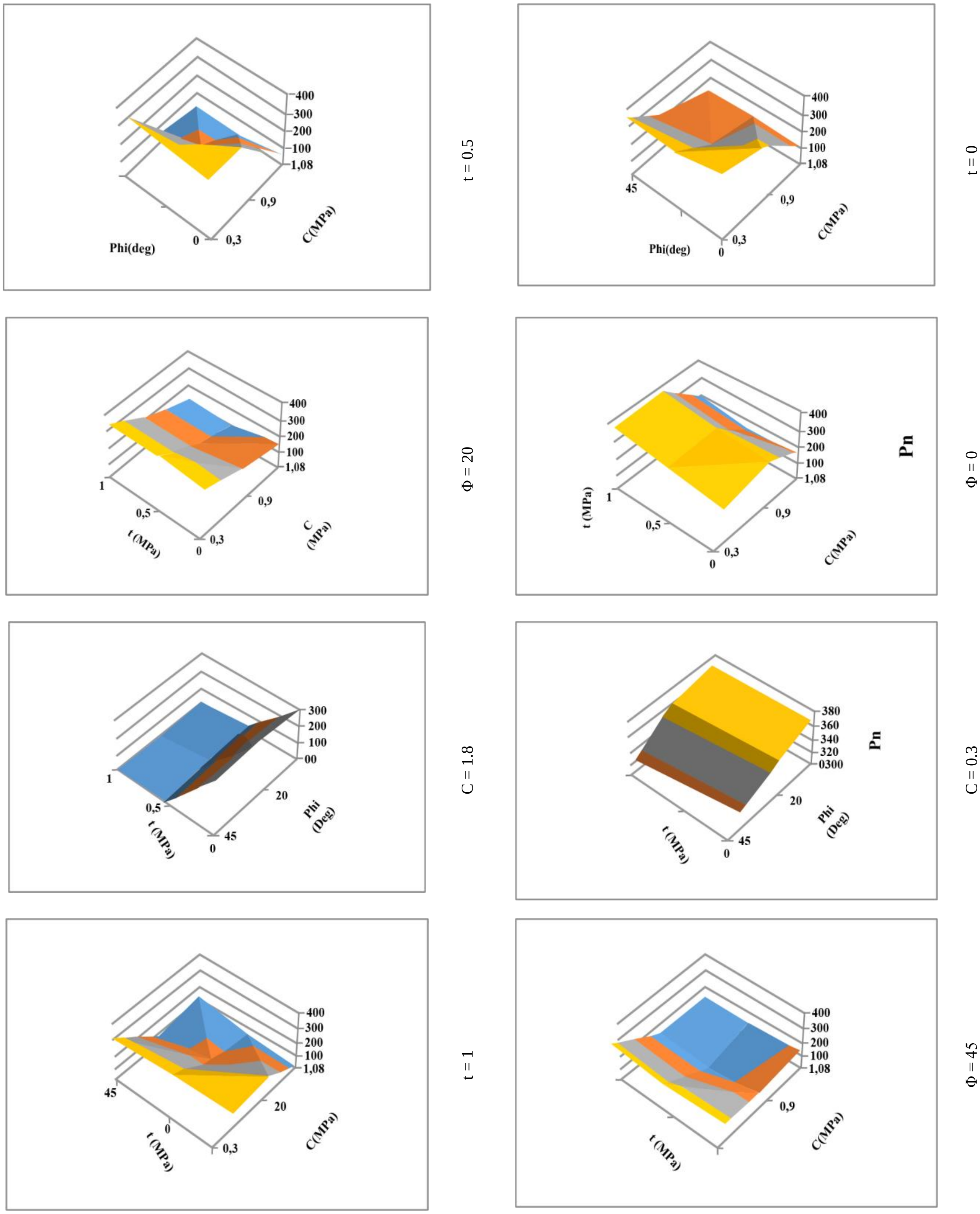


**Fig. 10 3D response surfaces**

### 7.3. Multiple Regression Analysis

The regression analysis tool analyzes linear regression using the theory of least squares, through which it is possible to analyze the extent to which a single dependent variable is affected by the values of one or Mohr non-dependent variables. This analysis aims to obtain a relationship between a dependent variable and a set of variables that affect the value of this dependent variable. In our case, the dependent variable is the number of plastic elements PE, and the variables are the cohesion coefficient C, the internal friction angle Ø and the tensile strength of the concrete lining thickness t. The general form of a linear function is:

$$PE = \lambda_0 + \lambda_1 C + \lambda_2 T + \lambda_3 \phi + \lambda_{12}(C,T) + \lambda_{23}(T,\phi) + \lambda_{13}(C,\phi) + \lambda_{123}(C,T,\phi) \quad (2)$$

Where:
PE: the number of plastic elements
λ0: constant
λ0, λ1, λ2 λ3, λ12, λ23, λ13, λ123: non-dependent variables and they are the values that must be determined as a result of the multiple regression analysis.

Multiple regression analysis of the studied values was carried out using the Satgraphics program.

$$PE = 18.18 - 65.18C - 24.15T - 41.7\phi - 37.14(C,T) - 11.47(C,\phi) + 4.44(T,\phi) - 1.3(C,T,\phi) \quad (3)$$

Figure. 11 shows all the values of the variables resulting from the analysis, and it appears from the figure that C and Ø have an essential effect on the behavior of concrete due to the high values of the variables associated with them. Moreover, their overlapping effect is greater than the overlapping effect between each and the tensile strength.

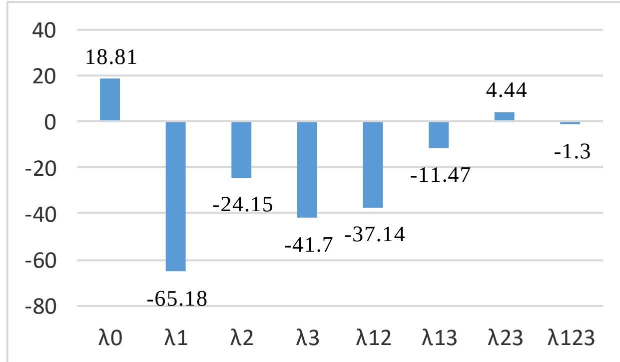


**Fig. 11 values of the variables computed by regression analysis**

## 8. Conclusion

The purpose of this paper was to simulate and identify ageing effects on the behavior of an old concrete tunnel using the distinct element method implemented by UDEC code.

Complete factorial experiments were performed. These experiments express the change of three mechanical properties of the concrete lining over time. The chosen properties were lining concrete tensile strength, cohesion and friction angle.

Analysis results show that both the coefficient of cohesion and the angle of internal friction significantly affect the mechanical behavior of the lining concrete, while the tensile strength of the concrete affects less. In addition, cohesion has the most significant effect among the three studied properties. The effect value of each of these coefficients and the overlapping effect value between them were determined by performing multiple regression analysis.

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