FATIGUE AND HEALING OF ASPHALT MORTAR

MSC THESIS

S.L. DIJKHUIS
APRIL 2016
Master Thesis

Fatigue and Healing of Asphalt Mortar

Simone L. Dijkhuis
4015428
s.l.dijkhuis@student.tudelft.nl

Civil Engineering TU Delft
Department Pavement Engineering

Thesis Committee
Prof.dr.ir. S.M.J.G. Erkens   TU Delft
Ir. G.A. Leegwater          TNO
Prof.dr. A. Scarpas         TU Delft
Prof.dr.ir. H.E.J.G. Schlangen  TU Delft

20 April 2016
Preface

This MSc thesis completes my Master’s degree of my study Structural Engineering at the Technical University Delft and is part of the specialization Pavement Engineering. The research is a collaboration between the Structural Reliability department of TNO in Delft and TU Delft. The tests are conducted in the TU laboratory.

I greatly enjoyed carrying out my own research for this Master Thesis. I would like to thank my committee members, Sandra Erkens, Tom Scarpas, Erik Schlangen, and Greet Leegwater for their help and guidance. Greet, thank you for your daily supervision, your enthusiasm is very contagious. You were able to help me see laboratory setbacks in perspective. For me, it felt we always worked together and it was a great feeling to have your continuous support.

I would like to thank TNO for giving me a graduate internship position. Spending most of my time at the university laboratory, I would also like to thank everybody at the faculty for creating an inspiring work environment and including me in the PPC. Most of all, thank you Marco, Jan-Willem, and Michèle for helping me and spending your scarce time to fix all my test set-ups requirements.

Furthermore, I would like to thank my parents for their unconditional support. We live far apart, but I do not feel this distance. And Tim, bro, thank you for being there for me, I love our skype sessions about chairs.

After almost 7 years in Delft, it feels like home thanks to all the friends I made. Without a doubt first of all: D01 aka the ParrotZone Rebound: thank you for the great friendships. Simone, thank you for all the support during our student lives. Vesper, I very much enjoy being part of a girly group in a city as Delft. Marloes, you travel around the world, nevertheless you always make time for me, which I very much appreciate. Finally, I would like to thank D01 once more.

Simone Dijkhuis
April 2016
Contents

Summary iv

1 Introduction 1

2 Research Objectives 2

3 Fatigue Test Procedure 3

3.1 Literature Review: Fatigue of Asphalt 3

3.1.1 Fatigue of Mortar 3

3.1.2 Phenomena influencing fatigue life 3

3.1.3 Fatigue tests 4

3.2 Research Approach: Determine a Fatigue Curve 5

3.2.1 Test Set-up 5

3.2.2 Loading and Testing Conditions 5

3.2.3 Number of Test Repetitions 6

3.3 Specimen 7

3.3.1 Specimen Geometry 7

3.3.2 Mortar Materials and Variations 9

3.3.3 Pen grade 10/20 10

3.3.4 Curing and Stabilization Time 12

3.4 Data Analysis 13

3.5 Test Results 17

3.5.1 Unaged Mortar 18

3.5.2 1 days aged Mortar 19

3.5.3 2 days aged Mortar 20

3.5.4 6 days aged Mortar 21

3.5.5 9 days aged Mortar 22

3.6 Additional to the test results 23

3.6.1 Curing Time 23

3.6.2 Creep 23

3.6.3 Self-heating 23

3.6.4 Difference between batches 24

3.6.5 Load Accuracy 24

3.7 Overview of the Test Results 25

3.7.1 Monotonic Tensile Tests 25

3.7.2 Fatigue Tests 25

4 Define the Fatigue Life 27

4.1 Literature Review 27

4.1.1 Method 1: 50% of the Initial Stiffness 27

4.1.2 Method 2: Transition Point 27

4.1.3 Method 3: Dissipated Energy 28

4.1.4 Method 4: Monotonic Failure Envelope 29

4.2 Research Approach: Determining Fatigue Life 29

4.2.1 Method 1: 50% of the Initial Stiffness 29

4.2.2 Method 2: Transition Point 33

4.2.3 Method 3: Dissipated Energy 35

4.2.4 Method 4: Monotonic Failure Envelope 45

4.3 Conclusion to defining the fatigue life 48

5 Discontinuous Loading to assess Healing Behavior 51

5.1 Literature Review 51

5.2 Research Approach: Discontinuous Loading 52

5.3 Results 52

5.3.1 Fatigue Tests with $T_r/T_l$ ratio of 9:1 52

5.3.2 Fatigue Tests with $T_r/T_l$ ratio of 4:1 54

5.3.3 Fatigue Tests with $T_r/T_l$ ratio of 4:1 using a different load pattern 55

5.3.4 Healing Factors and conclusion 56
Summary

Fatigue is one of the common failure mechanisms occurring in asphalt pavements. To better understand the underlying principles of these fatigue mechanisms, a procedure is developed to construct fatigue curves based on tests in uni-axial tension on asphalt mortar, leading to defining fatigue life using a variety of methods. The uni-axial tension loading mode is chosen to increase the insight of material behavior. To examine discontinuous fatigue mechanisms, tests are performed to assess the healing behavior of asphalt mortar.

Fatigue in asphalt mortar has not yet been investigated to a comprehensive extent so far. In mortar, it is expected that the behavior of the binder component is more pronounced when compared to asphalt mixtures. Mortar is a mixture of bitumen, filler, and fine sand with the ratio of 37.5 : 34.1 : 28.4. The bitumen used has pen grade 70/100, the used filler is Wigro 60K, and the sand is Norwegian sand sieved between 0.063 mm and 0.5 mm.

Initially, a test procedure is formulated to determine a fatigue curve of mortar columns tested in uni-axial tension. Cylindrical specimen with a height of 63 mm and a diameter of 16.5 mm are tested in a pneumatic 5 kN UTM (Universal Testing Machine). Both the frequency and temperature are fixed at respectively 10 Hz and 5°C for all these tests. The fatigue tests are performed in tension only, since this results in a relatively simple stress state in the cross-section. The tests are conducted using unaged specimens and four aged mortar specimens with varying ageing degrees. The ageing method used is temperature aged for 1, 2, 6, and 9 days in an oven at 85°C. Every fatigue test is executed six times to account for relatively large variations of fatigue tests.

After determining the fatigue curves, four different methods are applied to the fatigue test results in order to define the fatigue life of asphalt mortar. The classical method in pavement engineering is applied first, which defines the fatigue life when reaching 50% of the initial stiffness. Secondly, the fatigue life is defined at the transition point between Phase II and Phase III. This point is the maximum of the stiffness multiplied by the number of load cycles plotted against the number of load cycles. This is a mathematical approach instead of looking into the material behavior of asphalt mortar. The third method is based on the dissipated energy of each load cycle during a fatigue test using the formula Van Dijk postulated, an analytical approach in which the area of the stress-strain curve is defined as the dissipated energy. The fourth and final method is using the monotonic tensile test results as a failure envelope to the fatigue results, normally applied to linear elastic materials and is not commonly applied in pavement engineering.

The transition point approach shows results close to the actual fracture of the specimens. The definition of the fatigue life based on the dissipated energy results in a relatively low number of load cycles until fatigue failure occurs, but this is thought to be due to the available data and the applied data analysis. Overall, it can be concluded that using the transition point is the best method to define the fatigue life based on the experimental data found.

The 2 days aged mortar specimens show the highest number of load cycles, which is not in line with the expectations. The fatigue life was expected to decrease as the ageing period increased, which can be seen in the 2, 6, and 9 days aged mortar specimens. It is believed that performing fatigue tests on unaged mortar is not useful, since the material is too soft.

To assess healing behavior, discontinuous tests are performed using the same test set-up and parameters as in the cyclic fatigue tests. In the rest periods between the load cycles, the asphalt mortar has an opportunity to heal. Various loading patterns are applied to see their effect on the fatigue life and to determine the healing factor. The healing factor was found to be relatively low, but for a test temperature of 5°C it is thought to be a realistic value. It is found that the duration of the rest period does not increase the healing factor as expected.
1 Introduction

Fatigue is one of the major distresses in asphalt pavements. Fatigue cracking is generated by traffic loads and/or temperature variation. The damage can occur as bottom-up cracking and as top-down cracking [18]. Fatigue damage can occur in a pavement due to tensile stresses, bending or local stresses under the wheel load. Pavement design methods address the bottom-up cracks as fatigue failure mechanism. Repeated traffic loads induces tensile stress in the bottom of the asphalt layer which is causes bottom-up fatigue cracks. These tensile stresses propagate over time from micro cracks to macro cracks.

The binder of asphalt concrete plays a crucial role in pavement fatigue life. Fatigue in asphalt mortar, which has not yet been investigated to a comprehensive extent, is the topic of this research. In mortar, it is expected that the behavior of the binder is more pronounced when compared to asphalt mixtures. Investigating bitumen only could also be an option. However, it is believed that the difference between laboratory work and work in the field is smaller when mortar specimens are tested because in a pavement the bitumen is also mixed with and is influenced by the sand and filler. Therefore, only mortar specimens are investigated. Mortar is defined as a mixture of bitumen, filler, and fine sand. Sand are aggregate particle sizes between 0.063 mm and 0.5 mm. A sand fraction below 0.5 mm is adopted because greater particles are considered to be part of the aggregate skeleton [16].

A first step in this research is to formulate a test procedure for constructing a fatigue curve of mortar columns that are tested in uni-axial tension. The fatigue tests are performed to obtain the stiffness, a material property. To investigate the mortar material behavior it is preferable to subject the specimens to one simple state of stress and record the response. It is chosen to test the mortar specimens in uni-axial loading in this research.

The fatigue life of mortar will be defined with the help of various methods. In practice, fatigue life is related to both fatigue and the healing behavior of asphalt mortar. Therefore, the final part of this research focuses on how discontinuous loading assesses healing behavior.
2 Research Objectives

Fatigue in asphalt mixture is a complex phenomenon and the material behavior is not yet fully known. The goal is to investigate the possibility of developing a test method based on mortar which determines the fatigue life in uni-axial tension. The reason for testing on mortar and only using a tension load mode is to provide a better insight into the material behavior. This research will improve the fundamental understanding of fatigue in asphalt pavements.

One test method developed will allow making a link to the healing phenomenon. The specimens can be subjected to a discontinuous loading pattern to examine the effect of healing behavior. The influence of healing phenomenon in tension-tension loading is expected to be less compared to tension-compression. It will be investigated to what extent healing influences the results during a discontinuous loading pattern.

The objectives in this research are based on these challenges and formulated as follows:

1. Formulate a test procedure to construct a fatigue curve of mortar columns tested in uni-axial tension.
2. Determine the fatigue life of unaged and aged asphalt mortar.
3. Examine the effect of discontinuous loading on fatigue life to assess healing behavior.

Each of these three objectives is addressed in a separate chapter.
3 Fatigue Test Procedure

The first part of this research focuses on the initial research objective. A test procedure is formulated in order to construct a fatigue curve of mortar columns tests in uni-axial tension. After a literature review, the approach to achieve this goal is described. The test set-up and the mortar specimens used are explained. This first part will be completed by describing the method of data analysis and presenting the test results.

3.1 Literature Review: Fatigue of Asphalt

The fatigue life of a pavement is commonly assessed by performing a fatigue test on an asphalt concrete specimen. The asphalt specimens are exposed to a repetitive load at a high frequency. This result is described using a fatigue curve, also known as the Wöhler curve, where the stiffness versus the number of load cycles is graphically shown. A typical fatigue curve is shown in Figure 1. The fatigue damage can be divided into three phases [11] [20], each representing a part of the fatigue life of an asphalt pavement that can be described as follows:

Phase I: initiation process of micro cracks, in which, apart from fatigue, other factors contribute to the rapid decrease of the stiffness, such as non-linearity, self-heating and thixotropy.

Phase II: quasi-stationary propagation process of micro-cracks.

Phase III: the failure process, in which the stiffness rapidly decreases since the micro cracks grow to macro cracks, resulting in failure of the specimen.

![Figure 1: Typical Fatigue Curve distinguishing between the three phases](image)

3.1.1 Fatigue of Mortar

Asphalt mortar differs from asphalt mixtures in the absence of large aggregates, which means the strain distribution varies from asphalt mixtures. The strain between the aggregates of the regular asphalt mixture is larger compared to the total strain of the sample as a whole. This total strain is measured during laboratory tension tests. However, in mortar specimens the difference between the inter-aggregate strain and the total strain is smaller since the bitumen percentage for mortar is high. Mortar does only contain small aggregates (with a maximum size of 0.5 mm) which are stiff that their relative deformation is very small when a load is applied on the specimen.

If a small overall strain is applied to an asphalt mixture, a high strain level in the mortar between the aggregates may occur. Therefore, the fatigue curve of mortar specimens will probably differ from an SN-curve (Stiffness vs. Number of Load Cycles) which holds for asphalt mixture specimens.

3.1.2 Phenomena influencing fatigue life

The fatigue life is influenced by several factors that are associated with stiffness loss. The most important phenomena can be summarized as [20]:

- [Image 1](image)
- Non-linearity
- Self-heating
- Thixotropy
- Fatigue damage

These phenomena are interdependent and act simultaneously; however, the exact mechanism that underlies fatigue induced behavior including these phenomena has not yet been fully understood. The first three factors are thought to contribute significantly to the observed stiffness loss in Phase I of the fatigue curve.

Material non-linearity plays a significant role in asphalt mixtures at high strain levels. Due to the internal structure of an asphalt mixture, the binder will experience at inter-aggregate spaces a higher strain level compared to the overall mix, which results in a higher influence of the non-linearity phenomena.

Self-heating is defined as the energy that dissipates as heat in the viscous material. It is not negligible for a large number of loading cycles. It can be taken into account by measuring the temperature of the specimen. This can be done by inserting a thermocouple inside the sample. Normally, the thermocouple is placed in a drilled radial hole which is then filled with bitumen in order to assure the material continuity [10]. This method is not used in this research because the thermocouple is believed to influence the stresses in the specimen to an extent that would influence the results. Another option is to place a thermocouple on the sides or close to the sample. A drawback of this method, however, is that the air around the specimen is measured instead of the specimen itself.

Thixotropy is defined as the recoverable viscosity reduction after shear loading is applied. The shear loading causes the particle network to break, resulting in stiffness reduction. The rest period after this will provide the chance to slowly build-up the micro-structure, ensuring the stiffness recovery. Thixotropy is found to occur in bituminous materials [24] and is reversible.

The contribution of these three effects are more dominant in the first phase of the fatigue process, during which a drop in stiffness takes place. In Phase II, the steady state of the experiment, the bias effects are still present, but as they become constant, the visible decrease in stiffness can be attributed to micro damage in the material [20]. The bias effects (non-linearity, self-heating, and thixotropy) need to be born in mind when examining into the fatigue life. Investigating the bias effects can be a research topic on its own and falls outside the scope of this research.

3.1.3 Fatigue tests

Fatigue is a failure mode of a pavement structure which is induced by traffic loading. The wheel loads cause stresses in the asphalt leading to cumulative micro-damage that results in a stiffness loss: fatigue. The traffic load leads to bending stresses which translates to tension in the bottom part of the pavement structure. This is presented in Figure 2 where the state of stress in the bottom layer in a flexible pavement is shown during wheel loading. The stress state in a pavement structure is complex. In order to be able to fundamentally understand this material behavior, investigating a less complex stress state can help.

The most commonly used equipment for binder fatigue tests is the Dynamic Shear Rheometer (DSR), according NEN-EN 14770. The 4 Point Bending Test (NEN 12697-24) is a commonly used method to determine the fatigue life of asphalt mixtures. These tests are performed in shear or bending loading, performing an uni-axial tension test simplifies the loading mode to tension only. In addition, one state of stress is applied to the specimens.

![Direction of Movement](image)

Figure 2: Principal Stresses Beneath a Rolling Wheel [21]
3.2 Research Approach: Determine a Fatigue Curve

This part of the research aims to formulate a test procedure to determine a fatigue curve for mortar columns in uni-axial tension. The approach to reaching this goal, the test set-up and the parameters are outlined.

3.2.1 Test Set-up

The tests will be performed in the pneumatic 5 kN UTM (Universal Testing Machine). To find the adequate testing equipment, several options have been explored, as described in 'Appendix A - Quest for the Most Suitable Testing Equipment'. Trial tests were performed on the UTM to determine the optimal parameters, as explained in 'Appendix B - UTM Set-up Trials'.

The test set-up is shown in Figure 3. This set-up is used for the parabolic specimens and the straight specimens, as explained in Paragraph 3.3.1. For the small cylindrical specimens, a different clamping method is used; see: 'Appendix B - UTM Set-up Trials'.

A rigid frame is placed in a temperature-controlled cabinet of the UTM. The load cell is placed at the transverse bar of this frame, with the upper hinge directly underneath. The lower hinge is connected to the rigid frame at the bottom. The specimen is clamped at both ends at stainless steel rings with four screws. A schematic figure of this clamping system is shown in Figure 4 with a top view and a side view.

Three Solatron AX 10/S (range 20 mm) LVDTs (Linear Variable Differential Transformer) are placed around the specimen. Starting a test, the LVDTs are pressed down, and extend throughout a test. This way, the gravity will not be opposed to the moving direction.

3.2.2 Loading and Testing Conditions

Prior to a fatigue test, a monotonic tensile test will be performed until failure. This test is performed to determine the tensile strength of the mortar specimen. Based on the observed strength, an amplitude for the sinusoidal loading pattern during the fatigue tests will be chosen.

Temperature

The temperature during both the tensile test and the fatigue test was chosen to be 5°C. This is based on performing trial tests varying the temperature. Tests performed at 10°C made the specimen too viscous. Tests at 0°C were tried as well; however, for the test set-up it takes significantly more time to reach this temperature compared to 5°C. In addition, at 0°C the specimen gets near frozen which limits the internal movements. Therefore, the temperature is fixed to 5°C.

In order to be certain that this temperature is attained, a thermocouple is placed in the UTM temperature chamber. The integrated sensor of the UTM is placed at the left back corner at a height which will be higher than the location of the specimens. The thermocouple is placed near the location where the specimens will be tested and various temperature settings are tested. It
was found that if the UTM is set at 4.6°C the average temperature the thermocouple was 5.0°C. In a time slot of 24 hours the temperature had an accuracy of 0.3°C. The testing temperature in the UTM will be 5.0 ± 0.3°C.

**Tension-tension**
As stated in the literature review, fatigue damage occurs due to tensile and compressive stresses. In this research this one state-of-stress loading pattern will be used, in contrast to two states-of-stresses or shear loading. Asphalt is, like concrete, more fatigue resistant in tension compression than loading in tension only. In Figure 5 this is graphically shown using Mohr Circles. Uni-axial tests in tension can take less loading. The loading mode were the material behaves the weakest is desired because lower limits of the material response are known using this mode. Therefore, the choice was made to perform the uni-axial tests in tension only.

**Loading Pattern**
The fatigue tests are all force-controlled. The choice has been made to perform a test in tension only with a haversine shape of the load waveform in compliance with ASTM D7460, as can be seen in Figure 6. The peak-to-peak amplitude of the fatigue test is chosen to be 35% of the determined tensile strength. In literature [6] [12] a variety of percentages are also found (10, 20, and 30%); in this research the choice has been made to fix the percentage at 35% after several trial tests. Before performing tests using 35% of the tensile strength for the peak-to-peak amplitude, some tests were performed using 30%. However, this resulted in a maximum deformation of 20 mm without breaking the specimen. The three LVDTs used to record the displacement have a range of 20 mm and it is desired that failure occurs in the specimen at the end of the fatigue test. Therefore, it was chosen to increase the loading pattern to 35% of the tensile strength. If a test is performed with a minimum load of 0 N, it is possible that during testing small compression forces occur. If this is the case, the micro cracks created during tensile loading are pressed together. To ensure this does not occur, a minimum load of 5 N is introduced.

**Frequency**
In literature [33] [24] [14], a generally applied frequency is 10 Hz. The three common loading frequencies for fatigue tests are 0.1, 1.0, and 10 Hz [34]. A high frequency (e.g. 30 Hz) represents a high traffic speed, a low frequency (e.g. 0.1 Hz) is representative of a low traffic speed [15]. Since using 10 Hz keeps the fatigue tests in an acceptable time range and it is the maximum frequency when using the test equipment, it was chosen to fix the frequency at 10 Hz.

**3.2.3 Number of Test Repetitions**
Mortar specimens are sensitive to local weaknesses, resulting in the occurring localized failure. In order to address this variation in failure location, it is chosen to perform each fatigue test six times. In this way, more reliable results will be achieved, and the obtained data will be less dependent on a small defect present in one of the samples. The monotonic tensile tests until failure are performed to determine the tensile strength. Since tensile tests show more consistency than fatigue tests, it is believed that performing a tensile test three times is sufficient.
3.3 Specimen

The type of specimen used during fatigue tests influences the results. Therefore, a comprehensive description about the geometry, the material use, the sample preparation, and the variations used of the mortar materials is given in this section.

3.3.1 Specimen Geometry

When starting this research, the specimen geometry used was the DSR cylindrical columns which were used on LOT tests (Life Optimization Tool, a TU Delft project). These samples have a height of 20 mm and a diameter of 6 mm. It seemed convenient to use the same geometry that is used in the DSR. Firstly, this was because of the available equipment to produce these specimen, and secondly, because a comparison could be made with other research studies which are performed in shear. However, some issues occurred using this specimen geometry. The result of the monotonic tensile test until failure showed a tensile strength of the specimen of 74 N. Taking 30% of this value for the peak-to-peak amplitude of the sinusoidal loading during fatigue test results in 22 N. Taking into account the load cell of the UTM of 5 kN, the magnitude of the noise of the load cell becomes dominant over the magnitude of the applied loading pattern. A comprehensive data analysis has been carried out, in an attempt to exclude the noise of both the force and the displacement results. However, this did not give accurate results. It was concluded, that this geometry is not suited to use in an UTM set-up. Using specimens with larger geometry is thought to be the solution. An extensive description of the trials, results, and data analyses on the cylindrical samples with a height of 20 mm can be found in ‘Appendix D - Trials on Small Cylindrical Specimens’.

Parabolic Shaped Specimen

The next step is thus to perform tests on larger specimens in order to increase the tensile strength and reduce the impact of the noise of the load cell. It is chosen to use parabolic samples with a height of 63 mm, as shown in Figure 7. This geometry choice is due to the availability of the molds and stainless steel rings in the laboratory of TU Delft. The great advantage of using parabolic shaped specimen is the high probability the crack will appear in the middle. If a specimen cracks near the end caps, the stresses which occur near the transition of the rings and the mortar are probably the cause. This means the specimen fails due to other stresses than the one that was intended by a tension test.

The downside of using this geometry is that the strain is not equally distributed over the height of the specimen. This is assumed to be the case when determining the stiffness of the specimen. A comprehensive calculation using Finite Element Method software should be applied to determine an accurate stiffness.

The minimal diameter of the specimen is 17.75 mm and the outer diameter of the clamping rings is 21.5 mm. The thickness of the rings is 2.5 mm, which makes in inner diameter 16.5 mm. The loading on the parabolic specimen is expected to increase due to the increase of the geometry. The quantity of this increase is predicted by the increase factor of the diameter. The original small specimen of 20 mm high has a diameter of 6 mm, so a difference between the area of factor 8.75. This is shown in a comparison between the areas \( r^2 \pi \) of both specimen sizes: \( \frac{8.875^2 \pi}{2^2 \pi} = 8.75 \). Theoretically, the loads of these specimens will thus increase with a factor 8.75 compared to the small specimens. This is thought to let the measurements have a magnitude which is larger than the magnitude of the UTM noise. After some trial tests with parabolic specimens, it was found that this test set-up was sufficient. It is chosen to perform further tests on straight cylindrical specimens. The trial tests performed on parabolic shaped specimens can be found in ‘Appendix F - Trials on Parabolic Shaped Specimens’.

![Figure 7: Geometry of parabolic specimen [mm]](image-url)
The choice for straight specimens has been made to simplify the calculation of the strain distribution in the specimens. The strain level will be evenly distributed over the height, which is not the case when using parabolic shaped specimens. However, straight specimens will often crack near the rings, due to the concentrated stresses in this region. A tension crack occurs locally; after failure both halves are undamaged. The ends of the specimens will be clamped in the UTM at the stainless steel rings, which restrains radial deformation at the ends. The state of stress near the ends is disturbed and does not contain the intended state of uniform tensile stresses. The restrained ends are causing a 3D state of stresses and contraction of horizontal tensile stresses. The axial stresses near the rings are therefore smaller compared to uni-axial stresses. It is assumed that if a crack occurs far enough from the ends, these end effects do not influence the observed fracturing response.

To check whether it is possible to use straight specimens, molds of silicon rubber are made and ten straight specimens are tested to obtain the location of the crack and determine which crack near the end caps is within bounds of 5 mm. The specimen geometry is shown in Figure 8 and chosen in such a manner that the diameter of the mortar coincides with the inner diameter of the rings. The same stainless steel rings are used as for the parabolic shaped specimens. The diameter of the mortar increases near the rings, and the mortar will reach the outer diameter of the rings, as can be seen in Figure 8. This choice is made to minimize the possibility of a crack near the rings because less high corner stress can occur with this geometry.

Figure 9 shows the results of ten monotonic tensile tests which are performed to determine the location of the crack. The height between the rings, and the location of the crack are shown after a tests. The crack closest to the rings is 9 mm, which is thought to be far enough from the rings to give adequate results. Almost all specimens broke closer to the top ring, which is thought to be due to more air voids being present in the top part of the specimen. Another possibility might be due to the applied tension force from the top clamp. It is concluded, this geometry is possible to use in this research.

**Specimen height**

The height of the specimens can be interpreted in several manners. First, the total height of 62 mm including the rings can be considered. Another option is to use the height between the rings, which is 33 mm. The sample will be clamped at both ends of the rings. The displacement is based on the distance between the rings, thus the material within the rings does not contribute to the measured stiffness of the sample during tension loading. Therefore, the second option has been chosen to determine the height of the samples, 33 mm.
3.3.2 Mortar Materials and Variations

The use of various materials and the investigation of the difference between the material properties are not the main objectives of this research. One bitumen type will be used in this research: pen 70/100, from the manufacturer Q8. Pen 70/100 represents the penetration grade of the bitumen. It is an empirical method which involves a standardized needle penetrating the binder at a depth of 0.1 mm where the conditions of loading, time and temperature are kept constant. The penetration grade of 70/100 means that the penetration of the needle lies between 70 and 100 · 0.1 mm. A binder with a lower penetration grade is stiffer and will show more brittle behavior.

The other materials used in the mortar samples are Norwegian sand (sieved between 0.063 mm and 0.5 mm) and Wigro 60K filler. In literature several ratios between the bitumen, sand, and filler are proposed. For the filler-bitumen ratio values between 0.8 and 1.2 are used [22]. According to Superpave [28] this ratio has to lie between 0.8 and 1.6. Various compositions have been proposed for the material of mortar samples. The ratio by mass between bitumen:filler:sand is found in literature as 34 : 30 : 36 [13] or 37.5 : 34.1 : 28.4 [26]. In this research the mortar samples were chosen in accordance with the latter, which means that the filler:bitumen ratio is 0.9. The following composition by weight is used for the mortar samples:

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler</td>
<td>34.1%</td>
</tr>
<tr>
<td>Sand</td>
<td>28.4%</td>
</tr>
<tr>
<td>Bitumen</td>
<td>37.5%</td>
</tr>
</tbody>
</table>

Bitumen is temperature sensitive, thus the preparation of the samples influences the way the sample will react to the applied loading. Heating the bitumen to high temperatures will cause ageing effects. In order to perform this research as completely as possible a detailed description of the specimen preparation is given. The extensive protocol to prepare the specimen limits the difference between different sample batches. In 'Appendix C - Preparation Small Cylindrical Specimens' and 'Appendix E - Preparation Parabolic and Straight Specimens' this is comprehensively described for the specimens used in this research.

Material Variation: Ageing

The materials used for the mortar samples can vary in many possible ways, and here diversifying the ageing time of the mortar is chosen. Both unaged bitumen and aged bitumen will be tested. Bitumen in a new pavement differs from virgin bitumen. The in-situ bitumen have already undergone a short ageing process during the mixing, transporting, laying and compacting. During the life time of a pavement the materials undergo long-term ageing. To examine and compare the properties of this aged mortar, tests will also be performed on aged mortar, even though M.N. Partl et al. state that ageing has little influence on the fatigue results.

Most common ageing procedures are the RTFOT (Rolling Thin Film Oven Tester) for short-term ageing and the PAV (Pressure Ageing Vessel) for long-term ageing. However, it appears that temperature ageing gives a better correspondence to practice compared to the PAV ageing technique [31]. However, it is more slow. RTFOT is a more labor intensive ageing method compared to the temperature ageing method. In addition, in a black space graph (Complex Modulus $G^\ast$ versus Phase Lag $\phi$) a deviation can be found with the field ageing relation for both RTFOT and PAV laboratory ageing [31]. Therefore, it is chosen to use a temperature ageing process in this research. These oven tests have been used as an ageing protocol longer than the RTFOT and the PAV [4]. The mortar will be heated at 135°C for 4 hours, to simulate the short term ageing of the production process. The mortar will be placed in an oven at 85°C for 1, 2, 6 and 9 days. Afterwards, the standard sample preparation will be continued as described in detail in ‘Appendix C - Preparation Small Cylindrical Specimens’. This ageing procedure will be performed on bitumen with a pen grade of 70/100 before ageing.
3.3.3 Pen grade 10/20

Apart from mortar with pen grade 70/100 bitumen, tests on mortar containing bitumen of pen grade 10/20 were also planned. Both bitumen come from the same manufacturer, Q8. The reason for choosing one relatively soft (pen grade 70/100) and one harder (pen grade 10/20) type of bitumen is that other pen grades, of those that are regularly used in pavements, will lie between these values. Moreover, the pen grade of bitumen in situ is often assumed to become pen grade 10/20 due to environmental influences and ageing.

The test set-up that is used for specimens with pen grade 70/100, however, caused difficulties when using pen grade 10/20. The specimens failed at the point where the ring transitions into the ring. Six specimens were tested and all showed cracks with the same underlying reason for failure: a convex surface near a ring. A schematic representation and a picture of this mechanism are shown in Figure 10.

The monotonic tensile test was performed using the same parameter as tests on mortar with pen grade 70/100, thus at 5°C and a speed of 0.25 mm/s which is the same speed used for the tests on mortar with pen grade 70/100. Some trials are performed in an attempt to avoid this failure mode. Firstly, the tensioning speed is adjusted to 0.05 mm/s. Secondly, the temperature was set to 10°C. A higher temperature will reduce the stiffness of the specimens, and therefore it is thought to help to avoid a crack at the rings. The tests are performed with the same speed, 0.05 mm/s. However, increasing the temperature showed the same failure mechanism. In conclusion, the test performed with pen 10/20 does not yield usable results in the available test set-up.

Several solutions to solve this problem are proposed and tried. First, the pen grade can be scaled up to, for example, 20/30. However, the idea to have a very hard bitumen type which relates to the pen grade in a road is no longer the case. Furthermore, it is unknown whether this bitumen type is stiff to a significantly lesser degree to solve the occurring problem.

Secondly, a different geometry could be used for the specimens with pen grade 10/20. A known downside of straight specimens is the high possibility of the crack occurring near the clamping rings. The reason for choosing for straight specimens is due to the simplification it gives when determining the strains. The parabolic shaped specimens, were also tried at the initial stage of this research, and will be examined by performing tensile tests. Four out of six specimens broke at the rings, one of which is shown in Figure 11. The crack shows a convex cross-section, alike to the straight specimen. The crack near the rings all occurred at the side which was the top when filling the mold. The top side contains more air voids and is, therefore, weaker. Thus providing a possible explanation for the occurrence of these unexpected results.

The third solution is a change in the thickness of the clamping stainless steel rings. It is thought that maybe a thinner ring will cause fewer corner stresses at the transition of the ring to the mortar. The thickness of the rings are changed from 2.5 mm to a thickness of 1.5 mm to evaluate the influence on the occurrence of premature cracks. The outer diameter is kept the same, while the inner diameter is increased with 2 mm, as is illustrated in Figure 12. The blue hatched area shown on the right will become mortar instead of a thick ring. Six tensile tests carried out on specimen with these thinner stainless steel rings. All six specimen cracked near the ring, although the failure mechanism varied from the specimen with the thicker rings. The crack showed a straighter crack.
plane instead of a convex one. Half of the specimens failed at the ring which was the top ring during filling the mold. It was thought the sand is unevenly distributed over the height which could influence the crack location. Concluding, the influence of the ring diameter does not appear to contribute as much to the location of the cracks as was previously thought. Thus, these proposed three solutions did not solve the occurring problem in the specimens, and therefore it was decided not to include tests performed with pen grade 10/20 bitumen in this research.

Figure 12: Changing the ring thickness

Figure 13: Failure of specimen with a thinner ring
3.3.4 Curing and Stabilization Time

Bituminous samples need curing time prior testing, where curing time is defined as the time between the sample preparation and performing the test. What actually happens during the curing time of the bitumen is not fully understood yet, and the subject remains a point of discussion to this day. In the late 80s, it was proposed that during the curing time the specimens become stiffer and became more resistant to fatigue loading [30].

There are some plausible theories about the process occurring during curing time. A commonly accepted theory involves spatial arrangement within the asphalt mortar. The constituent parts of the bitumen need time to re-orientate among themselves and with the other materials within the mixture. In chemical terms, it is the formation of intra- and inter-molecular bonds and the formation of micelles. Moreover, some believe the curing time is needed for the bonding between the bitumen and the porous materials in the mortar: the sand and filler [9]. In the NEN-norm [1] a curing time of the specimen after sample preparation lies between two to eight weeks. Due to the desire to exclude any variation in the results due to this parameter, the samples will be stored for two weeks prior to testing. The sample preparation will be done in batches and the fatigue tests take time, thus not every sample of each batch can be tested on the same day. This results in the curing time of the samples last tested of one batch will be longer compared to the samples that were tested first of that same batch. A time range of a minimum curing time of 14 days and a maximum of 18 days is chosen.

The optimal temperature during the curing time lies between a high enough temperature for the material to allow internal movements (not frozen) and low enough to not allow deformation of the column geometry. The temperature chosen to store the specimens is around 5°C. The lab provides several fridges, of which the best option is one with fluctuating temperatures between 2°C and 6°C. On average, the curing of the specimen will thus be at 3.5 ± 2.5°C.

After the curing of the specimens, the tests are performed at 5°C in the temperature chamber of the UTM. The specimens need time to reach the desired temperature after being placed in the test set-up. This time slot is defined as the temperature stabilization time. In the NEN-EN 12697-24 [1] various time slots are given to reach a temperature equilibrium. For the two-point bending beam on prismatic shaped specimens one hour is given for stabilization. The specimens of the indirect tensile test need to be exposed to the specified test temperature for a minimum of four hours prior testing. This difference of three hours perfectly illustrates that the knowledge concerning the required need time is limited. Both these time slots are based upon tests performed on asphalt mixture. The mortar specimens tested in this research are smaller than the prior examples. Mortar is thought to be more temperature sensitive, and thus will adapt to the ambient temperature more rapidly compared to asphalt mixture specimens. Therefore, it is chosen to set the temperature stabilization time at a minimum of 30 minutes. Placing the specimen in the test set-up will cause the temperature within the UTM chamber to rise above 5°C. The 30 minutes stabilization time will start when the temperature is stabilized at 5°C again after placing the specimen in the test set-up. According to the NEN-norm [1] the maximum temperature stabilization time is six hours to prevent possible deformation and ageing of the specimen.

The UTM has a large temperature chamber compared to the specimen, which might result in some variation in the chamber itself. The allowed variation in this research is set to ± 0.5°C.

Figure 14: Specimen in a storage mold
3.4 Data Analysis

During a fatigue test, data from the displacement of the three LVDTs and the load cell is obtained through Mp3-software. The fatigue curve is constructed based on the change in stiffness of the mortar specimen.

The stiffness is determined as the stress divided by the strain. The stresses and strains can be defined as either 'engineering' stress and strain or as 'true' stress and strains. The 'engineering' stresses and strains are based on the initial cross-section. The 'true' stresses and strains take the changing cross-section and the elongation of the specimens into account. The total deformation of the specimens goes up to 50% of the initial length, the diameter decreases from 16.5 mm to around 12.5 mm. These changes in the specimen geometry influence the stiffness results. Therefore the actual stresses and strains are used to determine the stiffness, although several assumptions needed to be made. These stresses and strains differ from the 'true' stresses and strains. The stiffness is calculated with the following formulae:

\[
\begin{align*}
\text{Force} & \quad \sigma_{\text{max}} = \frac{F_{\text{max}}}{A(t)} \\
\text{Area}(t) & \quad \delta l_n = \frac{\delta l_n}{l(t)} \\
\text{Time} & \quad \epsilon_n = \frac{\delta l_n}{l(t)} \\
E & = \frac{\sigma_{\text{max}}}{\epsilon_n}
\end{align*}
\]

As can be seen in Equation (1), the stiffness is the stress divided by the strain. The stress is calculated using the force and the area. The tests are force-controlled, so the sinusoidal force data is constant throughout the test. The choice is made to use the maximum force. The area is defined as \(1/4\pi d^2\). The diameter, \(d\), needs to be known to determine the area, which changes throughout a test due to the deformation of the specimens during tension test. The diameter change is determined using the change in height, which is measured during the test. The diameter is known at the beginning and measured at the end of each test. It is assumed that the change in diameter is linearly related to the change in height that is measured (indicating a constant Poisson ratio). The maximum stress is thus determined using a constant maximum force and a decreasing area in time. To calculate the stiffness, apart from the stress, the strain needs to be determined as well.

The strain is based on the changing amplitude of the sinusoidal deformation pattern, which increases when the specimen becomes less stiff. The difference between the maximum and minimum of one cycle is recorded using the Mp3-software. To keep the noise within boundaries, the amplitude is recorded based on a moving average of 30 cycles. Figure 15 shows an exaggerated schematization of the deformation throughout time.

![Figure 15: Schematization of the increasing amplitude](image)

The amplitude is directly recorded by the Mp3-software. This measurement is based on the difference between minimum and maximum of the displacement pattern. As an example, the recorded amplitude during a fatigue test is shown in Figure 16. The three LVDTs around the specimen each show the change in amplitude, and the average that are used to calculate the strain. As can be
seen, the amplitude at this test start around $40 \mu m$ at the start of test and end up, before failure of the specimen, around $150 \mu m$.

![Figure 16](image)

**Figure 16:** The peak-to-peak amplitude during a fatigue test on unaged mortar

The strain is defined as the delta length divided by the length, see Equation (1). The delta length is thus the peak-to-peak amplitude. The length is defined as the length of the specimen, which is determined by taking the average of the deformation signals (see Figure 15), added by the length of the specimen at the start. Thus, both $\delta l$ and $l$ are time-dependent.

According to NEN-norm [1] the initial stiffness should be taken at the $100^{th}$ load application. This is, however, targeted at asphalt mixtures and not at mortar specimens. It is chosen to include the first 100 cycles in the shown results. It is believed this number might be too high for mortar specimens and if this is shown not to be true the cycles can always be discarded later.

This data analysis is based on the change in stiffness of each cycle. The stiffness is defined through the angle of the tangent line of one cycle in a stress-strain graph. In Figure 17 this method is graphically shown.

![Figure 17](image)

**Figure 17:** Determine the stiffness from stress-strain plots

In Figure 18 three cycles in a fatigue tests are compared with each other. The left figure shows the three chosen positions in the fatigue curve for comparison. The right side shows the three corresponding stress-strain cycles. The area of the cycles increases which indicates an increase in the dissipated energy. The fatigue curve and the three separate cycles show first an increase and later a decrease of the stiffness.
Influence of the changing parameters

The data analysis of the found experimental data is performed to observe the actual behavior of the material, so not using the engineering stresses and strains. The total deformation of the specimen is around 20 mm, thus an increase of more than 50% of the length. Assumptions are made to determine the length and the area that both change throughout a fatigue test. The influence of these parameters on the results is relative large which is shown in Figure 19.

The results of the applied data analysis is shown together with a result where the length and thus the area of the specimen are fixed. The area is based on the initial diameter of 16.5 mm and the length of the specimen is kept constant on 33 mm. It can be seen that the stiffness decreases more rapidly and reaches a lower level before failure occurs. It is believed that the data analysis applied is giving a correct observation of the stiffness in the material.

The use of ‘true’ stress/strain

The stresses and strains in the data analysis used differ from the ‘true’ stresses and strains, which are defined as follows:

\[ \sigma_T = \sigma_E \cdot (1 + \epsilon_E) \]  
\[ \epsilon_T = \ln(1 + \epsilon_E) \]

With:

- \( \sigma_T \) true stress
- \( \sigma_E \) engineering stress
- \( \epsilon_T \) true strain
- \( \epsilon_E \) engineering strain

The results of the fatigue curve when using the ‘true’ stresses and strains is compared with the data analysis of the stresses and strains used in this research as described above. Figure 20
shows the comparison. The results of the ‘true’ stresses and strains results in a stiffness which is decreasing exponential. A stiffness level of 0 N/mm² is already reached around cycle 800. This seems unrealistic, since the specimen fracture occurred around 1350 cycles. It is clear that the influence of the changing length and diameter during the tests is significant. The end length and diameter should be taken into account with the data analysis.

Figure 20: The use of the ‘true’ stresses and strains compared to the data analysis used
3.5 Test Results

The test results of unaged and aged mortar are presented and evaluated here. The ageing process is conducted in four different time ranges, so in total the results of five different specimens are shown. As described above, first monotonic tensile tests until failure are performed to determine tensile strength of the mortar specimens, followed by the results of the fatigue tests.

A tensile test is performed to determine the tensile strength. The tests are displacement controlled with a speed of 0.25 mm/s at a temperature of 5°C. Taking the height of 33 mm between the rings, the strain rate is 0.76%/s. The monotonic test are performed until failure. The tensile test results fluctuate more than expected, which could be due to a software issue or a mechanical irregularity on steel-to-steel contact of the cylinder. Since the tensile test is only performed to determine the maximum load, the results are thought to be acceptable for this use.

The fatigue tests are also performed until failure. The tests are force-controlled with a sinusoidal loading pattern with a frequency of 10 Hz. The minimum load is 5 N, and the maximum load will be determined using the tensile strength. The peak-to-peak amplitude will be 35% of the found tensile strength. The first 100th cycles are still included in these results.
3.5.1 Unaged Mortar

Monotonic Tensile Test
The results of the three tensile tests on unaged mortar specimens are shown in Figure 21a. The results of the maximum tensile strength are 760 N, 620 N, and 660 N, with an average of 680 N. Taking 35% of the load gives, rounded off, 240 N for the peak-to-peak amplitude of the sinusoidal loading during fatigue tests.

Figure 21b shows the tensile test results expressed in stresses and strains. The maximum stress in the asphalt mortar is around 3 N/mm² and the strain around 30%.

![Figure 21: Monotonic Tensile Test Results of unaged mortar](image1)

(a) Force-displacement  (b) Stress-strain

Fatigue Test
In Figure 22 the results of the fatigue tests conducted on unaged mortar specimens are shown. The sinusoidal loading pattern goes from 5 N to 245 N.

![Figure 22: Fatigue Test Results of unaged mortar](image2)
3.5.2 1 day aged Mortar

Monotonic Tensile Test
In Figure 23a the results of the monotonic tensile test of 1 day aged mortar are shown. The tensile strengths are found to be 695 N, 680 N, and 705 N, which gives an average of 695 N. The amplitude of the fatigue test, 35% of 695 N rounded gives 245 N. As can be seen, the results fluctuate around the maximum and therefore the average of these fluctuations is used as the maximum tensile strength.

Figure 23b shows the stress-strain plot of the three tensile tests. The maximum stress occurring in the specimens is about 3,25 N/mm². The total strain before failure of the specimen during a tensile test is around 30%.

![Figure 23: Monotonic Tensile Test Results of 1 day aged mortar](image)

Fatigue Test
In Figure 24 the results of the fatigue test on 1 day aged mortar can be found. The loading pattern is set to a minimum of 5 N and a maximum of 250 N.

![Figure 24: Fatigue Test Results of 1 day aged mortar](image)
3.5.3 2 days aged Mortar

Monotonic Tensile Test
In Figure 25a the three monotonic tensile tests with 2 days aged mortar is shown. The results of the tensile strength are 770 N, 695 N, and 765 N, making the average 743 N. The peak-to-peak amplitude for the fatigue test will be 260 N, which is 35% of 743 N.
The stress-strain results of the tensile tests are shown in Figure 25b. The maximum stress in the mortar columns is around 3.5 N/mm$^2$. The difference between the results regarding the occurring strain is striking. Result 2 shows a strain level of almost 30% before failure occurs, however, the two other results failed when around 15% strain occurred.

(a) Force-displacement  
(b) Stress-strain

Figure 25: Monotonic Tensile Test Results of 2 days aged mortar

Fatigue Test
In Figure 26 the results of six fatigue tests on 2 days aged mortar can be found. The cyclic loading pattern is set with a minimum of 5 N and a maximum of 265 N.

Figure 26: Fatigue Test Results of 2 day aged mortar
3.5.4 6 days aged Mortar

**Monotonic Tensile Test**
In Figure 27a the results of three tensile tests on 6 days aged mortar are shown. The results of the tensile strength are 805 N, 780 N, and 795 N, which results in an average of 790 N. Taking 35% of this value for the peak-to-peak amplitude of the sinusoidal load pattern during fatigue tests which, when rounded, gives 280 N.

Figure 27b shows the same results but expressed in stress and strains. The maximum stress is 4 N/mm$^2$ in 6 days aged mortar specimens. The strain which occurs before failure is at the three tensile tests more than 20%.

![Graphs showing force-displacement and stress-strain](image)

Figure 27: Monotonic Tensile Test Results of 6 days aged mortar

**Fatigue Test**
The results of six fatigue tests, are shown in Figure 28. The tests are performed with a sinusoidal loading pattern with a minimum of 5 N and a maximum of 285 N.

![Graph showing stress vs. number of cycles](image)

Figure 28: Fatigue Tests Results of 6 days aged mortar
3.5.5 9 days aged Mortar

Monotonic Tensile Test

In Figure 29a the results of three tensile test on 9 days aged mortar specimens are shown. The results of the maximum tensile strength of these three tests are 890 N, 880 N, and 905 N, with an average of 890 N. Taking 35% of this tensile strength gives a 310 N for the peak-to-peak amplitude of the sinusoidal loading pattern during the fatigue tests on 9 days aged mortar.

Figure 29b the tensile test results are shown as stress against the strain. The maximum stress occurring in the 9 days aged specimens is around 4.5 N/mm². The average strain at the moment of failure is about 15%.

Fatigue Test

In Figure 30 the results of the fatigue tests on 9 days aged mortar are shown, six tests in total. The pattern of the sinusoidal loading goes from minimum 5 N to a maximum of 315 N.

Figure 30: Fatigue Tests Results of 9 days aged mortar
3.6 Additional to the test results

This section provides some additional information regarding the performed tests. This comprises the curing time of each specimen, a creep test result, the results of a trial to measure self-heating, the repeatability of the tests, and the loading accuracy of the test set-up.

3.6.1 Curing Time

The curing time is defined as the time between the specimen preparation and the time of testing the specimen. The NEN-norm states that the curing time should be between 2 and 8 weeks [1]. As stated earlier, a time range between 14 to 18 days is chosen. However, due to time restrictions and restricted availability of the test set-up, this time range norm is taken as a guideline. An overview of the curing time of each specimen is given in Table 1.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged Tensile Test</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unaged Fatigue Test</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>1 day aged Tensile Test</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 day aged Fatigue Test</td>
<td>14</td>
<td>14</td>
<td>15</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>2 days aged Tensile Test</td>
<td>14</td>
<td>18</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 days aged Fatigue Test</td>
<td>7</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>6 days aged Tensile Test</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 days aged Fatigue Test</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>9 days aged Tensile Test</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 days aged Fatigue Test</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

3.6.2 Creep

The loading pattern during fatigue tests is chosen to be in tension only. In order to ensure this, a minimum load of 5 N is applied to all fatigue tests. This minimum load results in a minimal creep effect. To investigate how large this effect is, a test applying the minimum load only is conducted. A constant load of 5 N is applied, whereas the rest of the parameters are kept the same. The difference between the set load and the actual load also occurred here, the actual load was 20 N. The test was stopped after 60 minutes, the result of which is shown in Figure 31.

The total deformation after one hour is around 1 mm. The fatigue tests performed in this research last mostly less than 20 minutes. The creep will be 0.4 mm at the end of these tests, while the total deformation is around 18 mm. This results in a creep factor of around 2%. Taking this into account, it is thought this will not significantly change the fatigue test results. Therefore, the deformation due to creep will not be subtracted from the fatigue test results.

3.6.3 Self-heating

To check if the effect of self-heating could be measured, a thermocouple was placed near the specimen during a fatigue test. A more commonly used method for asphalt specimens is to place the thermocouple in the specimens. However, it is thought that due to the properties of mortar and
the small geometry of the specimens, this method will influence the results significantly. Therefore, the thermocouple is placed near the specimen.

Several fatigue tests were performed while measuring the temperature. Unfortunately, a higher temperature than the test temperature at the start of a test could not be distinguished. The method to measure the temperature is probably inaccurate because it is believed that self-heating occurs in the specimen. A reason might be that the UTM Temperature Chamber is relative large compared to the specimen, allowing the air within the chamber to flow. The accuracy of the temperature chamber is \( \pm 0.5^\circ C \), which is relatively high compared with the heat the specimen produces. This substantial temperature difference due to the air flow thus prevents the thermocouple of measuring the dissipation heat.

### 3.6.4 Difference between batches

The results of the fatigue tests, for each ageing period are results of specimens from various production batches. This means that the specimens might undergo a slightly different specimen preparation: heated to not exactly the same temperatures for dissimilar time slots. It is believed that these minor differences between the batches will not significantly influence the results. However, this possibility exists and is not investigated but should be kept in mind.

### 3.6.5 Load Accuracy

The loading pattern that is used as input for the UTM software is found to not be equal to the measured loading pattern. The UTM software and the Mp3 software both recorded the loading pattern; however, between these two measurement equipment there exists a difference as well.

<table>
<thead>
<tr>
<th></th>
<th>UTM Settings</th>
<th>UTM Software</th>
<th>Mp3 Software</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loading</td>
<td>Amplitude</td>
<td>Loading</td>
</tr>
<tr>
<td>Unaged</td>
<td>5 - 245</td>
<td>240 (35%)</td>
<td>25 - 230</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30 - 235</td>
</tr>
<tr>
<td>1 day aged</td>
<td>5 - 250</td>
<td>245 (35%)</td>
<td>20 - 235</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30 - 240</td>
</tr>
<tr>
<td>2 days aged</td>
<td>5 - 260</td>
<td>255 (35%)</td>
<td>20 - 250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35 - 260</td>
</tr>
<tr>
<td>6 days aged</td>
<td>5 - 280</td>
<td>275 (35%)</td>
<td>20 - 270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30 - 275</td>
</tr>
<tr>
<td>9 days aged</td>
<td>5 - 315</td>
<td>310 (35%)</td>
<td>25 - 295</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35 - 305</td>
</tr>
</tbody>
</table>

Table 2 provides an overview of the loading pattern settings and the measurements data of the UTM software and the Mp3 software. The Mp3 software is on average 10 N higher compared to measurements of the UTM software, this is thought to be due to a shift of the zero load point. For the data analysis the Mp3 software data is used because the sampling rate was higher.

The minimum load showed a constant trend to be higher compared to the set minimum load of 5 N. However, a minimum load between 20 N and 35 N is quite high. It can be a cause of the large total deformation.

The amplitude is set on 35% but the results show a lower peak-to-peak amplitude during loading. A lower amplitude is not a problem as long the amplitude is known. The idea was to have the same percentage of the tensile strength for the amplitude of each tests. However, as can be seen in Table 2, the percentages are not the same. This might be a cause of differences seen in the results, and should be taken into account when drawing conclusions.
3.7 Overview of the Test Results

The results of the five different specimens (one unaged and four types of aged) are shown separately in Section 3.5.1 to 3.5.5. An overview of the results is given here.

3.7.1 Monotonic Tensile Tests

Before a fatigue curve can be constructed, the tensile strength of the mortar columns is determined through tensile tests. In Table 3 the results of the tensile tests are shown. For each specimen type, the three found tensile strengths can be seen, as well as the average which is defined as the representative tensile strength. As expected, the tensile strength increases with the increasing ageing period.

Table 3: Overview of Monotonic Tensile Test Results [N]

<table>
<thead>
<tr>
<th></th>
<th>Tensile Test 1</th>
<th>Tensile Test 2</th>
<th>Tensile Test 3</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>760</td>
<td>620</td>
<td>660</td>
<td>680</td>
</tr>
<tr>
<td>1 day aged</td>
<td>695</td>
<td>680</td>
<td>705</td>
<td>695</td>
</tr>
<tr>
<td>2 days aged</td>
<td>770</td>
<td>695</td>
<td>765</td>
<td>743</td>
</tr>
<tr>
<td>6 days aged</td>
<td>805</td>
<td>780</td>
<td>795</td>
<td>800</td>
</tr>
<tr>
<td>9 days aged</td>
<td>890</td>
<td>880</td>
<td>905</td>
<td>890</td>
</tr>
</tbody>
</table>

In the stress-strain plots of the tensile test results shows that the maximum stress occurring is increasing with the ageing time of the mortar specimens. The unaged mortar results in a maximum stress of 3.25 N/mm$^2$, increasing to 4.5 N/mm$^2$ for the 9 days aged mortar specimens. The opposite holds for the strain at the time of failure of the specimen, it decreases. The unaged specimens show a strain of around 30% and 9 days aged specimens show a strain level of 15%. Ageing will cause stiffening of the mortar, thus the decreasing strain levels were expected.

3.7.2 Fatigue Tests

In Table 4 an overview is given of the loading pattern during the fatigue tests of the five specimen types. The minimum load of 5 N is kept the same for every test. This is chosen to ascertain that no compression occurs during fatigue tests. The maximum load is defined as 35% of the representative tensile strength.

Table 4: Overview of Fatigue Test Loading Patterns [N]

<table>
<thead>
<tr>
<th></th>
<th>Minimum Load</th>
<th>Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>5</td>
<td>245</td>
</tr>
<tr>
<td>1 day aged</td>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>2 days aged</td>
<td>5</td>
<td>260</td>
</tr>
<tr>
<td>6 days aged</td>
<td>5</td>
<td>280</td>
</tr>
<tr>
<td>9 days aged</td>
<td>5</td>
<td>315</td>
</tr>
</tbody>
</table>

In Figure 32 an overview of the fatigue curves is shown. The number of test results will not allow plotting all the fatigue curves in one graph as the overview would be lost. The variation of the results of six fatigue tests on the same specimen type was quite low for fatigue tests. Therefore, one of the six results of each specimen type is taken. The graphs are chosen based on representing an average of the six fatigue curves of that specific mortar type. These five results of each type are plotted together, as can be seen in Figure 32.
All results show a failure of the specimen around 15,000 load cycles, except for the 2 days aged mortar specimen. The reason why this specimen type can take up to 60% more load cycles is not known. An explanation might be that a different specimen preparation might have been occurred. However, these results consist of two different specimen batches. Another explanation could be that the test conditions were not similar to the other tests, but this seems highly unlikely because the settings of the temperature and the loading were kept the same.

The difference between all fatigue curves might be due to the various loading patterns. The tests were set on the same percentage of tensile strength to use for the peak-to-peak amplitude. However, as described in Section 3.6.5, these percentages were not the same at each mortar specimen type.

The shape of the fatigue curve also differ from each other. Only the 6 and 9 days aged mortar specimens show a constant decreasing stiffness and has the shape of a classic Wöhler curve. The less aged specimens show a slightly increase of the stiffness in the first half of the test. This might be due to a stiffening effect.
4 Define the Fatigue Life

Starting this research a method was developed in order to be able to construct a fatigue curve of mortar columns tested in uni-axial tension. The next step is using the fatigue data to define the fatigue life of mortar. In this part four analytical methods found in literature will be described and applied to determine the fatigue life, with varying degrees of success.

4.1 Literature Review

The fatigue life of an asphalt pavement is characterized as the number of axles passing until failure. A new road structure has to be dimensioned in such a way that it can take the required number of axles passing defined in the design requirements. The thickness of the pavement is proposed in the design process. A strain level at the bottom of the asphalt can be determined by the axle load, the material stiffness and the pavement thickness. The fatigue criteria is the number of load repetitions the material can take this strain level, including safety factors. A fatigue test on the pavement material using this strain level needs to withstand the required axle load repetitions.

In literature there are various approaches to define the fatigue failure of a pavement material in a fatigue test, varying from a certain degree of stiffness loss to complete fracture [27]. The approach chosen is to apply and compare the three most commonly used methods in pavement engineering found in literature and one method used in concrete engineering.

4.1.1 Method 1: 50% of the Initial Stiffness

The classic method to determine the fatigue life of a pavement material is the number of load cycles which corresponds with a reduction of 50 percent of the initial stiffness [19] [35], see Figure 33. The three phases typically seen at fatigue curves are also shown. The initial stiffness is defined as the stiffness of the 100th load cycle. This method is widely used and accepted as a failure criterion in the pavement engineering. An advantage of this method is that it requires no complicated analyses or models. However, the method is being questioned for its accuracy [30] due to not taking the shape of the curve into account, and consequently any underlying material behavior. This method is purely a mathematical approach to analyzing the data. For example, when using modified binders the possibility exists that the 50% threshold is already reached within Phase I. Therefore, alternative models are being developed. This method is included in order to be able to compare the other methods with this traditional fatigue life determination for asphalt concrete.

4.1.2 Method 2: Transition Point

The second method to define fatigue life is based on the change from the micro to macro cracks, i.e. the transition point. The transition point lies between phases II and III of the fatigue curve [20]. The fatigue life is strongly linked to the critical micro crack density, which starts at the transition point. Using a graphic method to determine the transition point is rather subjective. A more objective method is to multiply the stiffness with the number of cycles and plotting this against the number of cycles, as shown in Figure 34. The threshold between Phase II and Phase III

Figure 33: Method 1: 50% of the Initial Stiffness

Figure 34: Method 2: Transition Point
is defined when the relationship between the stiffness and the number of load cycles shows a drastic change. The number of load cycles which corresponds with the top of this graph is defined as the fatigue life.

### 4.1.3 Method 3: Dissipated Energy

Fatigue life can also be characterized by looking at the dissipated energy. The energy dissipated per cycle of stress can be related to the fatigue damage per cycle. The material has a phase lag between the applied stress and the resulting strain, thus is not purely elastic and will dissipate energy each cycle.

The energy which gets dissipated during a fatigue test occurs not only due to fatigue damage. The energy will also for example dissipate through self-heating of the material, see for more phenomena influencing fatigue life in Section 3.1.2.

There are two commonly used ways to express dissipated energy, analytical and as the area of the stress-strain curves. The first uses a formula for the dissipated energy of one cycle which Van Dijk [29] formulated in 1972, see Equation 4. The $w_i$ is determined for each cycle and plotted against the number of load cycles. During recent decades several studies on this topic have been carried out following this postulated method. Recent research supports to using dissipated energy as a fundamental material property to present the damage growth in the material. This method is broadly used to investigate the fatigue behavior of other materials than asphalt [27]. For visco-elastic material, such as mortar, a phase lag is observed between loading and deformation signals during sinusoidal loading.

$$w_i = \pi \cdot \sigma_i \cdot \epsilon_i \cdot \sin(\phi_i)$$

With:
- $w_i$: dissipated energy [Mpa]
- $\sigma_i$: stress amplitude of cycle i [N/mm$^2$]
- $\epsilon_i$: strain amplitude of cycle i
- $\phi_i$: phase lag of cycle i

The second way to analyze the data is to determine the area of a stress-strain curve as an equivalent for the dissipated energy. Mortar behaves as a visco-elastic material which means the loading and unloading path is different. The area of the stress-strain curve is determined manually, instead of using the phase angle in Equation 4.

For both approaches to look at the data, the number of load cycles which defines the fatigue life must be determined. The fatigue life can be characterized by a sudden change in dissipated energy. It is assumed that the dissipated energy of a non-damaged specimen is due to viscoelastic damping, and thus the dissipated energy remains constant with the number of loading cycles. At the moment the damage occurs in the specimen, next to the viscoelastic damping, additional energy is consumed, and the rate of change in dissipated energy rapidly increases. The sudden change in the dissipated energy is thus an indication for when the cracks will start to occur in the specimen, and thus also an indication of the fatigue life [25].

A different method to define the fatigue life is to use the RDEC (Ratio Dissipated Energy Change). The RDEC is defined according to Equation 5. Plotting the RDEC against the number of load cycles will, in theory, result in graph as shown in Figure 35. This plot shows a plateau in Phase II, the Plateau Stage. The start of fatigue failure is indicated if the RDEC increases dramatically.

$$RDEC = \frac{DE_{n+1} - DE_n}{DE_n}$$
4.1.4 Method 4: Monotonic Failure Envelope

A fourth method to determine the fatigue life is not a commonly used method in pavement engineering. However, this method is widely applied in analyses of the fatigue life of concrete. The results of the monotonic tensile test will be used and this graph will be plotted with the fatigue test results. For concrete materials the force-displacement curve forms a crack envelope [23]. The cycles of the fatigue test change in shape, in the first and third phase the displacement of each specimen is larger compared to the second phase. However, this method does not take the shape of the cycles into account. The cycle of the fatigue test which crosses the boundary of the failure envelope of the monotonic test result is defined as the number of loads where fatigue failure occurs, \( N_f \), see schematic Figure 36. This method has been investigated to determine whether it is applicable to asphalt mixtures using a four point bending test, which resulted in envelope behavior at low temperatures [17]. Hence, this method seems promising to determine the fatigue life.

4.2 Research Approach: Determining Fatigue Life

The four methods to determine the fatigue life described in the literature review will be applied to the obtained results given in Section 3.5. These methods are found to be the most commonly used methods, although they are based on asphalt mixtures and not on mortar specimens. The four methods will be investigated to ascertain which can be used best to define the fatigue life of mortar by comparing and evaluating each of them. For each method, the results are shown for the following sets of specimens, unaged, 1 day aged, 2 days aged, 6 days aged and 9 days aged, each set consists of six specimens.

4.2.1 Method 1: 50% of the Initial Stiffness

The first method to determine the fatigue life is the classical fatigue definition. The point of failure is when the initial stiffness is reduced by 50%. The initial stiffness is defined as the stiffness of the 100th load cycle. The fatigue life is defined as the number of load cycles when the mortar reaches this stiffness value \( E_{50,\text{initial}} \).

Results

An overview of the results of Method 1 is given in Table 5. In the last column the result of the fatigue life is given, if no result is listed it means that the specimen was already broken before reaching the 50% of the initial stiffness level.
Table 5: Results of Method 1 - 50% of the Initial Stiffness

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{initial}}$ [N/mm$^2$]</th>
<th>$E_{50,\text{initial}}$ [N/mm$^2$]</th>
<th>Fatigue life</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unaged mortar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1354</td>
<td>677</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1529</td>
<td>765</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1475</td>
<td>738</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1478</td>
<td>739</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1514</td>
<td>757</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1486</td>
<td>743</td>
<td>-</td>
</tr>
<tr>
<td><strong>1 day aged mortar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1326</td>
<td>663</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1038</td>
<td>519</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1012</td>
<td>506</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1036</td>
<td>518</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>2242</td>
<td>1121</td>
<td>14380</td>
</tr>
<tr>
<td>6</td>
<td>1156</td>
<td>578</td>
<td>-</td>
</tr>
<tr>
<td><strong>2 days aged mortar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1789</td>
<td>890</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1378</td>
<td>689</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1750</td>
<td>875</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1560</td>
<td>820</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1640</td>
<td>780</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1524</td>
<td>762</td>
<td>-</td>
</tr>
<tr>
<td><strong>6 days aged mortar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1434</td>
<td>717</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1473</td>
<td>737</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1054</td>
<td>527</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1570</td>
<td>785</td>
<td>11620</td>
</tr>
<tr>
<td>5</td>
<td>1458</td>
<td>729</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>2072</td>
<td>1036</td>
<td>15920</td>
</tr>
<tr>
<td><strong>9 days aged mortar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1829</td>
<td>915</td>
<td>12840</td>
</tr>
<tr>
<td>2</td>
<td>1939</td>
<td>970</td>
<td>13740</td>
</tr>
<tr>
<td>3</td>
<td>1876</td>
<td>938</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1654</td>
<td>827</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1854</td>
<td>729</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1700</td>
<td>850</td>
<td>-</td>
</tr>
</tbody>
</table>

In Table 5 the fatigue life could only be defined at five specimen, the other specimens were already broken before reaching the 50% stiffness level, which is contradictory to the theory. The five results are shown in Figure 37 to Figure 41. The dotted line represents the stiffness of 50% of the initial stiffness.

Figure 37: Fatigue Result 5 of 1 day aged unaged mortar with $E_{50,\text{initial}}$
Figure 38: Fatigue Result 4 of 6 days aged mortar with $E_{50,initial}$

Figure 39: Fatigue Result 6 of 6 days aged mortar with $E_{50,initial}$

Figure 40: Fatigue Result 1 of 9 days aged mortar with $E_{50,initial}$
Conclusion
The standard fatigue criterion which is widely used in pavement engineering, does not apply to the fatigue results obtained in this research. The first phase in the mortar response is shorter than for asphalt concrete, which introduces a substantial uncertainty in the determination of the initial stiffness. The choice of taking the 100th load cycle is believed to be high for the found experimental data, this percentage is based on experiments conducted on asphalt mixtures, not on mortar specimens. In addition, the second phase shows a very slowly decreasing stiffness. The results of the unaged mortar even show a constant stiffness in Phase II, a horizontal trend. Due to the specific shape of the fatigue curve the 50% criterion will most likely be in either Phase I or Phase III, which defeats the purpose of finding a realistic indication of the onset of damage propagation, a point close to the start of Phase III.
A possibility is to take a different percentage from 50% of the initial stiffness, which will result in a value for the fatigue life. However, this is not applied because it does not give information about physical behavior of the asphalt mortar. Another option is to define a criterion for the stable phase, Phase II, at which failure occurs when the results deviate from this stable phase. However, it does not help defining the fatigue life of asphalt mortar and the material behavior, although it might be mathematically correct.
4.2.2 Method 2: Transition Point

The second method to define the fatigue life is the use of the Transition Point, the transition from Phase II to Phase III. The maximum of the number of applied load cycles versus the stiffness multiplied by the number of load cycles is defined as fatigue failure.

Results

The results are shown in Figures 42 to Figure 46. The left vertical axis shows the stiffness, the same as the fatigue curves. On the right vertical axis, the stiffness times the number of load cycles is plotted.

Figure 42: Results of the Transition Method of unaged mortar

Figure 43: Results of the Transition Method of 1 day aged mortar

Figure 44: Results of the Transition Method of 2 days aged mortar
In Table 6 the results are shown using this method. The number of load cycles which represents the point of the maximum of the graph number of load cycles versus the stiffness times the number of load cycles. The average of the six tests is given, together with the standard deviation, SD.

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>14320</td>
<td>11730</td>
<td>11300</td>
<td>13600</td>
<td>13040</td>
<td>14640</td>
<td>13105</td>
<td>1240</td>
</tr>
<tr>
<td>1 day aged</td>
<td>13110</td>
<td>15200</td>
<td>13940</td>
<td>15050</td>
<td>15340</td>
<td>14690</td>
<td>14155</td>
<td>792</td>
</tr>
<tr>
<td>2 days aged</td>
<td>21980</td>
<td>19520</td>
<td>21080</td>
<td>22520</td>
<td>22610</td>
<td>25140</td>
<td>22140</td>
<td>1702</td>
</tr>
<tr>
<td>6 days aged</td>
<td>16020</td>
<td>16700</td>
<td>17130</td>
<td>11830</td>
<td>16620</td>
<td>15190</td>
<td>15550</td>
<td>1786</td>
</tr>
<tr>
<td>9 days aged</td>
<td>11920</td>
<td>12980</td>
<td>14570</td>
<td>12760</td>
<td>14020</td>
<td>11900</td>
<td>13025</td>
<td>995</td>
</tr>
</tbody>
</table>

**Conclusion**

The figures show that this method can be used to determine the fatigue life. It is also easily applicable since there is no comprehensive data analysis needed. It is a fast way to determine the fatigue life if the fatigue curve is available. Although mathematically the use of a transition point is straightforward, some doubt can be cast upon this method since it does not take material behavior into account. The bending point of the fatigue curve is defined as the transition between Phase II and Phase III: the question remains if this is the number of cycles when the material is behaving differently due to fatigue damage.
4.2.3 Method 3: Dissipated Energy

The third method to define the fatigue life is looking into the dissipated energy of each cycle during a fatigue test. As stated in literature, here two approaches are used to determine the fatigue life. The data analysis used in Chapter 3 is not taking dissipated energy into account, but this might give a good indication of the fatigue life. This method takes the effects of the strain and the dynamic properties of the mixture into account.

The two approaches as described in the literature review are using the Van Dijk formula and focus on the area of the stress-strain curve. The approach, the results, and the conclusion of both approaches are described.

Approach 1: Van Dijk formula

The first approach is to use the formula compiled by Van Dijk in 1975. An advantage is that no complicated data analysis is required. The dissipated energy of each cycle is defined according Equation 6.

\[
w_i = \pi \cdot \sigma_i \cdot \epsilon_i \cdot \sin(\phi_i)
\]  

With:
- \(w_i\) dissipated energy of cycle \(i\)
- \(\sigma_i\) stress amplitude of cycle \(i\)
- \(\epsilon_i\) strain amplitude of cycle \(i\)
- \(\phi_i\) phase lag of cycle \(i\)

The stress and the strain amplitude of each cycle can be easily determined by the data gained through the Mp3 software. The stress amplitude is determined by dividing the force amplitude by the area. An overview of the force amplitude is given in Table 7. The area of the specimen changes in time due to large deformations, and is determined using the same method as described in Section 3.4.

The phase angle is not included in the measuring data, thus this needs to be determined by hand, which is done using Matlab. In Figure 47, a graph showing a displacement and load signals to determine the phase angle is presented.

For unaged mortar specimens the phase angle at the beginning of a test is 15° and it increases to 23° at the end of a fatigue test. The phase angle is expected decrease as the mortar is more aged. This difference was found to be small, thus it is assumed the phase angle is for all specimens increases during the test from 15° to 23°.

![Figure 47: Displacement and load signal](image)

Table 7: Force Amplitude

<table>
<thead>
<tr>
<th>Mortar Type</th>
<th>Force Amplitude [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged mortar</td>
<td>205</td>
</tr>
<tr>
<td>1 day aged mortar</td>
<td>210</td>
</tr>
<tr>
<td>2 days aged mortar</td>
<td>225</td>
</tr>
<tr>
<td>6 days aged mortar</td>
<td>245</td>
</tr>
<tr>
<td>9 days aged mortar</td>
<td>270</td>
</tr>
</tbody>
</table>
Results

The results of the use of Equation 6 is presented in Figures 48 to Figure 52. The dissipated energy of a cycle is plotted against the number of cycles. The data used for this analysis has one data point every ten cycles. It is assumed that the dissipated energy within these ten cycles is constant: the found value is multiplied by ten.

In Figure 53 an comparison can be made between the various specimen types. The overview is lost when the thirty results are plotted in one graph, therefore, it is chosen to take a representative average results of each specimen type and plot these for comparison.

Figure 48: Results of unaged mortar

Figure 49: Results of 1 day aged mortar

Figure 50: Results of 2 days aged mortar
In Figure 53 can be seen that the results vary greatly. The shape of these curves do not show a stable phase, like Phase II of the Wöhler curve. The amount of dissipated energy grows exponential until failure of the specimen. The amount of energy which gets dissipated at the start of each test is about the same, around 1 kPa. Taking into account standard fatigue test variations, only the specimen of 2 days aged mortar has a remarkable longer life span.

It can be seen that the more the specimens are aged, the more energy can be dissipated in one cycle before failure occurs. The unaged specimens dissipate less than 4 kPa per cycle, while the specimens of 9 days aged mortar can dissipate up to 5.5 kPa energy each cycle before failure occurs.
The aged specimen are stiffer and thus less elastic, resulting in a more viscous specimen and thus the ability to dissipate more energy in one cycle.

**Defining the fatigue life**

To determine the fatigue life using the found dissipated energy curves, the number of load cycles till fatigue failure must be defined. The RDEC (Ratio Dissipated Energy Change), as explained in the literature review, is found to be not applicable to the data found in this research. The RDEC gives a scattered graph instead of a bathtub shaped graph where a clear distinction can be made between Phase II and Phase III, as can be seen in Figure 54.

![Figure 54: RDEC of Unaged Mortar Result 6](image)

A different method to determine the fatigue life is desired. The commonly used relationship between the dissipated energy and the number of load cycles is given in Equation 7. $A$ and $z$ can be determined by finding the transient line of the dissipated energy plotted against the number of cycles on log-log scale.

$$ W = A \cdot N^z $$

(7)

This method looks promising, however the curves presented in Figure 53 show a continues increasing dissipated energy and thus an early deviation of a transition line, resulting in an unrealistic low number of cycles before failure (less than 1000 cycles). This method is applicable if the change in dissipated energy follows a linear trend in Phase II, which is not seen in the data.

A new method to determine the number of load cycles to define the fatigue life is developed, based on the change in the sum of the dissipated energy. First the sum of the dissipated energy is determined. Only one in every ten data points is recorded thus to determine the sum of the dissipated energy Equation 8 is used. $DE$ stands for dissipated energy and $N$ stands for the number of the load cycle.

$$ \sum DE_j = \frac{DE_i + DE_j}{2} \cdot (N_j - N_i + 1) + \sum DE_i - DE_i $$

(8)

The result following from Equation 8 is plotted against the number of load cycles on a log-log scale. The transient line of the beginning of this graph is constructed, using the $W = AN^z$ form. The fatigue life is defined as the number of load cycles corresponding to the point where the dissipated energy sum deviates from the transient line. This is schematically presented in Figure 55.
Results of the fatigue life

Figure 56 shows the graphs resulting applying the method on the data. This example is an analysis of unaged mortar. The fatigue life is defined as the point the data deviates from the tangent line (the red line). From this graph, the exact point is not clearly visible. Therefore, the difference between the two graphs (the sum of the dissipated energy and the transient line) is plotted on log-log scale, as the point of deviation comes clear.

The parameters in the shape $DE = A \cdot N^2$ of the tangent line vary between the results. Table 8 shows the values of $A$ and $z$ that are used for each result. The value of the sum of the dissipated energy where the fatigue life is defined is also added. This amount of energy is the total dissipated energy until the cycle which is defined as the fatigue life. The parameters $A$ and $z$ vary but stay in the same range. The dissipated energy at $N_f$ show more fluctuations, especially the results of the 6 days aged mortar show large differences. Overall, an increasing trend can be detected in the total dissipated energy at the defined fatigue life.
Table 8: \( A \) and \( z \) of the tangent line and the dissipated energy at \( N_f \)

<table>
<thead>
<tr>
<th></th>
<th>( A )</th>
<th>( z )</th>
<th>( \sum DE )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0003870</td>
<td>1.090</td>
<td>4.458</td>
</tr>
<tr>
<td>2</td>
<td>0.0002894</td>
<td>1.123</td>
<td>3.966</td>
</tr>
<tr>
<td>3</td>
<td>0.0002687</td>
<td>1.136</td>
<td>3.824</td>
</tr>
<tr>
<td>4</td>
<td>0.0002473</td>
<td>1.152</td>
<td>7.091</td>
</tr>
<tr>
<td>5</td>
<td>0.0002870</td>
<td>1.124</td>
<td>4.628</td>
</tr>
<tr>
<td>6</td>
<td>0.0002968</td>
<td>1.121</td>
<td>7.415</td>
</tr>
<tr>
<td>1 day aged mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0001308</td>
<td>1.223</td>
<td>9.111</td>
</tr>
<tr>
<td>2</td>
<td>0.0001631</td>
<td>1.222</td>
<td>7.512</td>
</tr>
<tr>
<td>3</td>
<td>0.0001631</td>
<td>1.222</td>
<td>5.350</td>
</tr>
<tr>
<td>4</td>
<td>0.0002034</td>
<td>1.194</td>
<td>9.602</td>
</tr>
<tr>
<td>5</td>
<td>0.0003417</td>
<td>1.105</td>
<td>8.529</td>
</tr>
<tr>
<td>6</td>
<td>0.0002395</td>
<td>1.599</td>
<td>7.565</td>
</tr>
<tr>
<td>2 days aged mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0001236</td>
<td>1.235</td>
<td>18.942</td>
</tr>
<tr>
<td>2</td>
<td>0.0001236</td>
<td>1.235</td>
<td>11.023</td>
</tr>
<tr>
<td>3</td>
<td>0.0001559</td>
<td>1.214</td>
<td>19.657</td>
</tr>
<tr>
<td>4</td>
<td>0.0001444</td>
<td>1.211</td>
<td>19.233</td>
</tr>
<tr>
<td>5</td>
<td>0.0001814</td>
<td>1.183</td>
<td>19.219</td>
</tr>
<tr>
<td>6</td>
<td>0.0001229</td>
<td>1.225</td>
<td>25.443</td>
</tr>
<tr>
<td>6 days aged mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0004206</td>
<td>1.336</td>
<td>3.257</td>
</tr>
<tr>
<td>2</td>
<td>0.0000393</td>
<td>1.400</td>
<td>30.177</td>
</tr>
<tr>
<td>3</td>
<td>0.0000772</td>
<td>1.333</td>
<td>29.644</td>
</tr>
<tr>
<td>4</td>
<td>0.0000565</td>
<td>1.336</td>
<td>15.537</td>
</tr>
<tr>
<td>5</td>
<td>0.0000488</td>
<td>1.370</td>
<td>32.581</td>
</tr>
<tr>
<td>6</td>
<td>0.0003172</td>
<td>1.168</td>
<td>19.419</td>
</tr>
<tr>
<td>9 days aged mortar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0000625</td>
<td>1.364</td>
<td>20.503</td>
</tr>
<tr>
<td>2</td>
<td>0.0001500</td>
<td>1.262</td>
<td>14.018</td>
</tr>
<tr>
<td>3</td>
<td>0.0002616</td>
<td>1.194</td>
<td>13.984</td>
</tr>
<tr>
<td>4</td>
<td>0.0001744</td>
<td>1.243</td>
<td>13.460</td>
</tr>
<tr>
<td>5</td>
<td>0.0002460</td>
<td>1.198</td>
<td>12.629</td>
</tr>
<tr>
<td>6</td>
<td>0.0002616</td>
<td>1.194</td>
<td>11.470</td>
</tr>
</tbody>
</table>

In Table 9 the results of the number of cycles defined as the fatigue life using this method can be found. The average of the six results and the standard deviation (SD) is also added. The found average of the number of cycles to fatigue failure is believed to be relatively small compared to the number of cycles to failure of the specimen. According to these results after roughly half of the cycles fatigue failure occurs. Furthermore, the standard deviation is quite large, however, the found dissipated energy curves also show dispersive results.

This method to analyze the data clearly marks the change between Phase II and Phase III. This has its advantages for further research. Healing tests are wanted to have a rest period in Phase II, which is clearly shown if this method is applied.

Table 9: Results of Method 3 Approach 1

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>( N_f )</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>5230</td>
<td>4810</td>
<td>4530</td>
<td>7390</td>
<td>5440</td>
<td>8430</td>
<td>5972</td>
<td>1433</td>
</tr>
<tr>
<td>1 day aged</td>
<td>9120</td>
<td>6530</td>
<td>4900</td>
<td>8160</td>
<td>7150</td>
<td>570</td>
<td>7238</td>
<td>1321</td>
</tr>
<tr>
<td>2 days aged</td>
<td>15830</td>
<td>10040</td>
<td>15860</td>
<td>17090</td>
<td>16330</td>
<td>21940</td>
<td>16182</td>
<td>3462</td>
</tr>
<tr>
<td>6 days aged</td>
<td>2660</td>
<td>16010</td>
<td>15460</td>
<td>11770</td>
<td>17870</td>
<td>11150</td>
<td>12487</td>
<td>4985</td>
</tr>
<tr>
<td>9 days aged</td>
<td>11000</td>
<td>8700</td>
<td>8290</td>
<td>8570</td>
<td>8560</td>
<td>7830</td>
<td>8835</td>
<td>1035</td>
</tr>
</tbody>
</table>
Approach 2: Area of the stress-strain curve

The second method to define the fatigue life is to determine the RDEC (Ratio Dissipated Energy Change) which focuses on the change in dissipated energy between the cycles. To use this equation, the dissipated energy of each cycle needs to be known. In the first approach, this was determined using the Van Dijk formula. Here, a different method to determine the dissipated energy will be used, namely the area of the stress-strain curve of one cycle. A stress-strain curve constructed for one cycle, an example is shown in Figure 57. The area of the stress-strain curve is determine using the trapezoidal rule, following Equation 9. The stress and strain is determined for ten points in one cycle. The stress is calculated using the standard formula to divide the force by the area. The changing force level in one cycle is used, which differs from the Van Dijk analysis where a fixed force amplitude was used. The change in area throughout a test is also taken into account, in the same as described in Section 3.4. The strain is determined by dividing $\delta l$ by $l$. The length, $l$, is taken as the distance between the rings added to $\delta l$.

$$A_{cycle} = \sum_{n=1}^{10} \left\{ (\epsilon_{n-1} - \epsilon_n) \cdot \frac{\sigma_{n+1} + \sigma_n}{2} \right\}$$  \hspace{1cm} (9)

Results

Figure 58 to Figure 62 shows the dissipated energy curves of unaged and the various aged mortar specimens. It is chosen to determine the dissipated energy for every 1000 cycles to limit the time needed for this data analysis. The RDEC is only shown of the unaged mortar results, see Figure 58b. RDEC is defined as shown in Equation 5. The instabilities in dissipated energy are exaggerated by this formula. This clearly does not give an indication of the number of load cycles to define the fatigue life and is thus not included in the other figures showing the results.

Note that the first result of 6 days aged mortar specimen is missing, since there was a mistake in the data recording.
Figure 58: Results of unaged mortar

Figure 59: Results of 1 day aged mortar
Figure 60: Results of 2 days aged mortar

Figure 61: Results of 6 days aged mortar

Figure 62: Results of 9 days aged mortar
Conclusion RDEC
The idea of this analysis is to construct a plot of RDEC against the number of load cycles, as Figure 35. However, the dissipated energy curves show quite some fluctuations causing the RDEC graphs unlike the bath tub shape as found in literature. The change in the dissipated energy is magnified by Equation 5.
This result is thought due to the data analysis to determine the area of the cycles manually, rather than the material behavior. Firstly, the sampling rate is 100 Hz, which results in 10 data points in each cycle. This is believed to be low, and needs to increase to a minimum 200 Hz, thus 20 data points of each cycle, to give more adequate results. Secondly, the method to determine the area of the stress-strain curve could be more precise. For the data analyses the trapezoidal rule is used in Excel. Using a different software to determine the area is thought to increase the accuracy. Lastly, the results found using this method show lower dissipate energy levels compared to using first approach. It is believed these results are not adequate and no further analysis of conclusions will be drawn using these results.
4.2.4 Method 4: Monotonic Failure Envelope

The fourth method applied to the fatigue results to define the fatigue life is to use a monotonic failure envelope. The results of the monotonic tensile test and the fatigue test are plotted together in a force-displacement graph. The graph of the monotonic tests can be seen as a failure envelope. The cycle of the fatigue test which crosses the boundary of this envelope is defined as the number of cycles corresponding to the fatigue life. This theory is widely applicable for concrete materials. However, the question is if this method can also be used to determine the fatigue life of asphalt mortar. The trials and test adjustments using this method are outlined in this section.

Results

The monotonic tensile tests performed earlier in this research are used to determine the maximum tensile strength, which are displacement-controlled with a speed of 0.25 mm/s. In Figure 63 a monotonic tensile test results and fatigue test results are plotted together. The left graph shows an overview, which results in a block of the compacted fatigue cycles. On the right side the first part of the test is shown. As can be seen, the fatigue results at the start of the test are outside the envelope. Consequently, the criteria of this method are not met when the earlier results of the monotonic tests are used.

To achieve an envelope around the fatigue cycles, the speed of the monotonic tensile test needs to increase. The conditions of the monotonic and the cyclic tests must be the same to get a monotonic response that can be seen as a failure envelope. This means speed at the start of a test must be the same. To determine the speed of the monotonic tensile test, the slope of the fatigue test results are used, as shown in Figure 64. The frequency is 10 Hertz, thus five data points is 0.05 second. The speed is thus \((0.042804212 - 0.011170404)/0.05 = 0.63\) mm/s.

Two monotonic tensile tests were performed and both resulted in an early failure of the specimens near the rings. The total displacement was around 0.2 mm, which results in around the 100th cycle of the fatigue test results.

The difference between the total deformation during a fatigue test and a monotonic test is significant. The total deformation during Fatigue Tests varies from 18 mm to 20 mm. The deformation of the monotonic tensile test differs from 4.5 mm of the 9 days aged mortar specimens to 10 mm of the unaged mortar specimens. The results now available show that the total displacement of monotonic tensile test is less than half of the displacement of the fatigue curve. If, as suggested the speed of the monotonic test is increased to match the loading speed in the fatigue test, this will further decrease the total displacement of the failure envelope. So, this combination of monotonic...
and cyclic failure does not work out.
A possible explanation is that the fatigue tests are force-controlled and the monotonic tensile tests are displacement-controlled. A failure envelope can also be constructed using a force-controlled tensile test. The maximum force of the fatigue test is known, using this same value to perform a monotonic tensile test will construct a failure envelope. This theory is shown schematically in Figure 65.

![Figure 65: Failure Envelope of a force-controlled monotonic tensile test](image)

On both unaged mortar and 9 days aged mortar three monotonic tensile tests are performed. The total deformation of unaged mortar is around 19 mm, and of 9 days aged mortar 11.5 mm. These tensile test are very repeatable, but the average of three tests is taken for further data analysis. The results of the tensile test is plotted together with the fatigue test result. In Figure 66 one of the results is shown, an overview and a detail of the right side of the failure envelope. Using a force-controlled monotonic tensile test as a failure envelope seems to give realistic results. The fact that the monotonic test still fails before the cyclic ones may have to do with the viscous nature of the mortar. The theory (and proof) of the monotonic test as an envelope for the cyclic response comes from linear elastic materials like steel and concrete. In this test, once the load is applied, the monotonic test basically becomes a creep test which results in a different loading situation as the cyclic test. Despite this mismatch, the monotonic response is used on the data of unaged mortar and 9 days aged mortar to check the usability of this method.

![Figure 66: The results of Method 4 with a force-controlled monotonic tensile test](image)

In Table 10 an overview of the results of using this method is given. The results represents the number of load cycles within the tensile failure envelope. The table shows that some specimens were already broken and did not reach the displacement of the monotonic tensile test. For unaged mortar specimens the force-controlled tensile test had a total displacement of around 19 mm. Three fatigue tests broke before reaching this displacement: Result 2 had a displacement of 17.9 mm, Result 3 a displacement of 18.0 mm, and Result 4 reached 16.5 mm deformation at the moment of failure. The same holds for one test performed with 9 aged mortar: Result 3 failed at a displacement of 10.7 mm.
The time span of the monotonic tensile test and the fatigue tests differ: the monotonic test takes around 30 seconds and the fatigue test around 25 minutes.
Table 10: Results of Method 4 - Failure Envelope

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>16067</td>
<td>Broken</td>
<td>Broken</td>
<td>13417</td>
<td>15775</td>
<td>15086</td>
<td>1186</td>
<td></td>
</tr>
<tr>
<td>9 days aged</td>
<td>12420</td>
<td>13713</td>
<td>Broken</td>
<td>13585</td>
<td>14477</td>
<td>12389</td>
<td>13317</td>
<td>804</td>
</tr>
</tbody>
</table>

Results including fracture
The results shown in Table 10 show a high average value for the number of load cycles, due to the specimen which were already broken were not taken into account. To obtain a more true average, the broken specimen are included with the number of cycles until fracture occurred. In Table 12 the results are shown, with the values in red represents the fracture results.

Table 11: Results of Method 4 - Failure Envelope including fractured specimen

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>16067</td>
<td>12340</td>
<td>11920</td>
<td>13810</td>
<td>13417</td>
<td>15775</td>
<td>13888</td>
<td>1571</td>
</tr>
<tr>
<td>9 days aged</td>
<td>12420</td>
<td>13713</td>
<td>15210</td>
<td>13585</td>
<td>14477</td>
<td>12389</td>
<td>13632</td>
<td>1018</td>
</tr>
</tbody>
</table>

Dissipated Energy
This method results in a value of the number of load cycles which is defined as the fatigue life. The amount of energy which is dissipated by the monotonic test and the cyclic test up to the defined fatigue life differs. Energy gets dissipated at each cycle of the fatigue tests, which adds up to a higher value compared to the monotonic tensile test.

Table 12: Dissipated Energy of each test [MPa]

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Monotonic Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>21.1</td>
<td>16.3</td>
<td>13.2</td>
<td>19.0</td>
<td>17.7</td>
<td>19.5</td>
<td>0.30</td>
</tr>
<tr>
<td>9 days aged</td>
<td>25.3</td>
<td>29.2</td>
<td>31.0</td>
<td>27.7</td>
<td>27.8</td>
<td>23.5</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Conclusion
It is clear that using a displacement-controlled tensile test did not give usable results using this equipment. However, the failure envelope method seems to work if the monotonic tensile test is a force-controlled test. The results of unaged mortar show a number of load cycles which is close to the number of cycles of failure of the specimens (average 64 cycles). Half of the results are already broken and no results can be gained using this method. Thus based upon only the unaged results this method seems to give more an indication of failure of the specimen rather than the fatigue life. The results of 9 days aged mortar show this to a lesser extent, the average difference between the result and the fracture is 500 cycles. It is believed the results are an realistic indication of the fatigue life.
4.3 Conclusion to defining the fatigue life

In addition to fracture as the definition of fatigue life, four different methods are applied to the experimental data, each with its own degree of success. Each method is discussed and a comparison is made followed by conclusions.

Fracture

Before comparing the results of the methods to define fatigue life, the number of cycles until fracture of the specimens is given. This way an indication is given of the total number of load cycles the specimens can take, and therefore how comparable the various methods are regarding fracturing of the specimens. Table 13 shows the results of the number of load cycles until fracture of the specimen occurs. This point is defined when the specimen is fully cracked and no force can be passed on through the specimen.

<table>
<thead>
<tr>
<th>Test</th>
<th>Table 13: Number of load cycles at fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
</tr>
<tr>
<td>Unaged</td>
<td>16200</td>
</tr>
<tr>
<td>1 day aged</td>
<td>13350</td>
</tr>
<tr>
<td>2 days aged</td>
<td>22790</td>
</tr>
<tr>
<td>6 days aged</td>
<td>15980</td>
</tr>
<tr>
<td>9 days aged</td>
<td>13000</td>
</tr>
</tbody>
</table>

**Method 1: 50% of the initial stiffness**

The first method was based on the standard fatigue criterion used in pavement engineering, using 50% of the initial stiffness as the definition of the fatigue life. The first phase of the fatigue curve is shorter than expected, which introduces a substantial uncertainty in determining the initial stiffness. In addition, the second phase shows a very slowly decreasing stiffness or even a horizontal trend. This method resulted in only five outcomes, the other specimens were already broken before the 50% of the initial stiffness level was reached. The five results show a number of cycles close to the total number of cycles before failure occurred. It can be concluded that due to the shape of the fatigue curves found, this ensures this method is not usable.

**Method 2: Transition Point**

The second method focuses on the transition point of the fatigue curve. The maximum of the product of the stiffness and the number of load cycles is defined as the fatigue life. No complicated data analysis is needed to use this method and the result is unambiguous. This method is a purely mathematical approach and does not include the physical behavior of the specimens. However, the results seem to show a realistic indication of the moment the damage propagation starts, i.e. the start of Phase III.

**Method 3: Dissipated Energy**

The third method to define the fatigue life is to focus on the dissipated energy per cycle. Two approaches are taken: an analytical one and an investigation of the area of the stress-strain curves. The first approach resulted in constantly increasing dissipated energy curves. The fatigue life is defined as the moment the tangent line deviates in graph of the sum of the dissipated energy against the number of load cycles. These load cycles show low results compared to the fracture of the specimens. An advantage of this method is that it clearly marks the change between Phase II and Phase III. This indication of Phase II might help for further healing research, since the rest periods in healing tests are required in Phase II, which is clearly shown if this method is applied. The second way to analyze the data is to determine the dissipated energy by manually determining the area of the stress-strain curve. However, this data analysis did not give any fatigue life results. One cycle of the stress-strain curve has ten data points, which is less than desired when using this method. The data analysis is done manually using the trapezoidal rule, a time-consuming method, which is the reason only one data point every 1000 cycles has been determined. To gain more precise results the sampling rate should be increased and the method to determine the area of the stress-strain curve needs a more precise data analysis. Is is chosen not to use this method to define the fatigue life.
Method 4: Monotonic Failure Envelope

The last and fourth method is to use the monotonic tensile test results as a failure envelope to the cyclic test results. The theory of this method comes from linear elastic materials. The monotonic tensile test on asphalt mortar becomes a creep test.

The method is applied to unaged and 9 days aged mortar specimens. Some specimens did not show a result due to failure at a smaller total deformation as the tensile test and thus not crossing the boundary of the failure envelope. The results found were close to the number of cycles of failure of the specimens. Therefore, the applicability of this method may be doubtful. This method might be useful to perform a fast fatigue test and give an indication of the fatigue life by only performing a tensile test.

Comparison

The results found are outlined in Table 14. \( N_f \) stands for the number of load cycles defined as the fatigue life and \( SD \) is the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Unaged</th>
<th>1 day aged</th>
<th>2 days aged</th>
<th>6 days aged</th>
<th>9 days aged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture</td>
<td>13857</td>
<td>1517</td>
<td>14312</td>
<td>1138</td>
<td>23345</td>
</tr>
<tr>
<td>Transition Point</td>
<td>13105</td>
<td>1240</td>
<td>14105</td>
<td>792</td>
<td>22140</td>
</tr>
<tr>
<td>Dissipated Energy</td>
<td>5972</td>
<td>1433</td>
<td>7238</td>
<td>1321</td>
<td>16182</td>
</tr>
<tr>
<td>Failure Envelope</td>
<td>13888</td>
<td>1571</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The results are visualized in Figure 67, Method 1: 50% of the initial stiffness is not included here because applying this method to the found experimental data did not result in a number of load cycles defining the fatigue life.

The 2 days aged mortar specimen shows the highest number of load cycles, which is not in line with the expectations. It was expected that the unaged mortar specimen would show the highest fatigue life and become smaller as the ageing period increases. A high resistance against fatigue failure at the start of the use of a pavement is desired. The fatigue life decreases as the structure becomes more aged. These expected results can be seen in the 2, 6, and 9 days aged mortar specimens: the fatigue life decreases.

The second method uses the transition point and shows results very close to the actual fracture of the specimens. No complicated analyses are needed to apply this method, and the results are unambiguous. On the downside, this method is a purely mathematical approach. Method 3 (based on dissipated energy) is based on the material behavior of the asphalt mortar. It shows a low number of load cycles for the fatigue life. This is thought to be due to the method to define the fatigue life of the constantly increasing dissipated energy per cycle curves. In addition, the standard deviations of these results are relatively large compared to the other methods, especially the result of the 6 days aged mortar specimens. Therefore, some doubts can be cast on these results.

The fourth method, the use of a failure envelope, only gives results of unaged and 9 days aged mortar specimens because only these specimens were tested. The results are in the same range as the actual fracture of the specimens. It is believed to be not usable to define the fatigue life. Further research is recommended, since this method could be used as a quick indication of the fatigue life.

Overall, it is concluded that using Method 2, the transition point, is the best fit to define the fatigue life with the available data. Method 3, based on dissipated energy is a promising method, although a better definition of the fatigue life is required.
Figure 67: Results of the fracture and the various methods.
5 Discontinuous Loading to assess Healing Behavior

As a third part of this thesis the influence of discontinuous tests is investigated. Discontinuous loading pattern is defined as tests with rest cycles between the load cycles. These tests with rest periods between the cycles are also known as ‘healing tests’, as the specimen has time to heal between the load cycles.

5.1 Literature Review

Conventional tests of fatigue damage in asphalt samples are performed under the condition of constant stress-mode or strain-mode. However, traffic loading on pavement structures is not continuous due to two reasons. Firstly, the time interval between each passing vehicle and the traffic intensity varies throughout days and seasons. Secondly, a discontinuous loading on a pavement is the lateral wandering of the vehicles. The track varies between each vehicle, so that on a small scale the loading might differ from the traffic load on the pavement structure.

The rationale behind testing discontinuous loading is giving the material the chance to heal and to (partly) restore its initial properties, as happens in the field. Nevertheless, there will always be a difference between laboratory work and field results. In the design of an asphalt pavement the healing ability of asphalt is taken into account by a healing factor. This is an empirical value based on life span results from laboratory and field experiences with the same mixture. The factor describes the shift between these results. It is unknown to which extent healing contributes to this shift factor [7].

In literature, a variety of discontinuous loading methods can be found. Van den Bergh [30] performed tests with 30 loading cycles and 90 rest cycles. Healing tests with 10,000 loading cycles and 24 hours rest period can also be found. The optimum rest period between the applied loads strongly depends on the temperature. The direction of the stress prior to the rest period was also found to be an important factor [21].

The effect of the healing property on the total fatigue life of asphalt mixtures in road design is expressed by a healing factor. In Belgium for standard asphalt mixtures a healing factor of 7.1 is used. In the Netherlands the standard healing factor is 4. This factor lies between 4 and 1, depending on the fraction of Reclaimed Asphalt (RA) in the mixture and the grade of the bitumen. The healing factor is mostly determined in the laboratory as the ratio between fatigue tests and healing tests, i.e. tests with and without rest periods [5].

Qi [23] has compared several results of fatigue tests with and without rest periods found in literature, as can be seen in Figure 68. The healing factor is plotted against an increase number of rest periods. $N_r / N_w$ is the ratio between the fatigue life with rest periods and the fatigue life without rest periods, and $T_r / T_w$ is the ratio of rest periods and loading periods. All the results follow the same trend: beyond a certain ratio between the load cycles and rest cycles the healing factor stabilizes. Taking the average of the results shown in Figure 68 this ratio is around 10.

In addition to the rest periods ratio, also the influence of the test temperature can be derived from the results shown in Figure 68. The higher the temperature, the larger the healing factor becomes. In this research, the test temperature is fixed at 5°C, thus expected is see a relatively low healing as a result of testing the mortar columns.
5.2 Research Approach: Discontinuous Loading

In the first part of this research a fatigue curve is constructed, using a mortar specimen subjected to a sinusoidal load in tension. All the parameters of the test are kept the same: the temperature (5°C), the specimen geometry and specimen preparation. The same sinusoidal loading pattern is used but as a discontinuous pattern with a rest period between the cycles. In this research the goal is not to find the most optimal rest time between the loads, but to investigate the influence of the rest period on the fatigue life of mortar.

It is chosen to perform discontinuous tests with two different $T_r/T_l$ ratios. $T_r$ is defined as the rest cycles and $T_l$ are the cycles with loading. Firstly, tests are performed with nine rest cycles between the loading cycles: 9:1 ratio, as shown in Figure 69a. Secondly, tests with the $T_r/T_l$ ratio of 4:1 are conducted, i.e. with four rest cycles between the loading cycles, as can be seen Figure 69b. Due to time constraints, it is chosen to perform discontinuous tests only using unaged and 9 days aged mortar specimens.

Note that the rest periods between the loading cycles are not without loading. The loading is kept constant at the minimum load of the cycles which is 5 N.

![Figure 69: Schematization of the Discontinuous Loading Pattern](image)

5.3 Results

The results of discontinuous fatigue tests of unaged and 9 days aged mortar is presented here. The results are compared to the fatigue results presented in Chapter 3: the continue tests. Of the six continuous tests the average result is taken to make a comparison with the discontinuous test results. These comparisons are based on the moment of fracture of the specimens. The different methods proposed in Section 4 are not applicable here since the data of the end of each test is not available. The range of the LVDTs is 20 mm, so the last part of each test is not recorded, which is the crucial part for determining the fatigue failure.

5.3.1 Fatigue Tests with $T_r/T_l$ ratio of 9:1

The first discontinuous tests are performed with a $T_r/T_l$ ratio of 9:1: having nine rest cycles between each load cycle. The fatigue tests are performed on unaged and 9 days aged mortar.

Unaged mortar

In Figure 70 the result of the loading pattern is shown. The UTM was set to have a minimum load of 5 N and a maximum load of 245 N. However, Figure 70 shows the actual loading path between a minimum of 40 N and a maximum of 230 N.

In Figure 71 the results of a discontinuous test is plotted with the results of a fatigue test without rest periods between the cycles. The specimen did not break at the end of the discontinuous fatigue test, and the maximum deformation of 20 mm, which is the range of the LVDTs, was
reached. The test was continued without recording the displacement data, which did not result in broken specimens either. Before the specimen failed the maximum possible displacement of the UTM was reached, around 25 mm. Based on the results, the specimens were not close to point of failure.

Striking is the difference of the stiffness level of Phase II of the fatigue curve. The stiffness of continuous tests start around 1480 N/mm²; the discontinuous tests show a stiffness of around 1200 N/mm².

9 days aged mortar

The same discontinuous tests with a discontinuous loading pattern of $T_r/T_l$ ratio 1:9 are performed on specimens of 9 days aged mortar. The loading pattern has a minimum of 40 N and a maximum of 290 N. This means that during the rest periods a constant tension force of 40 N occurs.

Figure 73 shows the two test results. The result of a continuous fatigue test is added for comparison. The same problem occurred as with the unaged mortar specimens: the total deformation exceeded 20 mm. The LVDTs were out of range after 25,000 cycles, the specimens both broke after around 26,000 load cycles. The total deformation at the moment of failure was 23 mm. As can be seen, the stiffness of the discontinuous result is lower in the beginning and follows a horizontal trend. The stiffness decreases slowly after 13,000 cycles. In the graph the last 1,000 cycles are not shown because the displacement was out of range of the LVDTs.
5.3.2 Fatigue Tests with $T_r/T_l$ ratio of 4:1

To investigate the influence of the rest periods on the healing of mortar, it is chosen to perform tests with $T_r/T_l$ ratio of 4:1, so with four rest cycles between each load cycle. In Figure 74 the loading pattern of these tests is shown, which has a minimum of 40 N and a maximum of 300 N. This maximum load is, for no specific reason, 10 N more compared to the tests with a $T_r/T_l$ ratio of 9:1.

The tests above showed that the un-aged specimen were not close to failure. Therefore, tests with the 1:4 $T_r/T_l$ ratio will be performed on 9 days aged mortar specimens only.

In Figure 75 the discontinuous results and a continuous result is shown. The data shown is not until failure of the specimens, since the LVDTs were out of range. The specimens were broken after a deformation of 22 mm. The test was continued, although it was not possible to record
displacement data with the LVDTs, the number of cycles to failure of the specimens is known. The first specimen failed after 36,880 cycles, the second was broken after 34,700 cycles. The specimen which underwent a $T_r/T_l$ ratio of 9:1 failed after 26,000 load cycles. This is around 10,000 cycles less compared to these results. Healing might have reached its maximum level within four rest periods, meaning the effect between prolonging the rest period to 9 cycles would not increase the life span. The difference between the results might be within the reproducibility ranges of fatigue tests. These discontinuous tests have only been performed twice, which is below the standard of performing six fatigue tests. However, this seems not very likely since the two results showed similar fatigue curves. In addition, the maximum force of the load cycles was 10 N higher, which would indicate a smaller number of load cycles until failure occurs.

Figure 75 shows that the initial stiffness of the discontinuous results are lower compared to the continuous result. These initial stiffness results of the six cyclic tests (Section 3.5.5) give a range between 1300 N/mm$^2$ and 1500 N/mm$^2$, thus these discontinuous results do not lie within this range. In addition, the stiffness increases during the first phase of the fatigue curve. This is believed to be due to the used data analysis used, as explained in Section 3.4.

5.3.3 Fatigue Tests with $T_r/T_l$ ratio of 4:1 using a different load pattern

A change in the loading pattern with the same $T_r/T_l$ ratio is tried to see its effect on healing capacity. In Figure 76 the changed loading pattern is shown, which is chosen because it is thought to be closer to the wheel load on a pavement structure, i.e. two loading cycles with one rest cycle in between, and continued with seven rest cycles.

![Figure 76: Changed Loading Pattern](image)

The results of two fatigue tests with this loading pattern is shown in Figure 77. The first specimen broke at 31,800 cycles, 1,200 cycles after the LVDTs were out of range. The second test resulted in a failure after 33,700 cycles, the displacement data is not recorded after 32,000 cycles because the total deformation was larger than the 20 mm range of the LVDTs. The total deformation at the fracture of the specimens was 21.3 mm.

These results show a smaller number of load cycles before failure of the specimens occurs compared to the standard loading pattern using the 4:1 ratio of load cycles vs. rest cycles. The healing is therefore smaller when using this different loading pattern, as expected.
5.3.4 Healing Factors and conclusion

The healing factor is the ratio between the number of load cycles until failure of the discontinuous test and the continuous test. For the tests conducted here, the healing factor is determined. The results of the unaged specimens are not known since failure did not occur within the boundaries of the UTM.

Note that these tests take up to 8 hours, resulting in creep having a larger influence compared to fatigue tests without rest periods. During the rest periods a constant force is applied of around 40 N which will have a creep effect on the material; however, this is neglected in the results shown.

\[
H = \frac{N_{\text{discontinuous loading}}}{N_{\text{continuous loading}}} \tag{10}
\]

\[
H_{9:1} = \frac{26000}{14000} = 1.86 \tag{11}
\]

\[
H_{4:1} = \frac{36000}{14000} = 2.57 \tag{12}
\]

\[
H_{4:1 \text{ changed pattern}} = \frac{32750}{14000} = 2.33 \tag{13}
\]

The results of the tests with the \(T_r/T_l\) ratio of 9:1 show a lower number of load cycles until failure compared to the tests with \(T_r/T_l\) ratio of 4:1. This means that less loading will result in an earlier failure of the mortar specimen. This seems highly unrealistic and it is thought that the tests with \(T_r/T_l\) ratio of 9:1 are not adequate.

In Figure 78 an overview of the results is shown, including in red the expected range of the healing factor of tests with a \(T_r/T_l\) ratio of 9:1. A healing factor somewhere between 3 and 4 is therefore expected instead of the found 1.86.
This part of the research is a start of looking into the effect of rest periods to assess healing behavior. Each test is performed twice, which is a small number considering fatigue tests are normally performed six times. The results found give an indication of the healing behavior when subjected to discontinuous loading. It is found that the duration of the rest period does not influence the healing factor as much as was expected. The healing factor even decreased when the rest period was increased from 4 cycles to 9 cycles. However, due to the restricted amount of data and the spreading within this data, no further conclusions are drawn based on the results found.
6 Conclusions and Recommendations

6.1 Conclusions

A test procedure has been formulated to perform a fatigue test on mortar columns tested in uniaxial tension. A test set-up using the UTM was found to be adequate for the use of cylindrical mortar columns. Test parameters such as frequency, temperature, and loading pattern are determined after a trial and error process. The frequency is fixed at 10 Hz and the temperature is kept constant at 5°C. The peak-to-peak amplitude of the sinusoidal loading pattern in the force-controlled fatigue tests is taken as 35% of the tensile strength. The displacement recording required special attention, as the total deformation of the specimens is largely due to the tension-tension loading, whereas a high precision is needed to measure the deformation per loading cycle. Experience has shown that the displacements can be adequately measured using three LVDTs around the specimen with a range of ±10 mm.

After the fatigue curves are constructed for unaged and 1, 2, 6 and 9 days aged asphalt mortar specimens, the fatigue life is determined using the following five methods: complete fracture, 50% of the initial stiffness, use of the transition point, dissipated energy of each cycle, and the monotonic tensile test as a failure envelope.

Of these five methods, two methods did not show a fatigue life at a part of the data set and could therefore not be used. 50% of the initial stiffness was found to be inapplicable to the data since most of the specimens did not reach 50% of the stiffness. The other non-usable method tries to take a step towards a quick determination of the fatigue life. The monotonic tensile test is used as a failure envelope of the fatigue data, which is usually applied to linear elastic materials. This is a promising method; however, further research is desired to develop this method. Three analysis methods resulted in fatigue life data of which the use of the transition point is preferable. The use of the transition point between constant crack growth and progressive crack growth shows unambiguous results and no complicated data analysis is needed. However, this is a mathematical approach instead of looking into the material behavior. The method that analyses the dissipated energy of each cycle provides the desired additional insight into the material behavior.

All specimens show a fracture of around 15,000 load cycles, except the 2 days aged mortar specimens: for these the number of load cycles to failure is 23,000. The fatigue tests on unaged and 1 day aged mortar are believed not to be useful, since the material is too soft. The fatigue life decreases between the results of 2, 6 and 9 days aged mortar specimens, which is in line with expectations. Based on the transition point analysis the average number of load cycles decrease from 22,140 for 2 days aged mortar to 15,580 for 6 days aged mortar and finally to 13,025 load cycles for the 9 days aged asphalt mortar specimens.

The fatigue test is also used to assess healing properties by applying a discontinuous loading pattern, using different combinations of load cycles and rest cycles. It is found that the number and duration of the rest period does not influence the observed healing systematically. The healing factor found using the 4:1 ratio between load cycles and rest cycles was 2.57, whilst using a 9:1 ratio resulted in a healing factor of 1.86. This suggests that under the applied conditions there is no observable relation between healing and the rest period. Due to the restricted amount of data and the spread within this data, no further conclusions are drawn from the results.
6.2 Recommendations for further research

This research was conducted over a short time period, and therefore, several decisions were made dictated by the limited time available. To improve the results, several recommendations for performing the tests are given below. In addition, some recommendations regarding data analysis improvement are made. Furthermore, possible extensions of this research are proposed.

Frequency
The used frequency throughout this research is 10 Hz, which was chosen based on literature review. Although this is a commonly used frequency for fatigue tests in asphalt materials, this frequency is close to the limits of the used testing equipment. The accuracy of the LVDTs will improve using a lower frequency. By using data analysis to determine the dissipated energy, results will improve. It is therefore recommended a lower frequency, such as 5 Hz or 8 Hz be used.

Method to record displacement
The LVDTs are used to record the displacement in all the tests. LVDTs are a common method applied to measure the displacement in the laboratory. However, the necessary measurements require a large total deformation (20 mm) and a high accuracy for amplitude of the sinusoidal loading (30 µm), which resulted in some difficulties. Of the three LVDTs used during a test, one often did not met the required measurements. Therefore, it is recommended to improve the method used to record the displacements during the tests. Using new LVDTs will improve the measurements because the used LVDTs may be worn and not working optimally. Looking into other methods to record the displacement, e.g. lasers of a high speed camera, is also a possibility.

Mp3 Software Settings
The Mp3 software is recording the displacement data of the three LVDTs during the fatigue tests. The settings to determine the displacement amplitude is using a filter value to the raw data. The found values of the amplitude below this value is not seen as a cycle. This value is needed otherwise noise in the displacement signal will be seen as a sinusoidal period. This concept is schematically given in Figure 79. The two circled areas show a small fluctuation in the displacement signal which are wanted to exclude from the recorded data.

The first phase of the fatigue curves shows not the rapidly decreasing stiffness as in a typical Wöhler curve. A reason might be because the occurring displacement signal has a lower amplitude than the filter value used. To solve this possible problem, an indication of the initial amplitude of the displacement signal could be investigated by performing one pulse test before conducting the fatigue tests. This way the peak-to-peak amplitude is known, and the filter setting can be chosen based on this information.

Temperature
While conducting research, significant attentions has been given to the temperature. The conditions during curing time of the specimen could be improved. The specimens are placed in a fridge in which the temperature fluctuates between 2°C and 6°C. It is recommended to place the specimen in a chamber where fewer temperature fluctuations occur.

In addition, it is recommended to never place the specimens in a freezer to stop the curing process. This causes the mortar to shrink and the adhesion between the mortar and the steel clamping rings is lost. After several days in the fridge this adhesion is restored, but believed to still influence the results. Thus, it is preferable to have a longer curing time at 5°C instead of placing the specimens in a freezer to stop the curing process.

Change of diameter during a fatigue test
During a fatigue test the geometry of the specimens changes significantly, and on the unaged speci-
imens the deformation is almost 20 mm. Therefore, the change of area is also taken into account when determining the stiffness, as described in Section 3.4. To determine the diameter throughout a test, it is assumed that the ratio between the length and the diameter of a specimen stays constant. To have a more correct data analyses, it is recommended to determine the ratio and use the following formula to determine the diameter change:

\[
\delta d = -d_{n-1} \cdot \nu \cdot \frac{h_n - h_{n-1}}{h_{n-1}}
\]  

(14)

With:
- \(d\) diameter
- \(\nu\) Poisson Ratio
- \(h\) height

During the data analysis to determine the stiffness, the influence of the change in diameter was found to be significant. Therefore, using this more precise method to determine the diameter may result in a more correct stiffness and is therefore recommended.

**Specimen Geometry**

The specimen geometry used in this research is an upscale of the geometry of cylindrical columns used in the DSR at the TU Delft because a comparison between other researched could be possible. Various tests were stopped before failure of the specimen occurred due to the limitations of the LVDTs. The maximum range is 20 mm, the total deformation exceeded this value. Therefore, it is recommended to look into the advantages and possible disadvantages of using a geometry with a smaller height.

**Clamping System**

The specimens are clamped in the test set-up using four screws which press against the steel ring of the specimen. This is not an ideal clamping system, because it might induce stick-slip between the screws and the ring. So, using a system which clamps around the ring is recommended to make the occurrence of stick-slip less likely.

In addition, the used clamping system might introduce a small offset between the specimen and the load cell. Therefore, the specimen might be pulled slightly of its center causing a bending moment in the specimen, as shown schematically in Figure 80. The specimen is clamped at the bottom and the force is applied at the top.

The maximum possible bending moment is determined using the maximum force (310 N) and the maximum possible offset (5 mm):

\[
M = 310 \cdot 5 = 1550 \text{ Nmm}
\]

The maximum stress occurring in the mortar specimen due to this bending moment is determine in Equation 15.

\[
\sigma = \frac{M \cdot y}{I_x} = \frac{1550 \cdot 8.25}{58214} = 0.22 \text{ N/mm}^2
\]  

(15)

With:
- \(\sigma\) stress
- \(M\) bending moment
- \(y\) distance to the neutral axis: \(16.5/2 = 8.25 \text{ mm}\)
- \(I_x\) moment of inertia around x-axis: \(I_x = \frac{\pi}{4} \cdot r^4 = \frac{\pi}{4} \cdot 16.5^4 = 58214 \text{ mm}^4\)

A stress of 0.22 N/mm² is relative high, it is almost 10% of the stress which occurs during fatigue tests. This value is based on the maximum force and the maximum offset possible in the clamping system. The specimen are all carefully placed that no visible offset could be seen. This does not eliminate the possibility a bending moment to occur, thus it is recommended to develop a clamping system which does not allow an offset.
Introducing a preload

The starting phase of the fatigue curve, Phase I, cannot be seen as clearly as expected. A possible reason for this is that during the beginning of each test the specimen needs to be pulled straight in the test set-up. It is thought that introducing a small preload prior to the sinusoidal load would help straightening the test set-up. This preload could be the same amplitude as the minimum load: 5 N. Exploring the influence of applying a preload to the first phase is recommended.

Using other pen grades

As explained in Section 3.3.3, at the beginning of this research, a soft and stiff type of bitumen was meant to be included in the tests. However, some difficulties occurred during testing specimen with pen grade 10/20, therefore in this research only pen grade 70/100 bitumen is used.

An adjusted method of the specimen preparation might result in usable parabolic specimen of pen grade 10/20. Currently, the same specimen preparation is used as the specimen with 70/100. According to the NEN norm [2] a lower pen grade can be heated to a higher temperature during laboratory mixing. It is recommended to try this to see if it influences the usability of pen grade 10/20 with the parabolic specimen geometry.

Another geometry which induces the crack in the middle of the specimen by using a small notch might result in a usable specimen. It is recommended to look into these geometrical possibilities.
References


Appendices
Appendix A - Quest for the Most Suitable Testing Equipment

In order to find sufficient equipment to perform a sinusoidal uni-axial tension test on mortar columns, various test equipment is tried. The process of finding the most suitable equipment, to meet the specific testing needs, is expanded upon in this section.

DMA at Pavement Engineering
The laboratory of the Civil Engineering faculty possesses a Dynamic Mechanical Analyzer (DMA) 450+ from MetraVib. In the first phase of this research, the use of this equipment for the fatigue tests was a logical choice. Nevertheless, some hurdles had to be taken when using the DMA. Starting of, the DMA has two load cells, one of 150 N and one of 450 N. The 450 N load cell can only perform with a maximum frequency of 1 Hz, so this is not an option for the planned tests with a frequency of 10 Hz. The 150 N load cell can perform tests above a frequency of 1 Hz. The maximum force using this load cell is 100 N, whereas it is expected that the measurements required exceed this value.

Another problem that occurs using the DMA is a limitation of the software. Since in the last part of this study, tests with a discontinuous loading are planned. While the currently available software version does not support the option to model rest periods in-between the loading cycles. A newer software version is required before the desired use case scenario of the required specific loading path can be executed.

Some other hurdles were found during trial tests. The options for temperature control of the chamber are limited. To add to that, the regulation with nitrogen does not work optimal. This results in some experienced hiccups with high temperatures in the chamber, before the temperature is stabilized to the required testing condition.

These described minor issues amount to undesired discrepancies in the found test results, leading up to a convincing argument in favor of the search for more adequate equipment to better meet the desired goals.

DMA elsewhere at the TU Delft
The TU Delft has several DMAs, as there are three other laboratories which have one in their possession. Since the original planning was using a DMA for this research, it would be fitting to explore the options, summed up below:

- Faculty of Applied Sciences has a DMA 7E from PerkinElmer with a maximum loading capacity up to 8 N;
- Faculty of 3mE has a DMA from TI with a maximum loading capacity of 18 N;
- Faculty of Aerospace Engineering has a DMTA (Dynamic Mechanical Thermal Analyzer), with a maximum capacity of 8 N.

Immediately the main problem is clear: the maximum loading capacity of 8 N or 18 N. Using a different DMA is clearly not an option for the test in this research which are expected to be around 100 N for the small cylindrical column specimens.

DSR
With the Anton Paar Dynamic Shear Rheometer (DSR) located at the Pavement Engineering laboratory, it is possible to perform tension tests on cylindrical columns. Two issues occur when the tests in this research are performed on this equipment. First, the maximum loading capacity in tension is 70 N which is not high enough for the tension-to-failure tests, although the forces required might just fit within the limited range. The second reason is decisive not to use the DSR, the incapability of the DSR to perform dynamic sinusoidal loading in tension which is needed for the wanted fatigue tests. In tension, the possibilities are limited to a constant value or a ramp. To conclude, this specific DSR is not usable in this research.

UTM
The UTM (Universal Testing Machine) is a logical option to explore for fatigue tests since tension tests with wave loading are possible. However, in this machine the capacity of the load cell is relatively high, which might lead to problems with accuracy for samples of 20 mm height in this equipment.
Appendix B - UTM Set-up Trials

In 'Appendix A - Quest for the Most Suitable Testing Equipment' the process of finding adequate testing equipment to perform uni-axial tension test with sinusoidal loading is described. Decided is that for best results, the tests are performed using the UTM (Universal Testing Machine). But in order to decide whether the UTM is actually usable to perform the specific tests required for this research, this appendix expands further on the UTM. The results of these trials are outlined in this appendix.

In the beginning phase of the fatigue tests, it was found that the signal of the applied load showed quite some unwanted noise. Three factors of the used test set-up are therefore investigated or adjusted, being the UTM displacement recorder, the load cell and the PID-tuning of the UTM. The UTM has a displacement recorder with a 30 mm range, from -15 mm to +15 mm. This gave results with a significant amount of noise. The displacement of mortar columns during tension-to-failure tests is around 2 mm. For this reason, the displacement was measured with an LVDT ±1, so a range of 2 mm. The displacement was found to be somewhat bigger than 2 mm, so the samples tried with this LVDT did not break. An LVDT with a range of 5 mm demonstrated a better performance. The displacement was large enough to break the sample and the results showed less fluctuation compared with the 30 mm range recorder.

Secondly, the load cell is causing some difficulties with the fatigue tests on the UTM. The current load cell in the UTM is a 5 kN load cell. As found in the PID tuning the average error of the data with the expected data is 2.5 N during sinusoidal tests, this is 10% of the actual load during fatigue tests. The load cell of 5 kN is accurate enough for tensile test to failure, however for tests with sinusoidal loading the fluctuated results with this load cell might cause problems. The tests are load controlled, so the question that remains is that since the results show a lot of fluctuation, does that mean that the applied load is also fluctuating.

The third factor which was tried to enhance the results is fine-tuning the PID settings of the UTM. PID stands for Proportional Band, Integral and Derivative. These three settings control the response of the UTM to changes of the measured signal. ‘PID Tuning’ is meant to choose the proper values for the three modes [8]. It is hypothesized that the noise in the experimental data is caused by improper settings of the PID values in the UTM, so tuning might improve the results. The effect of changing the three modes was investigated by mixing stepwise adjustments, both to a lower and higher value.

The results are compared based on the sum of the error at each point for every 0.01 second. The error is the difference between the experimental data and a sinusoidal curve which represents the set loading path.

The standard values in the UTM for PID are $P = 2000$, $I = 15$ and $D = 1500$. The $P$ was changed to $P = 1000$ and $P = 3000$, the $I$ to $I = 10$ and $I = 20$ and the $D$ to $D = 1200$ and $D = 1800$. It is chosen to compare the samples based on the results of 2 seconds, from 8 seconds up to 10 seconds. The results of one test are shown in Figure 81.

![Comparison experimental data and theory with PID = 2000, 15, 1500](image)

Figure 81: Results of the test performed with PID values of 2000, 15, and 1500

An overview of the total error of the two second time lab is given in Table 15. As well as a column with the average error of each testing point. With a time span of 2 seconds and 10 Hz this means...
that the total error divided with 200 gives the average error at one point.

As can be seen in Table 15, the found precision is around 2.5 N. The accuracy is in the same range for each setting, except if the P is taken with a low value. A precision of 2.5 N with a force fluctuation of 20 N is significant. Concluded can be that the noise in the results are mainly caused by the noise generated by the load cell, and is not due to the tuning of the UTM. The question remains whether this noise is a problem when defining the stiffness of the specimens.

<table>
<thead>
<tr>
<th>P</th>
<th>I</th>
<th>D</th>
<th>Error [N]</th>
<th>Average Error [N]</th>
<th>Maximum Error [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>15</td>
<td>1500</td>
<td>534.57</td>
<td>2.66</td>
<td>7.8</td>
</tr>
<tr>
<td>1000</td>
<td>15</td>
<td>1500</td>
<td>772.16</td>
<td>3.84</td>
<td>16.5</td>
</tr>
<tr>
<td>3000</td>
<td>15</td>
<td>1500</td>
<td>495.61</td>
<td>2.47</td>
<td>10.1</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
<td>1500</td>
<td>519.66</td>
<td>2.59</td>
<td>10.0</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
<td>1500</td>
<td>460.92</td>
<td>2.29</td>
<td>10.2</td>
</tr>
<tr>
<td>2000</td>
<td>15</td>
<td>1200</td>
<td>507.87</td>
<td>2.53</td>
<td>9.4</td>
</tr>
<tr>
<td>2000</td>
<td>15</td>
<td>1800</td>
<td>483.60</td>
<td>2.41</td>
<td>12.5</td>
</tr>
<tr>
<td>3000</td>
<td>20</td>
<td>1800</td>
<td>488.97</td>
<td>2.43</td>
<td>10.3</td>
</tr>
</tbody>
</table>
Appendix C - Preparation Small Cylindrical Specimens

In this appendix the preparation of column specimens is described. The small cylindrical mortar columns have a height of 20 mm and a diameter of 6 mm. On both ends of the specimen stainless steel rings are placed enable clamping the specimens during testing. These rings have a height of 4 mm and an outer diameter of 8 mm. The diameter of the mortar increases near the rings, the mortar will reach the outer diameter of the rings. This is chosen to minimize the possibility of a crack near the rings because high corner stress can occur to a lesser extent in with this geometry, see Figure 82.

Bitumen is temperature sensitive, thus the preparation of the samples influences the way the specimens will react to the applied loading. Heating the bitumen to high temperatures can cause ageing effects. A standardized preparation method will help to limit the influence of the difference between the specimen batches. The steps taken in the specimen preparation are described step wise.

- Preheat the oven at 150°C

Prepare the mortar materials

Bitumen

- Preheat two putty knives
- Scoop the needed amount bitumen from the can, into a small can
- Place the can in the oven

Filler

- Take with a spoon the filler from a plastic can and weight the needed amount filler in a small aluminum tray
- Place the tray in the oven

Sand

- Sieve the sand by hand between the aggregate particle sizes between 0.063 mm and 0.5 mm
- Weight the needed amount of sieved sand in a small aluminum tray
- Place the tray in the oven

Preheat the three materials in the oven at 150°C for at least 1 hour.

Prepare the mold

While the materials heat up, the mold can be prepared. The required equipment for the mold is shown in Figure 83. Two halves of the silicon mold, 10 stainless steel rings, 6 wing nuts, 6 bolts, 12 washers, and a steel plate wrapped in silicon paper.

Mixing the materials

The mixing is done by hand using a scalpel, in the bitumen can. Stirring will be easier if the scalpel itself is also preheated.

- Place the scalpel in the oven for 5 minutes
- Add the sand to the bitumen and stir
- Add the filler to the sand-bitumen mix and stir thoroughly.

Judge the mixture visually in order to ensure that the three materials are mixed to a homogeneous substance. If this cannot be reached by stirring, place the can in the oven for 5 minutes. The bitumen will become more viscous, hereby easing further stirring.

- Place the mortar in the oven at 150°C for a minimum of 30 minutes.

**Filling the mold**

- Place the heated mold with the steel plate on a clean horizontal surface.
- Take the mix out of the oven, stir again and pour the mix into the mold using the scalpel, see Figure 84. If the mix is already too little viscous to pour, place the can in the oven for 5 minutes. Take care to fill all molds sufficiently, i.e. with a small bulge on top.

![Figure 84: Pour the mortar into the mold with a scalpel](image)

- Place the filled mold in the oven for at least 10 minutes. This step is added in order to remove air voids in the mortar. The air voids content is found to be 0.22% by volume through CT-scans. Skipping this step will result in a void content of 1.5% [30].

**Cooling down**

- Take the mold on the steel plate out of the oven and place it on a horizontal surface.
- Let cool down at room temperature for 4 hours.
- Place the mold on the steel plate in the freezer around -25°C for 1.5 hours, again the mold should be horizontal.

**Removing the specimens from the mold**

- Remove the mold from the freezer. The mortar will be a little bit sagged, which is the reason of the needed small bulge on top during filling the mold.
- Preheat a putty knife to 150°C on a heating plate. Make sure the temperature of the heating plate does not exceeds the 150°C, since using a knife that is too hot might damage and/or age the mortar.
- Scrap with the putty knife the mortar from the top of the mold until the rings are visible.
- Unscrew the molds.
- Carefully pull the two halves of the mold apart, using a thin putty knife by twisting between the two halves of the mold.
- Bend the mold at the grooves to release the specimen from the mold. Remove the specimen one by one. If the specimens became too soft to remove from the mold, place the mold back in the freezer for 5 minutes. See Figure 85 for the specimen after the two halves are separated.
Clean the steel rings with a cotton swab dipped in dichloromethane. Hold one side with a tweezer, the specimen might heat up from contact with hands.

Store the specimens

- Place the specimen in a tray with fine sand, the same as the fines used in the samples. The sand provides a continuous support which prevents damage, noting that the shape of the specimen is sensitive to bending. Another option to store the specimen in a silicon rubber mold. Both options are shown in Figure 86.
- Store the samples in the fridge until testing with maximum of 7°C

Air Voids

The asphalt mortar samples are not supposed to contain air voids. By this, relatively large air voids which influence the location of the crack of the mortar column specimen are meant. The tests are performed to determine the properties of the mortar materials, so specimens without large air voids is desired.

Earlier own experience showed that not all air voids were removed from the mortar columns using the standard preparation method where the filled molds are placed in the oven for 10 minutes. According to CT-scans performed by Woldekidan [32], the specimens contain 1.5% air voids.

Two other methods are found to remove the air voids. The first is devised by Van den Bergh [30], who places the samples on a vibrating plate when the mortar is still hot. The second method is a method developed in-house: place a small vibrating steel rod in to the filled molds. This steel rod comes from a small milk foam that has been cut off at the end. This method was found to help avoid air voids, although it is messier. In addition to these two new methods, the filled molds can be placed in the oven for a longer period, around 30 minutes. It was concluded that this latter method worked sufficiently and demands less work. Therefore, this method was used throughout this research.
Appendix D - Trials on Small Cylindrical Specimens

In the beginning phase of this research small cylindrical specimens are used for the fatigue tests. The various trial testing using this specimen geometry are outlined in this appendix. In order to maintain overview, some trials are only stated to be performed but the results are left out of this report.

The specimens are small cylindrical columns with stainless steel rings (height: \( h = 4 \, \text{mm} \), diameter \( \phi = 8 \, \text{mm} \)) on both ends to enable clamping the samples during testing. The geometry, the same as DSR columns, was chosen for both comparison with other research studies and the available equipment (e.g. the molds). The geometry is shown in Figure 87. These small specimens are usually not tested in the UTM. The holders from the DMA are used to clamp samples.

In ‘Appendix C - Preparation Small Cylindrical Specimens’ the preparation of these specimens is comprehensive described. After preparation the specimens undergo a curing time. The curing time is defined as the time between the sample preparation and the testing. For the small cylindrical samples is chosen for a curing time of two weeks. The temperature stabilization time was a minimum of 30 minutes. By this, the time of placing the specimens in the test set-up and starting the test is meant.

Monotonic Tensile Tests Trials

The trial testing starts with performing a monotonic tensile test to determine the tensile strength of the specimens. The temperature and the speed are two factors greatly influencing the results, these parameters need to be chosen for the test.

A common temperature found in literature is \( 10^\circ \text{C} \). Therefore, the first tests are performed at this temperature. The tensile strength found was relatively low compared to the accuracy of the machine. Consequently a lower temperature was applied of \( 5^\circ \text{C} \), with this temperature a reasonable tensile strength was found. Since for the fatigue tests 30% of this force will be used, it is desirable to have a relatively high force (e.g. around 100 N). Moreover, at \( 10^\circ \text{C} \) fatigue tests will take longer compared to tests performed at \( 5^\circ \text{C} \). Therefore the temperature is chosen to fix to \( 5^\circ \text{C} \) for all tests.

Next to the temperature, the speed of tensioning the sample influences the results. For the trials, this speed is varied between 0.05 mm/s and 0.25 mm/s. A higher speed will result in a higher maximum force and a more brittle behavior.

The results of tension-to-failure performed on mortar samples made with Q8 70/100 bitumen are shown in Figure 88. These tests trials are performed at \( 5^\circ \text{C} \) and with a tension rate of 0.25 mm/s.
The first five seconds of the test are set without loading in order to define the zero point and to check whether the noise on the results also exists if no force is applied to the specimens and to which extent. The samples were broken in the middle or just below the middle. The maximum force of the three tests are found to be as follows:

- 70 N
- 73 N
- 80 N

This gives an average value of 74 N, and 30% of this comes down to 22.2 N. This value is thought to be large enough peak-to-peak value that fits in the range to perform fatigue tests in the UTM.

**Fatigue Tests Trials**

The tensile strength is determined, thus 30% of this value will be used for the peak-to-peak amplitude of the sinusoidal loading during the fatigue tests.

After several test trials with changing the temperature and the frequency, the fatigue tests are chosen to perform at 5°C and with a haversine loading only in tension: between 1 N and 20 N. During the fatigue test, the diameter and the height change, which logically influences the stiffness. The increase of the height of the sample can be determined by using the deformation data from the LVDT. The diameter is measured at the beginning and at the end of a test and thus assumed to decrease linearly.

To analyze the gained results of the fatigue tests, two calculation methods are proposed, both described in this section.

**Trial I: using minimum and maximum deformation values**

The way to determine the strain is chosen to be the increase of the difference between the maximum and minimum displacement. The average of the minimum and maximum values of the deformation will be taken over a time slot of 3 seconds. The maximum (or the minimum) value within a time slot of 0.2 seconds is filtered from the data. After this the average of these values within one second is calculated. So each second has three different values. This is to check the influence on the dispersion of which time slot is chosen. The values are calculated for the 3 seconds within in the time slot and give values for $\Delta l$. An graphic example of this calculation method is given in
This new calculation method resulted in fatigue curves given in Figure 90. The results of three tests are given, as well as the average of these three results. The samples were all broken at the end of the test. As can be seen, the stiffness increases the first 15 minutes, after this it slowly decreases. The expected SN-curve, as introduced in Figure 1, cannot be found in these results. The first phase differs greatly, the high variations in stiffness are observed, which can have no real physical meaning as the material will not change this rapidly. The second phase seems to head towards the expected results, and the third phase is non-existing. Next to this, striking is the stiffness at the breaking point which is higher than the initial stiffness.

These unexpected results might be due to the relatively large influence of one high value compared to the values surrounding. Therefore, the same method is performed using the second minimum and maximum for the calculations. This resulted in a smaller strain and thus a higher stiffness. Nevertheless, the shape of the graphs were not influenced greatly. An example is shown in Figure 91.
Another reason for the found unexpected fatigue curve shape might be due to pre-tension loading in the UTM influencing the start of the test. To investigate this possibility, the fatigue tests using the same parameters is performed on a steel rod. In the found results one can see a shift of the displacement of 1.5 \( \mu \text{m} \) within the first 20 seconds. The fatigue tests on mortar samples show a difference between the minimum and maximum displacement is 7 \( \mu \text{m} \) and 13 \( \mu \text{m} \). The found 1.5 \( \mu \text{m} \) is significant large to have influence. However, the stiffness increase occurs in the first ten minutes and not only the first 20 seconds. Concluded, any existing pretensioning in the UTM is not influencing the results causing a different fatigue curve than the expected SN-curve.

Furthermore, the next trial to gain an expected SN-curve is to change the temperature and the loading, to exclude this influence. The temperature is set on 0\(^{\circ}\)C instead of 5\(^{\circ}\)C. The loading is set from -1 N to -40 N (instead of -20 N). The results of two tests are shown in Figure 92. As can be seen, the same factors has previous tests can be detected. In the first phase something happens which is hard to explain, the second phase looks towards expected and the third phase in non-existing.
Figure 92: The fatigue curve at 0°C and loading pattern from -1 N to -40 N

**Trial II: Fourier Transformation**

The results of the fatigue tests contain significant noise, which is thought to influence the results when constructing a fatigue curve. To smooth out the results, a Fourier transformation is proposed. This method is applied on the same data which is used for the calculations of Trial I. For this analysis the standard Fourier transformation formulas are applied, as shown:

\[
f(t) = \frac{A(0)}{2} + \sum_{n=1}^{\infty} \left( A(n) \cos(na) + B(n) \sin(na) \right)
\]

\[
A(n) = \frac{1}{\pi} \int_{0}^{2\pi} f(a) \cos(na) da
\]

\[
B(n) = \frac{1}{\pi} \int_{0}^{2\pi} f(a) \sin(na) da
\]

For the applied analysis the formulas are adjusted for this particular data set. Chosen is to take an interval of 1 second, meaning 100 data points in each interval. The formulas result in:

\[
f(t) = \frac{A(0)}{2} + \sum_{1}^{100} \left( A(n) \cos(na) + B(n) \sin(na) \right)
\]

\[
A(n) = \frac{1}{50} \sum_{1}^{100} f(a) \cos(na)
\]

\[
B(n) = \frac{1}{50} \sum_{1}^{100} f(a) \sin(na)
\]

\[
a = \frac{2\pi t}{1.0} = 2\pi t
\]

Chosen is to use the values of the 15th-order calculations, this is thought to be an accurate result to smooth the results with noise. An example of the comparison between the rough data and the 15th order Fourier Analysis is shown in Figure 93. The steps to calculate the stiffness after the Fourier Analysis is the same manner performed as with the Trial Method. The only difference is
the chosen value of the force. Here the average force is used in the calculations, but in the trial method the maximum force is taken.

![Image](https://example.com/image1.png)

Figure 93: An example of the Fourier Analysis: data, 1st order and 15th order

Test results with loading path from 1 N to 22 N
The three samples were all broken at the end of the test. The sample of test A was cracked just below the middle of the column. The mortar specimens of test B and C were cracked just above the bottom ring.
Logically, the stiffness shows a higher value using the maximum force. Also, the curve does fluctuate more compared to the curves which are based on calculation with the average force. Overall, the Fourier Analysis shows higher stiffness of the mortar samples. The shape of the fatigue curve differs with each data set, and seems random.

![Image](https://example.com/image2.png)

Figure 94: Results A of the data analysis, using the two different methods
Test results with loading path from 10 N to 30 N

The results of the fatigue tests with a loading path from 1 N to 22 N showed not the expected SN-curve. Due to the found maximum error with the standard PID settings of 7.8 N (see ‘Appendix B - UTM Set-up Trials’), it is thought changing the load path might solve the problem. The test with the loading path of 1 N to 22 N, is not a test in pure tension, as shown in Figure 97. It can be seen, the force also shows negative values. Thus the specimens becomes compressed and the test is not purely performed in tension.
In Figure 98 are the results shown of the fatigue tests performed with a loading path from 10 N to 30 N. These calculations are both based using the average force. The specimen was broken within 14 minutes, which is fast compared to the tests performed with a lower loading path. The crack occurred 5 mm above the lower ring of the specimen. Next to this, the stiffness is higher compared to the test described before. Striking is the difference between the two calculation methods. This shows that the results contain high fluctuations and depend highly on which time slot the calculations are based.

Change of the LVDT

Investigate the displacement in the first 10 minutes of the tests. Meaning, measure the displacement more precise by adding an extra LVDT for the first 2 mm. This LVDT has a range of 2 mm (from -1 mm to +1 mm). The total displacement with fatigue tests lies between 4.5 mm and 5 mm, so still the LVDT with a range of 5 mm is needed. However, this displacement recorder is relatively large for the small displacements between minimum and maximum load (around 10 µm).

A comparison between the results using a LVDT of 2 mm and a LVDT of 5 mm is shown in Figure 99. The LVDT with a range of 2 mm shows less fluctuations as expected. However, the results of the stiffness did not improved significantly.
Foundings of test trials on cylindrical specimens

Based on the foundings described in this appendix, concluded can be that this test set-up and specimen geometry will not provide adequate results. The load cell is too rough for such small displacements.
Appendix E - Preparation Parabolic and Straight Specimens

The preparation of the parabolic shaped specimens and straight specimens are almost the same, apart from the type of mold being used. Therefore, the preparation of the specimen preparation is merged into one description.

To limit the difference between various specimen batches, the steps in this preparation are taken during each. In the NEN-EN-12697 [1] the needed time to heat up the materials is proposed. The sand and filler need to be heated at 160°C for a minimum of 8 hours. The bitumen is needed to be heated to 155°C. In this research the small amount of materials being used during one batch, and the available ovens, it is chosen to heat up all three materials to 150°C.

- Preheat the oven at 150°C

Prepare the mortar materials

Bitumen

- Preheat two putty knives
- Scoop the needed amount bitumen from the can, into a small can
- Place the can in the oven

Filler

- Take with a spoon the filler from a plastic can and weigh the needed amount filler in a small aluminum tray
- Place the tray in the oven

Sand

- Sieve the sand by hand between the aggregate particle sizes between 0.063 mm and 0.5 mm
- Weight the needed amount of sieved sand in a small aluminum tray
- Place the tray in the oven

Preheat the three materials in the oven at 150°C for at least 1 hour.

Prepare the mold

While the materials heat up, the mold can be prepared. The required equipment for the mold is the silicon rubber mold, two tie-wraps, 12 stainless steel rings, and a steel plate wrapped in silicon paper.

- Push the steel rings into the mold
- Place the tie-wraps around the mold, and tighten
- Place the mold on the steel plate, see Figure 100

Mixing the materials

The mixing is done by hand using a scalpel, in the bitumen can. Stirring will be easier if the scalpel itself is also preheated.

- Place the scalpel in the oven for 5 minutes
- Add the sand to the bitumen and stir
- Add the filler to the sand-bitumen mix and stir thoroughly

Judge the mixture visually in order to ensure that the three materials are mixed to a homogeneous substance. If this cannot be reached by stirring, place the can in the oven for 5 minutes. The bitumen will become more viscous, hereby easing further stirring.

- Place the mortar in the oven at 150°C for a minimum of 30 minutes
Ageing Method

The procedure to make aged specimen needs the ageing steps in between the normal procedure, these steps are described here. In this research is chosen to compare the unaged mortar with various ageing time frames: 1, 2, 6, and 9 days.

- Pour the mortar in a aluminum tray, the thickness of the mortar is around 6 mm
- Place in a oven for 4 hours at 135°C, see Figure 101 for the aluminum tray in an oven
- Set the oven to 85°C and heat the mortar for 1, 2, 6, or 9 days depending on the wanted ageing period
- Heat the mortar to 150°C for 30 minutes in order to be able to pour

Filling the mold

- Place the heated mold with the steel plate on a clean horizontal surface
- Take the mix out of the oven, stir again and pour the mix into the mold, see Figure 102. If the mix is already too little viscous to pour, place the can in the oven for 5 minutes. Take care to fill all molds sufficiently, i.e. with a small bulge on top
- Place the filled mold in the oven for at least 10 minutes

Cooling down

- Take the mold on the steel plate out of the oven and place it on a horizontal surface
- Let cool down at room temperature for 24 hours
- Place the mold on the steel plate in the climate chamber around 14°C for 2 hours, again the mold should be horizontal

Removing the specimens from the mold

- Take the two tie-wraps of the mold
- Carefully take the specimens from the mold
- Cut off the overflow of bitumen at both ends using a heated putty knife

Store the specimens

To store the specimens, silicon rubber storage molds are made. This will give an evenly support to the specimen, so that the specimens will keep their geometry. Store the samples in the fridge until testing with maximum of 7°C.

Silicon rubber thermal expansion coefficient

Silicon rubber is used to make the molds and the storage molds. This exists of two components, silicon rubber (PS81020) and a harder, after mixing it will dry within 24 hours. The expansion coefficient of this material is not known during heating up to 150°C, which is done during specimen preparation. According to Poly-Service, the supplier, the rubber can withstand temperatures up to 200°C. It is thought that the expansion of this material does not influence the shape of the specimens.
Appendix F - Trials on Parabolic Shaped Specimens

At the beginning of this research, small cylindrical column specimens were tested, as described in ‘Appendix C - Preparation Small Cylindrical Specimens’ and ‘Appendix D - Trials on Small Cylindrical Specimens’. Next, chosen was to test parabolic shaped specimens. The preparation of these specimens is described in ‘Appendix E - Preparation Parabolic and Straight Specimens’. The results of the tests performed on these specimens are expanded upon this appendix. The tests performed on the parabolic shaped specimen are trial tests to check whether this geometry is sufficient for the test set-up in the UTM, whether the force magnitude exceeds the UTM noise. At a later point, it was decided to switch from parabolic specimens to straight cylindrical specimens.

Monotonic Tensile Tests

The monotonic tensile tests until failure are performed at $5^\circ C$ and the tension speed is set to 0.25 mm/s. The result is shown in Figure 103. A jump in the beginning of Result 1 can be seen, which is not visible in Result 2 and 3. This might be explained by the fact that these tests are performed using a different UTM, although an identical test set-up and parameter were used. The maximum tensile forces are determined as 625 N, 750 N and 840 N, averaging out at 740 N. Taking 30% results in 220 N, which will be used for the peak-to-peak amplitude during fatigue tests.

The tensile strength of the small cylindrical sample was measured at 74 N. The hypothesis was, based on the increasing diameter as described before, an increase of 8.75 times the tensile force. But the experimental data shows an increase with a factor 10, this is thought to be due to the parabolic specimens and the use of a different clamping system. Although, the variation between the three results is relatively large and perhaps not significant enough to draw conclusions. Part of the variation between the three results is assumed to be caused by an incorrectly operating cylinder in the UTM. This is replaced before further tests are executed in order to get more accurate results.

![Figure 103: The tensile test results on parabolic shaped specimens](image)

Fatigue Curve

Loading Pattern

For the fatigue test, a percentage of the tensile strength will be used as the amplitude of the sinusoidal loading. Taking 30% of the average value of the found tensile strength values results in a peak-to-peak amplitude of 200 N. This value is rounded from the obtained result of 221 N. The frequency of 10 Hz and a temperature of $5^\circ C$ is taken.
In the first fatigue tests, a difference between the set loading path and the recorded loading path was found. The loading path was sinusoidal with a minimum of 0 N and a maximum of 200 N. Due to small errors in the signal, some values of the measured loads were found to be compression forces. The loading was not performed in pure tension, but contained some small compression forces. This resulted in choosing a loading path with the minimum tension force of 5 N. Combining this with the peak-to-peak amplitude of 200 N, the sinusoidal loading path is chosen to have a minimum of 5 N and a maximum of 205 N.

Displacement signal
Due to a continuous tension load the specimens are strained extensively during a test, the total permanent deformation of the specimens will be around 15 mm. The displacement with every load cycle is at the beginning of a fatigue test around 30 \( \mu m \) and at the end of the test around 50 \( \mu m \). Both the total deformation of 15 mm and the displacement of each load cycle are to be recorded. The LDVTs with a range of 2 mm and 5 mm are incapable of measuring the total displacement. LDVTs with a range of 10 mm and 20 mm are used in other trial fatigue tests in this research. In Figure 104 the results of the sinusoidal loading measurements at one minute during fatigue tests are shown. As can be seen, the measurement of the LDVT ± 1 mm gives an accurate representation of the sinusoidal displacement pattern. In contrast, the LDVT ± 10 mm produce highly fluctuating results. During a fatigue test three LDVTs are used and placed between the two parts of the clamping device.

![Figure 104: The sinusoidal loading measurements using two LDVTs](image)

It is thought that the reason for this result lies not in the LDVTs but rather in the hardware which the UTM-2 uses, which is a 12 bit AD-converter, meaning that one bit translates to a 2.44 \( \mu m \) displacement, which is more than 10% of the peak-to-peak amplitude of a sinusoidal loading with a peak-to-peak amplitude starting at 30 \( \mu m \). This value is calculated based on the range that is divided over 10 Volts and 12 bits:

\[
\frac{10}{2^{12}} \cdot 1000 = 2.44\mu m.
\]

To improve the results, several possibilities exist. One option is to use a different UTM present in the Pavement Laboratory of TU Delft, UTM-1. The displacement recorder of the UTM-1 is connected to a 16 bit AD-converter, translating to a precision of 0.15 \( \mu m \), which is 0.5% of the peak-to-peak amplitude.

In order to test the impact of the hardware on the displacement signal, a fatigue test is performed on this UTM, using the same parameters: 5°C, a frequency of 10 Hz, a loading pattern of a sinusoidal load ranging from 20 N to 220 N. As shown in Figure 105, a clear improvement of the 16 bit UTM can be seen in comparison to the results of the 12 bit UTM that was previously used. However, these results are still not sufficient enough to determine the fatigue life due to another issue which is related to the sampling speed of the data. At the results of the UTM-2 flattened results can be found at maximum and minimum values of the sinusoidal load. These discrete jumps indicate a hardware limitation, since the results are sampled with 100 Hz, thus corresponding with ten data points for each period of the sinus. This will cause inaccurate results at the minima and maxima values of the sinusoid. It is thought that the minimum frequency of the gained data is 200 Hz, resulting in 20 data points for each period of the sinusoidal load.
The second possibility to improve upon the results is to send the measured data to external hardware that is able to record data with a higher sampling frequency. The software on the UTM computer is used to control the test and set the parameters. Also the results of the applied force will be gathered by this UTM software. However, the results of the three LDVTs are recorded using an external laptop, these measurements are collected using Mp3-software. The total displacement and the difference between the minimum and maximum of the sinusoidal loading, the range, is recorded. The data is sampled at 2500 Hz. The use of two measurement signals via different systems might cause a time lag between the force and the displacement which cannot be resolved. However, the test is force-controlled and thus the force will have the same sinusoidal loading path throughout the test. Therefore, the average force value is used to calculate the stiffness, thus possible time lags between the two measurement systems will not cause difficulties. The results of a trial test using an external method of recording data (e.g. a laptop) to process the measurements of the LDVTs is shown in Figure 106. Each graph represents stiffness which is calculated using displacement data from a different LVDT.

The three LVDTs give various results, while the data is gained from the same test. The results of LVDT 1 and LVDT 2 show the expected SN-curve. The results gained with LVDT 3 differs in the beginning of the fatigue test. A possibility is that the problem lies within the LVDTs itself and not with the test set-up. Another possibility could be that the clamps were not horizontally aligned which causes a LVDT at one side of the specimen to be pulled out instead of being pressed in. Eventually in this research, the average of the three LVDTs will be used to calculate the stiffness.
Note that the first 100th cycle are included in the results shown in Figure 106 as well.

**Stiffness Analysis**

The first 100 cycles of the sinusoidal load are not taken into account, because according to NEN-norm [1] the initial stiffness should be taken at the 100th load application.

The diameter of the specimens is not recorded as a parameter during the test. Therefore, several fatigue tests are stopped after 10 minutes and 30 minutes to measure the diameter change of the mortar columns. These results were found to be repeatable and showed a linear change of the diameter in time. In the data used in this section, the diameter is measured at the beginning and at the end of a test and assumed to decrease linearly.

The stiffness of the mortar samples are calculated with the following formulae:

\[
E = \frac{\sigma}{\epsilon} \tag{23}
\]

\[
\sigma = \frac{F}{A} \tag{24}
\]

\[
\epsilon = \frac{\Delta l}{l} \tag{25}
\]