# Influence of bituminous specimens preparation on fatigue properties

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## RESUMO

This paper presents the results of a study where the fatigue life of three mixes was evaluated and compared. The mixes were all produced with the exact same materials. However, the preparation process differed. One was mixed and compacted in laboratory, the other was mixed in plant and compacted in laboratory and the third was mixed and compacted in the field. The mixes were compacted in the laboratory using the rolling wheel compactor. The field compaction was achieved by tire and steel rollers.

The fatigue life of the mixes was compared based on the results of the four point bending beam test executed at 10 and 25°C. Furthermore comparisons were made between fatigue life predicted by the Shell, Brown, The Asphalt Institute, SHRP-A003A program procedures and the laboratory test results.

## 1. INTRODUCTION

The fatigue life of bituminous mixtures is influenced by several factors such as temperature and frequency of applied loads. Others factors such as the mixture design, material properties and compaction effort influence fatigue life. The fatigue life, stiffness, phase angle between applied loads, mixture response and dissipated energy can be investigated with laboratory tests.

One of the most common methods used to evaluate fatigue life is the fatigue flexural bending beam test. This test was developed more than thirty years ago, has been widely used, and can be executed under strain or stress loading conditions.

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Generally, specimens are prepared in the laboratory under conditions that attempt to produce specimens with properties similar to those obtained from field cores. Although every attempt is made to duplicate, in laboratory, the same conditions under which the mixture is placed in the field, it is necessary to investigate if those conditions do affect performance based properties such as fatigue life.

This paper shows a comparison of the fatigue performance of three types of specimens named A, B and C: Specimen A - sawed from the road three days after compaction (average air void content was 5.0%); Specimen B - sawed from laboratory rolling wheel compacted slabs using mix produced in the field plant (average air void content was 6.2%); Specimen C - sawed form laboratory rolling wheel compacted slabs using laboratory prepared mix (average air void content was 6.8 %);

The comparison among fatigue performance of these three mixtures allows for conclusions and recommendations about the laboratorial production of bituminous mixtures. The mixture used in this study is primarily used in Portugal as basecourse material. This pavement layer is subjected to the highest tensile strains and therefore subject to fatigue life under the conditions simulated by the four point bending fatigue test.

## 2. SPECIMEN PREPARATION

### 2.1. Materials

The bituminous mixtures of this study are a dense bitumen macadam with a maximum aggregate size of 37.5 mm and were manufactured according the Portuguese standards. The aggregate used was a 100% crushed granit with the grading is shown in Table 1.

Table 1. Aggregate grading

| Sieve | Percentage passing |
|---|---|
| 1 1/2" | 100 |
| 1" | 91 |
| 3/4" | 85 |
| 3/8" | 63 |
| #4 | 54 |
| #10 | 42 |
| #40 | 18 |
| #80 | 15 |
| #200 | 7 |

The specific unit weight of aggregate was 2.7 g/cm$^3$, the water absorption was 0.97 % and the Los Angeles wear was 24%. The bitumen was a 60/70 penetration grade and the selected content was 4.4% by weight of aggregate. The bitumen properties are presented in table 2.

Table 2. Properties of bitumen

| | Before RTFOT | After RTFOT |
|---|---|---|
| Penetration, 25C, 100 g, 5 seg., 0.1mm | 62 | 27 |
| Softening point, C | 53.1 | 67.3 |

## 2.2. Mixtures

Table 3 shows the production and compaction sites and temperatures used for the different mixes and types of compaction for the three different specimens used in this project.

Table 3. Production and compaction sites.

| Speci mens | Produced | Compacted | Production temperature Agreg / Bitum | Compaction temperature | Compaction type |
|---|---|---|---|---|---|
| A | Mix plant | Road | 175 / 160 | 160 | Tires + Steel |
| B | Mix plant | Laboratory | 175 / 135 | 135 | Lightweight |
| C | Laboratory | Laboratory | 168 / 140 | 140 | steel roller |

## 2.3. Test specimens

The "A" specimens were obtained from a slab extracted from the road. This slab was sawed, in laboratory, to produce nine beams 38.1 cm long by 6.25 cm wide by 5.0 cm high. The remaining parts of the slab were used to measure the air void content and the specific unit weight. To produce the "B" specimens, about 80 Kg of bituminous mixture was collected from the contractor mix plant and compacted in laboratory in a wooden mold with a lightweight vibratory steel roller. One day after compaction the slab was extracted from the mold and one week later the slab was sawed to produce the specimens.

The amount of mixture that was placed in the mold was controlled to yield the desired void contents. The "C" specimens were mixed in laboratory using the procedures proposed by Pais et al. (1995). The four aggregate stockpiles sizes were combined with the bitumen at the appropriated percentage to yield identical mixes. The remaining process is similar to the one used to produce the B specimens. The specific unit weight, air void content and bitumen content for the beams of each slab are presented in table 4.

Table 4. Air void and bitumen content of the mixes.

| Specimens | Bitumen content (% w. Agg.) | Air-void content (%) |
|---|---|---|
| A | 4.4 | 5.0 |
| B | 4.7 | 6.2 |
| C | 4.6 | 6.8 |

## 3 RESPONSE OF BITUMINOUS MIXTURES

### 3.1. Stiffness

The bituminous mixtures exhibit linear-viscoelastic behavior as such that their response is time of loading and test temperature dependent:

$$S_{mix} = \frac{\sigma}{\varepsilon}(t,T) \tag{3.1}$$

where $S_{mix}$ = mixture stiffness; $\sigma$ = stress level; $\varepsilon$ = strain level; t = time of loading; T = test temperature.

### 3.2. Fatigue life

One of the major modes of distress considered in the asphalt concrete pavement design is the fatigue cracking. When an asphalt pavement layer rests on an untreated aggregate base layer, the passage of a wheel load causes the pavement to deflect. The larger this deflection is, the greater the propensity for fatigue cracking (Hveem 1955).

A fatigue model has been established using a linear regression between fatigue life logarithm, *log* $N_f$, and the initial strain logarithm, *log* $\varepsilon_t$, for controlled strain tests. The fatigue model proposed by Monismith et al (1971) is as follows:

$$N = a\left(\frac{1}{\varepsilon_t}\right)^b \tag{3.2}$$

where $N$ = number of repetitions to failure; $\varepsilon_t$ = tensile strain applied; a and $b$ = experimentally determined coefficients.

Some organizations today use an evolution of the equation (3.2). The equation has the form:

$$N = K\left(\frac{1}{\varepsilon_t}\right)^a\left(\frac{1}{S_{mix}}\right)^b \tag{3.3}$$

where $S_{mix}$ = stiffness; K = factor that recognize the influence of asphalt content and degree of compaction; the others factors have the same meaning in equation (3.2).

Based on equation (3.3), the Asphalt Institute (1981) proposes the following equation:

$$N_f = S_f A * N_{lab} \tag{3.4}$$

where $A = 10^M$; $M = 4.84\left(\frac{V_b}{V_b + V_v} - 0.69\right)$; $N_{lab} = 0.04325*(\varepsilon_t)^{-3.291}*(S_{mix})^{-0.845}$; $N_f$ = fatigue life; $S_f$ = shift factor to convert laboratorial results in field expected results, the recommended factor is 18.4 for a 10% cracked area; $\varepsilon_t$ = tensile strain applied; $S_{mix}$ = stiffness of a mix in PSI; A = adjustment factor; $V_b$ = asphalt content; and $V_v$ = air void content.

The equation proposed by Shell (1978) is as follows:

$$N_f = \left( \frac{\varepsilon_t}{(0.856V_b + 1.08) S_{mix}{}^{-0.36}} \right)^{-5} \tag{3.5}$$

The Asphalt Institute and Shell equations are widely used in Portugal to predict fatigue life of asphalt mixes. The Nottingham researchers (Brown et al. 1982) have developed a relationship between the tensile strain and the number of loadings to failure based in the asphalt content and the ring and ball softening point temperature expressed as follows: equation (3.6)

$$\log(\varepsilon_t) = \frac{14.39\log(V_b) + 24.2\log(T_{RB}) - 40.7 - \log(N_f)}{5.13\log(V_b) + 8.63\log(T_{RB}) - 15.8} \tag{3.6}$$

where $T_{RB}$ = are the ring and ball softening point temperature.

In SHRP program (Tayebali et al. 1994) have propose the following equation to predict the fatigue file: equation (3.7)

$$N_f = S_f * 2.738E5 * e^{0.077VFB} * \varepsilon_o{}^{-3.624} S_o''^{-2.720} \tag{3.7}$$

where: $S_f$ = shift factor to convert laboratorial results in field expected results, the recommended factor is 10 for 10% cracked area and 14.0 for 45% cracked area; e = base of natural logarithm; VFB = percentage of voids filled by bitumen; $\varepsilon_o$ = strain level and $S_o''$ is the loss stiffness.

## 4. TEST APPARATUS

The test apparatus used in this study was a CS7800 Axial Testing System (figure 1) and a Flexural Beam Device (FBD), both fabricated by James Cox and Sons, CA, USA. The FBD has free translation and free rotation at the reaction points and at load points, as represented in figure 2. The machine is controlled by a microcomputer using the ATS software that provides a feedback closed-loop control to the servohydraulic system, test temperature and data acquisition.

The flexural beam device allows testing beam up to dimensions of 50 mm by 63 mm by 380 mm. The reaction points distance was set to 355.6 mm and the load points distance was set to 118.5 mm. This device is placed in an environmental chamber that maintains the test temperature by circulating air. Although fatigue tests are normally executed at temperatures below 30 °C, the machine can provide temperature control between -20 °C and 70 °C, with an accuracy of 0.5 °C.

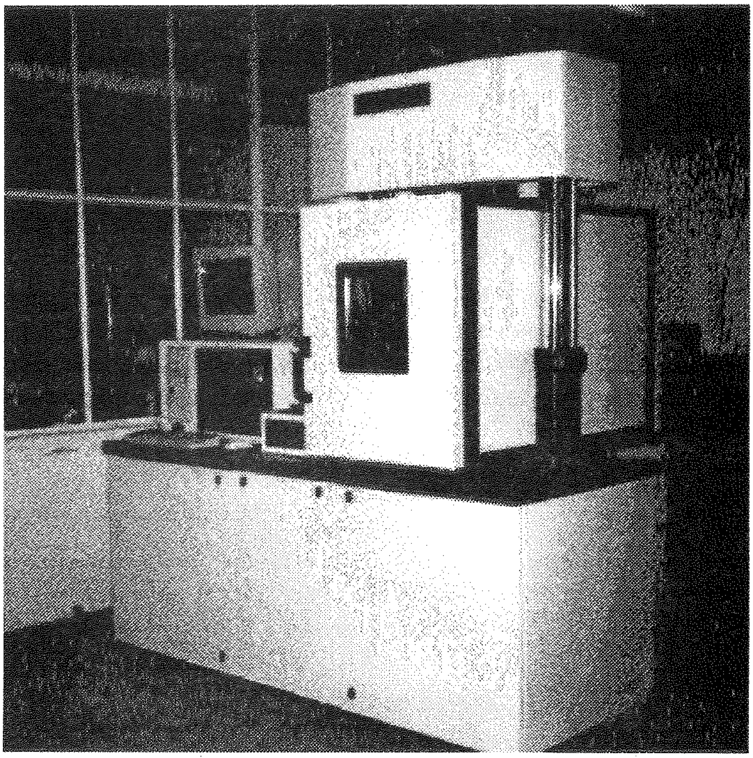

Figure 1 - CS7800 Axial Testing System installed in the University of Minho.

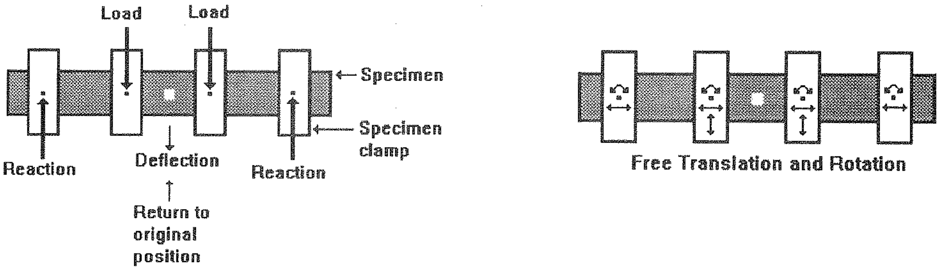

Figure 2. Flexural beam device.

The closed-loop control of the servohydraulic system can execute tests of any frequency up to 20 Hz. The loading conditions include both the controlled-load and controlled-deformation modes. These capabilities allow the equipment to be used to define frequency response of a material over a wide range of temperatures, frequencies and strains.

This flexural beam device, in association with the software capabilities, has considerably improved the reliability of results compared with earlier devices. Good reliability can be obtained with as few as 4 specimens, compared with the 21 to 26 reported in the literature (Sousa 1993).

# 5. TEST PROCEDURE

The test procedure used in this work is identical to that followed by Tayabali (1994), Sousa et al. (1993) and Azevedo et al. (1993). In this study the procedure takes one day and is conducted by testing a minimum of 4 specimens in controlled-strain mode of loading. The test procedure is as follows:

1 - Test two beam specimens at a high strain level, 600 to 800 * E-6, so that the specimen will last for about 2000 to 30 000 cycles. These two tests will take approximatelly 2 hours.

2 - The third beam must be tested at a middle strain level, 400 to 500 * E-6, so that the specimen will last for about 100 000 cycles. This test will take about 4 hours and it can be done after the previous.

3 - The last specimen must be tested at a low strain level, 200 to 300 * E-6, so that the specimen will last for about 500 000 cycles. This test will take about 16 hours and can be done from the evening until the morning of the next day.

The test procedure for these mixtures include two tests: a frequency sweep test and a fatigue test.

## 5.1. Frequency sweep test

The frequency sweep test measures the stiffness and the phase angle of a mixture when subjected to different loading frequencies. A frequency sweep test was executed on the same beam used for the fatigue test. All the frequency sweep tests of this study were executed at a strain level of 200 micros mm/mm, and at 10, 5, 2, 1 Hz. To minimize damage of the beam only 100 cycles were applied for the first three frequencies and for the last frequency 10 cycles were applied. This frequency sweep procedure takes only 90 seconds. Prior to testing, the specimen was placed at the environmental chamber for two hours.

## 5.2. Fatigue test

The fatigue test was executed after the conclusion of the frequency sweep test and was done in control-strain mode. In this control mode the failure is defined at the point were the stiffness of the specimen decreases to 50% of the initial stiffness. The four-point bending tests were executed imposing a repetitive sinusoidal displacement to the center of the beam with a frequency of 10 Hz.

# 6. TEST RESULTS

The test data of the frequency sweep and fatigue tests were analyzed with the ATS software. For the fatigue tests only the last 90% of data were considered. The start of the stiffness versus the number of load cycles curve must be eliminated because during this phase the decrease of the stiffness is due the heating of the specimen (Di Benedetto et al. 1996) (figure 3).

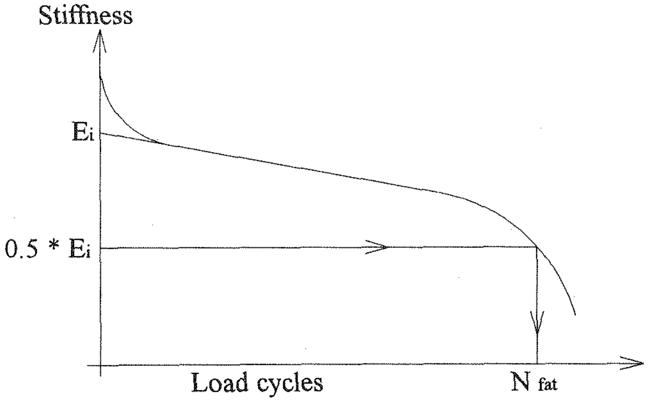

Figure 3 - Stiffness behaviour in controlled strain fatigue tests.

### 6.1. Frequency sweep test results

The results of frequency sweep tests are shown at Figure 4 and 5, where the stiffness and phase angle frequency-dependence is visible. The frequency sweep results at 10 °C show the same ranking of 25 °C. As expected the stiffness at 10 °C is greater than at 25 °C. The stiffness ranking A-C-B means that some differences exist between the three mixes. Mix A has air void content lower than the others, thus it is possible that the greater stiffness is due the air void content difference.

The main difference between mix B and mix C is the mix preparation procedure. Mix C was not subjected to any conditioning after mixing and before compaction as recommended by SHRP-A003A (Tayebali 1994). Probably the lesser compaction temperature is responsable the difference between B and C specimens.

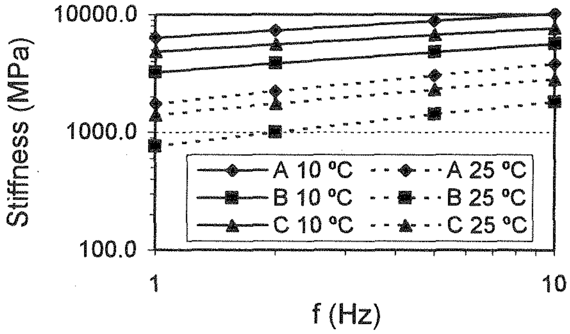

Figure 4. Stiffness as function of load frequency.

Figure 5 shows the phase angle results for the different type of specimens. The phase angle results show the visco-elastic behavior of the three specimens.

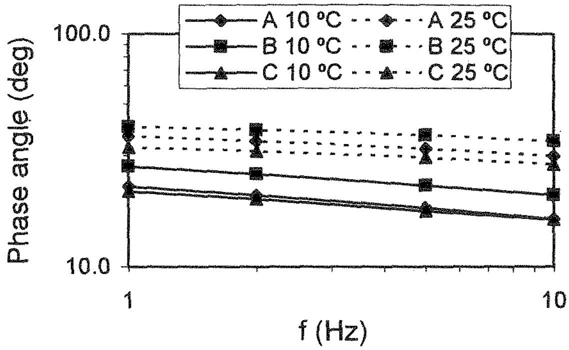

Figure 5. Phase angle as function of load frequency.

6.2. Fatigue test results

Figure 6 presents the fatigue life for the three mixes and one can see that they are very close. At 25 °C C specimens appears to exhibit lower fatigue life than A and B. This is either due to the lower binder content and higher air void content or to the lack of conditioning process on the laboratory preparation procedure. The fatigue behavior at 10 °C is not identical to that obtained at 25 °C as the fatigue curves show different slopes and intercepts.

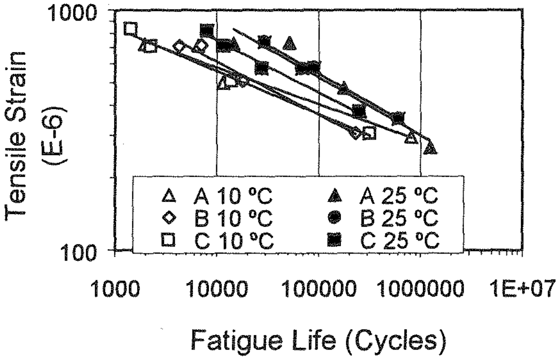

Figure 6. Fatigue curves for the different specimens.

Table 5 presents a summary of the application of equation (3.2) at 25 °C. The high $R^2$ coefficient indicates the good relationship between the log of the number of load cycles and the log of tensile strain level. At 10 °C the test results present also high $R^2$ coefficients as is shown at Table 6.

Table 5. Coefficients a and b of equation (3.2).

| | T=25 °C | | |
|---|---|---|---|
| Specimens | a | b | $R^2$ |
| A | 2.554E-9 | 4.143 | 0.918 |
| B | 1.931E-9 | 4.200 | 0.927 |
| C | 4.963E-11 | 4.575 | 0.987 |

Table 6. Coefficients a and b of equation (3.2).

| | T=10 °C | | |
|---|---|---|---|
| Specimens | a | b | $R^2$ |
| A | 8.648E-18 | 6.502 | 0.929 |
| B | 3.535E-11 | 4.494 | 0.976 |
| C | 8.850E-15 | 5.546 | 0.991 |

## 7. COMPARISON OF FATIGUE LIFE LAWS

Table 7 and 8 show a comparison study between the fatigue life given by the model proposed by The Asphalt Institute (eq. 3.4), the model proposed by Shell (eq. 3.5), the model proposed by Brown (eq. 3.6), the model proposed by Tayabali (eq. 3.7) and the values obtained for the mixes of this project.

This comparison was made to two strain levels at each test temperature. The strain levels were 100E-6 and 400E-6. The 100E-6 is a usually strain level for the Portuguese flexible pavements. The 400E-6 was the average strain tested.

Table 7. Comparison between fatigue life laws at 25 °C.

| Strain | Number of cycles to failure (1000) | | | | |
|---|---|---|---|---|---|
| E-6 | Lab *10 | Tayabali | AI | Shell | Brown |
| 100 | 990 247 | 468 967 | 7 538 | 106 256 | 10 190 |
| 400 | 1743 | 4183 | 95 | 154 | 29 |

Table 8. Comparison between fatigue life laws at 10 °C.

| Strain | Number of cycles to failure (1000) | | | | |
|---|---|---|---|---|---|
| E-6 | Lab *10 | Tayabali | AI | Shell | Brown |
| 100 | 1 351 896 | 152 176 | 3 292 | 18 538 | 10 190 |
| 400 | 619 | 643 | 34 | 18 | 29 |

The laboratory fatigue life presented in Table 7 and 8 were calculated using the fatigue model (eq. 3.2) and a shift factor of 10 was applied to predict the performance of the asphalt mixes in the pavement. This shift factor of 10 was select because it was proposed by Deacon et al (1995) for results obtained in the strain control fatigue tests.

The lowest strain level tested in laboratory, for the test mixes, was 250E-6. To reach the strain level of 100E-6 the fatigue life was extrapolated. The stiffness and the phase angle for the fatigue models was calculated using the Figure 7 and Figure 8. These figures show that the stiffness and phase angle are tensile strain dependent.

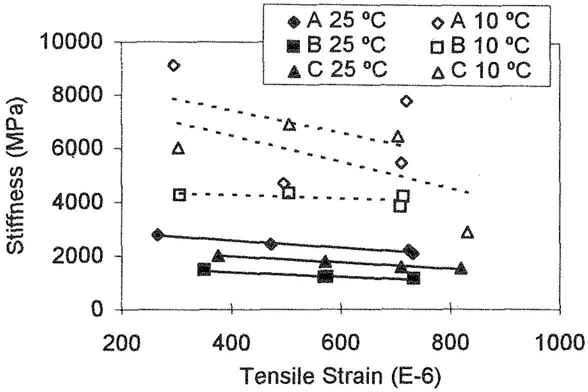

Figure 7. Stiffness as function of tensile strain.

The comparison between the laboratory fatigue life and the fatigue life proposed by the models presented in Table 7 and Table 8 shows some differences when these models are applied to the asphalt mixes used in this study. In part some of the differences are likely to be caused by the mode of loading used in the development of the fatigue equations.

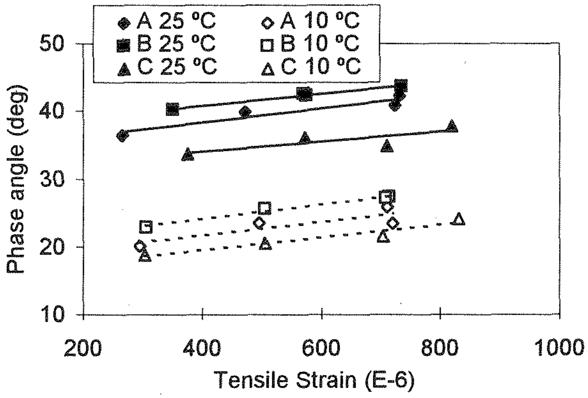

Figure 8. Phase angle as function of tensile strain.

## 8 CONCLUSIONS

The fatigue life of three types of specimens was determined in laboratory using the AASHTO TP8-94 procedure.

The specimens were fabricated using the same materials but mixed and compacted by different methods.

Their fatigue life was compared with precuctions made by several procedures (Shell, Brown, Asphalt Institute and SHRP A003A) for the same materials.

The results indicate that, based on fatigue tests at 25 and 10 °C, the mixing and the rolling wheel laboratory compaction produces specimens with fatigue properties identical to those obtained from specimens obtained from the field. The differences encontred could be attributed to the binder content and air void content differences.

Significant differences were found between the fatigue life prediction obtained by the different methods. SHRP A003A prediction equation yield results close to those obtained in laboratory. This can be explained by the fact that it was developed based on the results of strain control tests while the others were developed based on stress control tests.

Which method is best suited for actual field fatigue prediction may depend on mode of loading considerations.

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