

# Fatigue behavior of lime- and/or cement-treated soils: Database analysis

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**ABSTRACT:** Treated soil structures are traditionally used to reinforce subgrade layers of linear transport infrastructures such as roads or high-speed rail line. Due to a better understanding of the material, soil treatment application has recently expanded, including hydraulics structures like embankments and dikes. These new applications introduce new challenges regarding the durability of this type of material and structures that can be exposed to cyclic mechanical loads. As a result, fatigue phenomenon becomes even more critical concern to ensure the stability of these constructions over their service life. In order to gain a better understanding of fatigue in treated soils, a database was created by compiling laboratory experimental results available in the literature. It included about 410 tests investigating the fatigue behavior of soil specimens treated with lime and/or hydraulic binders (CEM I, CEM II, CEM III) from around the world. The database made it possible to explore the mechanical behavior mainly of gravel and sandy soils, and some clayey soils. Soil type, physical parameters, curing time and conditions, test conditions (loading) and results (number of cycles till failure) were summarized to enable cross-analysis. In particular, the impact of curing time was studied to determine its effect on material fatigue behavior. Trends analyses with three different periods of curing 0-28 days, 90-120 days and more than 120 days gave new results: long term and short-term fatigue behavior of treated soil were very different. To conclude, curing time is essential to understand treated soil fatigue behavior.

**KEYWORDS:** Fatigue, Treated soils, Database, Lime, Hydraulics binders

## 1 INTRODUCTION

Soils treated with lime and/or hydraulic binders are commonly used in various geotechnical structures, such as road subgrades, railway platforms, and more recently dikes, and embankments. These treatments improve the mechanical performance of natural soils, enabling the use of local materials while enhancing their long-term stability. Such infrastructures are frequently subjected to repeated cyclic loads due to traffic in linear structures or to variations in water levels in hydraulic works. These repeated loadings correspond to the phenomenon of fatigue, which is characterized by the progressive degradation of a material mechanical performance over time.

Understanding the fatigue behavior of treated soils is therefore essential to ensure the long-term durability of these infrastructures and to minimize the risk of failure. Several studies have highlighted the influence of key parameters such as the applied stress level, soil granulometry, binder type, and especially curing duration on the fatigue resistance of stabilized soils. However, due to the complex interplay between these parameters, a reliable prediction of fatigue performance remains a challenge.

To contribute to this understanding, a database was developed by collecting and processing data from a wide range of experimental studies (Biswal et al., 2020; Festugato et al., 2021; Jiang et al, 2020; Lv et al., 2018; Preteseille, 2014; Shoban and Das, 2007). This dataset integrates various influential factors and provides a foundation for statistical analyses. The objective of this study is to explore fatigue behavior using this database and propose a new empirical model. In particular, the study introduces a novel approach by focusing on the influence of extended curing durations, which are often overlooked but play a crucial role in the long-term behavior of treated soils. In particular, the impact of curing time was studied to determine its effect on material fatigue behaviors.

## 2 DATABASE PRESENTATION

### 2.1 Database building

The database contains the result of 410 laboratory tests reported in 12 articles published between 1984 and 2025 (Krzewinski et al, 2025). Most of laboratory tests are bending fatigue test, two-point bending fatigue test (Nguyen and Mulders, 1984), three-point bending (Bhattacharya and Pandey, 1986), four-point bending tests (Xie et al., 2018). Moreover, other tests like indirect tensile, or splitting fatigue tests can be found in the database.

Those tests were carried out on diverse soils from clayey soil, thought silty soils, sandy soils to gravelly soils. These soils were treated by hydraulics binders such as cement and/or lime.

The database is composed of 25 parameters, class by categories: Identification (title of the article, the journal, and the publication date), the soil characteristics (USCS classification, USCS classification simplify, the mass of gravel content (%), the mass of sand content (%), the mass of fine particle content (%), Plastic index (IP) (%), Liquid limit (LL) (%), Plastic limit (PL) (%)), the treatment of the soil Cement content by mass (%), the classification of the cement, Lime content by mass (%), the curing duration (days), the curing temperature (°C)), the specimen characteristics (Volume ( $cm^3$ ), compaction methods, water content (%), density ( $g/cm^3$ ), extra condition of cure (like addition of other binder)), the test conditions (Type of test, Frequency (Hz), Stress ratio apply) and finally, the result which is the number of cycles to failure ( $N_f$ ). All parameters give us bases to understand fatigue behavior of treated soils and help to do practical analysis.

During the tests, parameters have to be chosen. In addition of the frequency (Hz), the stress ratio (SR) has to be defined. It corresponds to the ratio between  $\sigma_{app}$  the loading applies during the fatigue test, by  $\sigma_{max}$  the maximum strength obtained from a monotonic test. To generalize the testing methods, the apparatus applies a cyclic loading on the specimen. It stops by the failure of the specimen giving the number of cycles to failure ( $N_f$ ).

To create the database all parameters were not available in tables or in the texts, or data were not homogeneous. A homogenization was effectuated for the type of soil by the USCS standard. Graphical reading of a lot of value like SR and  $N_f$  on graphs conducted. Then an uncertain estimate was performed and quantified. To reduce those uncertainty a software to give coordinates on graph was used. In this paper the maximal error was retain. For SR the uncertainty was fixed at 0.025, the quarter of the smallest gradation which is 0.1. For  $N_f$ , the reading was conducted on a logarithm axis, the margin error is estimated at 26% giving by the Equation 1. This equation is derived from an empirical approach. In logarithmic scale the unity corresponds at the multiplication  $10^x$ , where x is the unity giving a margin error of  $10^x-1$ , when we take the smallest gradation as the reading accuracy.

$$\frac{\Delta N_f}{N_f} = 10^{(\text{smallest gradation})} - 1 = 10^{0.1} - 1 = 0.26 \quad (\text{eq.1})$$

## 2.2 Database description

We will focus on 5 parameters influencing the fatigue resistance: the granulometry of soils, the cement content, the curing duration, the number of cycles to failure ( $N_f$ ) and the stress ratio (SR).

As presented earlier the database is composed of various specimen. In detail the repartition of soil is as follows: 13% of clayey soils, 3% of silty soil, 40% of sandy soils and 44% of gravelly soils taking the simplified classification of USCS, which only retained the first letter to indicated the primary soil type. Those statistics show that the database is mainly gravelly and sandy soils, with 183 and 165 tests each. The fatigue performance of silty soils is a field to study. But most of sandy soils when USCS is used, are classified as either clayey sand or silty sand representing around two-thirds of sandy soils tests.

Figure 1. describes the others parameters in form of histograms. Figure 1.A shows the cement content in samples. Values varies from 0 to 9 %. Values above 5% are rare. There are four principal cement contents: 0% with 40 tests, 3 and 4% with 70 tests each and 5% with more than 125 tests. These values are commonly encountered on construction sites and in engineering world applications of treated soils.

Figure 1.B represents curing duration. Three peaks are observed, one around 28 days, another around 90 days and finally one around 160 days. The range of curing duration is 3 to 360 days. We find two curing categories defined by SETRA (2007), the short term below 28 days of cure, and the long term above 90 days. The third peak can be defined then as the very long term with more than 120 days of cure.

Figure 1.C shows SR repartition used during tests. It has a good repartition around 0.5 to 0.9 with a peak at 0.6. Some extremes values are found: 0.2 and a little more than 1. Although 1 is the highest theoretical value for SR, values greater than 1 do exist. These are attributed to the heterogeneity of the soil. The monotonic tests do not use the exact same specimen each time due to the destructive nature of the testing procedure.

Figure 1.D presents the  $N_f$  values on a logarithmic axis, the range of values are from 3 cycles to  $5.25 \times 10^7$  cycles. The majority of tests have a  $N_f$  between  $10^4$  and  $10^6$  cycles. There are a few tests with low number of cycles and around 60 results exceeding  $10^6$  cycles.

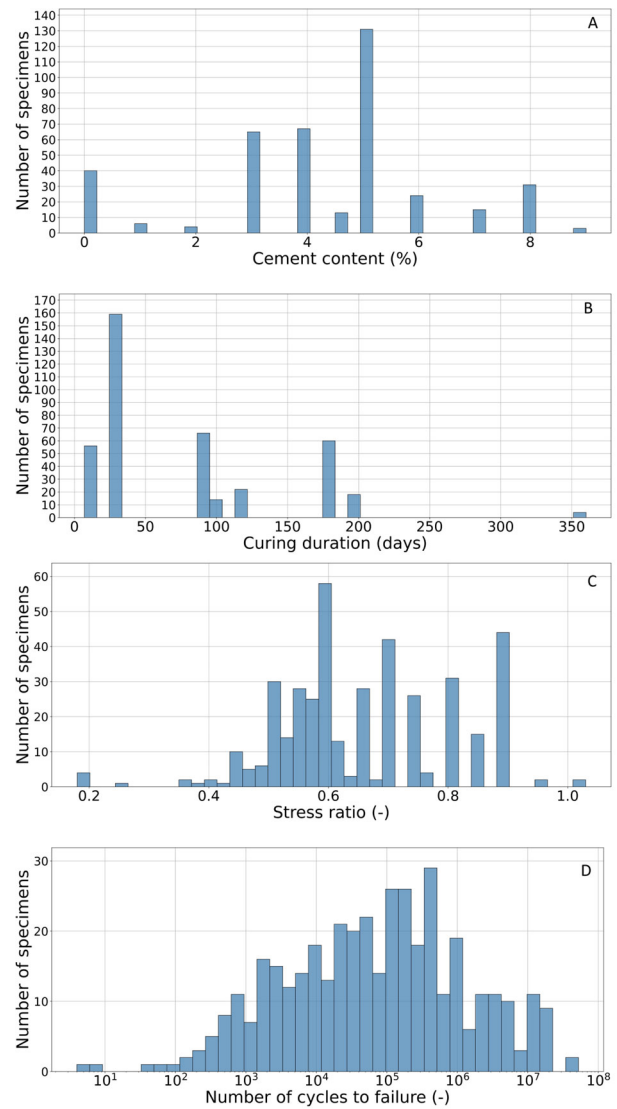


Figure 1. Distribution of the main parameters in the database. (A) Cement content (%), (B) Curing time (days), (C) Stress ratio, (D) Number of cycles to failure.

## 3 RESULTS

### 3.1 Global analysis

To exploit the database effectively, the Wöhler diagram is used to represent the data. It is also known as S-N curve (Stress-Number). It is a common representation for fatigue analysis, the x-axis represents  $N_f$  in a logarithmic axis and the y-axis represent the stress ratio. Figure. 2 shows all data in a Wöhler diagram. Three areas can be observed. The first one in purple is the low fatigue with high SR and a low  $N_f$ . The second one is the black area circle, it is where a slope is observed, the stress ratio is lower between 0.75 and 0.65 and the number of cycles to failure increases. The last area is in orange, a plateau can be found and the number of cycles to failure is higher than  $10^6$  and the SR is below 0.60. The failure seems more random and due to local default of treated soils.

Figure. 2 present different results for the same stress ratio highlight by an arrow. Those results are not only due to the type of soil or treatment, it is mainly due to heterogeneity of soils giving a randomness of the failure.

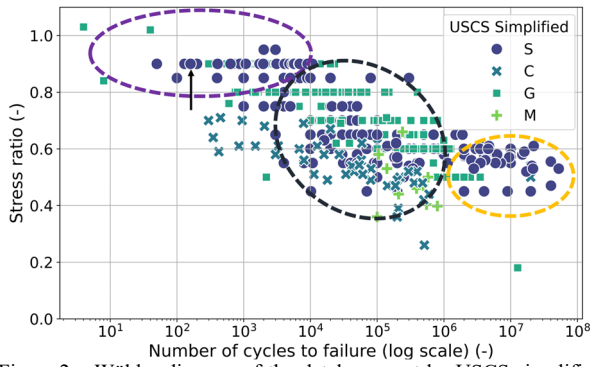


Figure 2. Wöhler diagram of the database, sort by USCS simplified parameter

### 3.2 Curing duration parameter

This section will analyze the curing duration parameter, by doing correlations and statistical analysis.

First, we decide to effectuate a Shapiro-Wilk test. This test demonstrated that data have a non-gaussian repartition. We opted for a non-parametric test to assess the correlation named Spearman test. The test was effectuated on curing duration parameter and the number of cycles to failure, the result is a correlation of 0.22 with a low p-value of  $2.52 \times 10^{-6}$  indicated a non-hazardous relationship. To affirm a correlation the p-value has to be lower than 0.05. The lower it is the higher the correlation is correct. Although the correlation is low, it remains statistically significant compared to other parameters. We decided to split in four categories the curing duration parameters. The Figure. 1.A helps to define those categories: the short-term (0-28 days), the middle-term (28-80 days), the long-term (81-120 days) and the very long term (more than 120 days). The database does not have results with middle-term curing duration, there will be no result for this category. The 410 tests are split into 215 tests for the short-term, 114 for the long-term and 84 for the very long-term. There is enough data to do correlation tests. Spearman tests was used on all three categories of curing duration:

- Short-term has a p-value of  $1.8 \times 10^{-3}$  and a correlation of 0.077
- Long-term has a p-value of  $1.76 \times 10^{-9}$  and a correlation of 0.506
- Very long-term has a p-value of  $1.38 \times 10^{-7}$  and a correlation of 0.543

The three tests have different results. The short-term does not have a correlation with  $N_f$  and the p-value is correct. The others parameters seem to have a bigger impact on the result and the curing duration does not have an impact on it. The long-term curing duration has a significant relationship with  $N_f$  and a low p-value. The very long-term has an even higher correlation but the p-value a higher but it is already a very low p-value. The relationship between the curing duration and  $N_f$  changes over the time. It begins with no influence on  $N_f$  and jump with a high relationship that continue overtime (SETRA, 2007). The chemical reactions happening inside specimen continue to improve mechanical characteristics.

The Figure 3 displays the three categories of curing duration in Wöhler diagrams. The three figures show the behavior for each curing category. The short-term (Figure 3.A) has a large variety of  $N_f$  for a SR given around 3 orders of magnitudes. The long-term (Figure 3.B) has a 2 to 3 orders of magnitude for the same SR. The very long-term has only one to two orders of magnitude for the same SR. The two first figures display a S-shape curves. But Figure 3.C shows a more linear relationships in this semi-log axis.

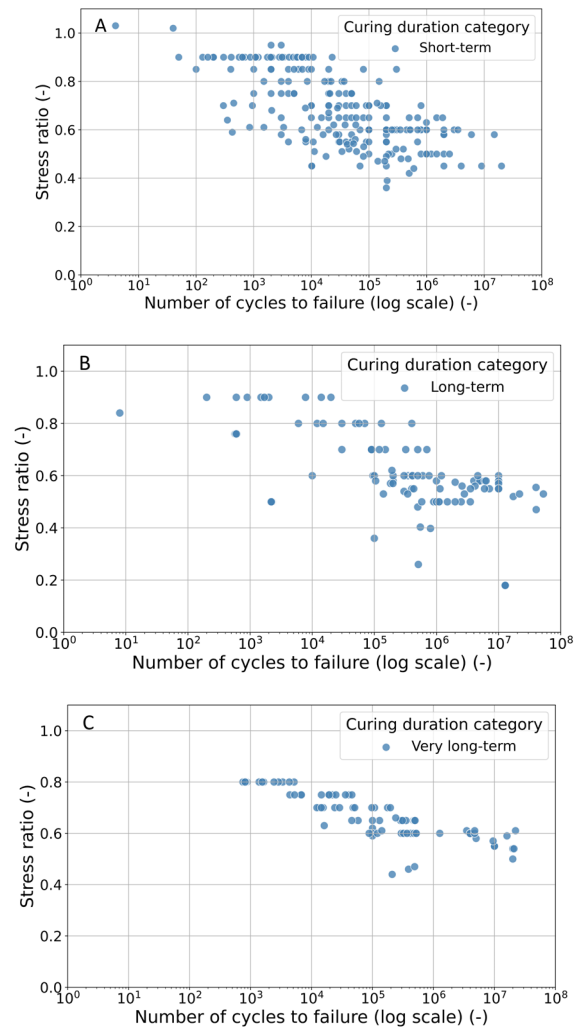


Figure 3. Wöhler Diagrams (S-N Curves) in Semi-Logarithmic Scale: (A) Curing Time from 0-28 Days, (B) Curing Time from 80-120 Days, (C) Curing Time Over 120 Days.

## 4 EMPIRICAL MODEL

To describe fatigue in Wöhler diagram, an empirical model was proposed. Within a semi-logarithmic space some model was proposed mainly linear (Lenoir et al., 2016; Bhattacharya and Pandey, 1986). The linear model goes through a theoretical point ( $SR=1, N_f=0$ ), this point represents the maximum stress ratio apply to break a sample. We choose an arctangent function to model the S-shape of results.

The regression is performed in four steps. The first step consists of calculating the median values of the results, grouped by intervals of 0.1 for the stress ratio. The median is calculated if there is more than 10 points in the interval. This allows for the reduction of data dispersion and provides a more representative trend before applying the regression model. The second step consists in assigning greater weight to the results: the more data points available to calculate the median, the higher the weight. Then the theoretical point is add ( $SR=1, N_f=0$ ) to have a better model. Finally, the arctangent function has four parameters to have the maximum of flexibility, with the following equation (Equation 2):

$$SR = a \tan^{-1}(b \log(N_f) + c) + d \quad (\text{eq.2})$$

a (-): Controls the vertical scale of the curve.

b (-): Controls the slope of the curve.

c (-): Adjusts when the transition happens along the  $\log(N_f)$  axis.

d (-): Controls the overall vertical positioning of the curve.

With the empirical model a point at  $10^6$  cycles is predicted. It is the beginning of the plateau. An increase of SR is observed for each curing duration to 0.48, 0.55 to 0.58 (Table 1) for the short, long and very long-term respectively.

Table 1 present the parameters for each curing duration. It can be observed that the  $R^2$  is really close to 1 and the short-term and long-term have similar parameters but the very long-term has different ones. Figure 4. represents the results on one graph. The short and long-term have a S-shape. There is gap between the two curves where the short term has a weaker resistance against fatigue compare to long-term. The very long-term is more linear but we do not have a lot of data for the higher SR. The curves show a weaker resistance against fatigue for 0.7-0.8 SR when the very long-terms curing duration has a better one.

Table 1. Regression Parameters and Fatigue Performance According to Curing Duration

Parameters and predictions	Curing duration		
	0-28 days	81-120 days	>120 days
a (-)	-0.213	-0.182	-0.399
b (-)	1.129	1.249	0.205
c (-)	-4.966	-5.346	-0.912
d (-)	0.710	0.747	0.705
$R^2$	0.978	0.940	0.975
SR (-) at $N_f = 10^6$	0.48	0.55	0.58

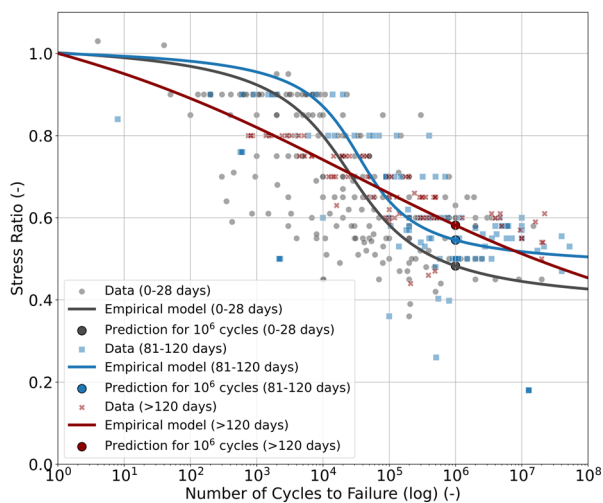


Figure 4. Empirical arctangent model in Wöhler diagrams for each curing category, with SR prediction at  $10^6$  cycles

## 5 CONCLUSIONS

The analysis of a comprehensive database, which includes 410 laboratory fatigue tests from existing literature, has provided valuable insights into the fatigue behavior of soils treated with lime and/or hydraulic binders. Statistical approaches revealed that the fatigue resistance of these soils is significantly influenced by curing time. A notable correlation was found between long curing periods (over 80 days) and improved fatigue resistance, whereas shorter curing periods (up to 28 days) showed minimal effects on fatigue strength.

Further analysis demonstrated that after 120 days of curing, the results became more homogeneous, regardless of other test parameters such as cement content or loading

frequency. This stabilization suggests a shift in the behavior of treated soils over extended curing periods.

A semi-logarithmic model was developed to describe the fatigue behavior more accurately for soils that had undergone extended curing times. This model demonstrated a better fit for the long-term behavior of treated soils compared to conventional approaches.

Overall, these findings provide a clearer understanding of the fatigue phenomenon in treated soils, especially in relation to curing time. This deeper insight opens the door for optimizing soil treatment methods to meet the specific needs of geotechnical applications, particularly in projects involving prolonged exposure to cyclic loading. The consistency observed in long-term behavior raises intriguing questions regarding the underlying mechanisms, suggesting that further microstructural studies could offer more precise explanations for these results.

## 6 DATA AVAILABILITY

Data will be made available on request.

## 7 ACKNOWLEDGEMENTS

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