Evaluation of *Jatropha curcas* and Pistachio Shell Particles as Modifier for Asphalt Binder

Abraham Venegas-Martínez, Beatriz Adriana Salazar-Cruz, José Luis Rivera-Armenta *, Claudia Esmeralda Ramos-Galván and María Yolanda Chávez-Cinco

Tecnológico Nacional de México/Instituto Tecnológico de Ciudad Madero, Petrochemical Research Center, Parque de la Pequeta y Mediana Industria, 89600 Alamira, Tams, Mexico; abrahamvenegas11@gmail.com (A.V.-M.); beatrizadriana1973@hotmail.es (B.A.S.-C.); cesemeralda@hotmail.com (C.E.R.-G.); yolcin5@yahoo.com.mx (M.Y.C.-C.)

* Correspondence: jlriveraarmenta@itcm.edu.mx; Tel.: +52-833-283-2873

**Abstract:** In recent years, the use of waste materials from agricultural sources has attracted interest as a research field. Several kinds of waste particles have been studied as additives for asphalt modification, and good results in terms of rheological and physical properties have been discussed in recent literature. In the present work, two types of seed shell particles were evaluated as asphalt modifiers. The shells of *Jatropha curcas* and pistachio are considered waste materials with no further industrial applications; therefore, in this study, they were incorporated into asphalt at different concentrations in order to evaluate their effect on the binder’s properties. Modified asphalt mixtures were prepared through the hot mix method, and the physical, rheological, and thermal properties of the modified samples were measured and compared to those of the unmodified binder. According to the results of softening point, viscosity, and rheological characterization, the particles obtained from *Jatropha curcas* and pistachio shells can be used as efficient additives for asphalt modification. Pistachio shell particles act as an asphalt modifier, while *Jatropha curcas* behaves more like a filler agent since using it at high concentrations causes an inverse effect on the modified performance and properties of the asphalt. Finally, the results obtained showed that both shell particles were useful for improving the binder’s resistance to rutting and permanent deformations, compared to the pure asphalt’s original behavior.

**Keywords:** asphalt binder; *Jatropha curcas* shell particles; pistachio shell particles; storage stability; rheological behavior

**1. Introduction**

Agricultural wastes have been recently studied for asphalt modification; for instance, one of the most evaluated materials for this application is rice husk. Nanometric rice husk particles were found to be easily incorporated into the asphalt, producing environmentally friendly and sustainable binders that showed better performance when exposed to moisture, as well as improved fatigue and rutting resistance [1].

Table 1 presents some waste materials that have been evaluated as asphalt modifier in several ways. The main findings show that rice husk is one of the most studied waste materials among the agricultural sources, along with some shells. The seed shells selected in this work, however, have not been studied before.
**Table 1. Different types of waste material used in asphalt modification.**

| Waste Material                      | Function     | Phase       | Findings                                                                 | Reference                           |
|-------------------------------------|--------------|-------------|--------------------------------------------------------------------------|-------------------------------------|
| Sugarcane bagasse, rice husk, and  | Additive     | Mixture     | Improves the chemical properties and the adhesive bond between the binder and the aggregates | Caro et al. [2]                     |
| corncobs                            |              |             |                                                                           |                                     |
| Rice husk ash                       | Additive     | Mixture     | Causes significant changes in morphology, and found that the dissipation energy of the binder is related to its adhesive properties | Hossain et al. 2017 [3]             |
| Rice husk and bio-oil               | Additive     | Mixture     | Improves thermal sensitivity and the adhesive force between binder and the aggregates with 4% by wt. | Han et al. 2017 [4]                 |
| Rice husk ash                       | Substitute of | Mixture     | Good compatibility between asphalt and rice husk particles, improving the Marshall quotient | Mistry et al. 2019 [5]              |
| Rice husk                           | Additive     | Mixture     |                                                                           | Arabani and Tahami, 2017 [6]        |
| Rice husk and coal waste            | Substitute of | Mixture     |                                                                           | Ameli et al. 2020 [7]               |
| Coconut shell                       | Aggregate    | Mixture     |                                                                           | Jeffry et al. 2016 [8]              |
| Coconut shell and palm oilshell     | Additive     | Mixture     |                                                                           | Al-Mansob et al. 2013 [9]           |
| Nanocharcoal coconut shell          | Additive     | Binder      | Improvement in penetration, softening point, viscosity, and rheology.     | Jeffry et al. 2018 [10]             |
| Coconut fiber                       | Additive     | Mixture     |                                                                           | Maharaj et al. 2019 [11]            |
| Coconut shell                       | Filler       | Binder      | Improvement in physical properties: rigidity, stability, and flow behavior. | Yacoob et al. 2017 [12]             |
| Coconut shell and coconut fibers    | Aggregate    | Mixture     |                                                                           | Ting et al. 2017 [13]               |
| Eggshell waste                      | Additive     | Mixture     |                                                                           | Nejres et al. 2020 [14]             |
| Eggshell                            | Additive     | Binder      |                                                                           | Razzaq et al. 2018 [15]             |
| Coffee grounds                      | Additive     | Binder      |                                                                           | Zofka and Yut 2012 [16]             |
| Peanut shell                        | Additive     | Binder      |                                                                           | Arabani and Esmaeili 2020 [17]      |
| Oyster shell                        | Filler       | Binder      |                                                                           | Necri et al. 2018 [18]              |
| Oyster shell                        | Aggregate    | Binder      |                                                                           | Kuo et al. 2013 [19]                |
| Clam shell                          | Filler       | Mixture     |                                                                           | Nwaobakata et al. 2015 [20]         |
| Crayfish shell waste                | Filler       | Binder      |                                                                           | Lv et al. 2020 [21]                 |

Pistachio is one of the top three most preferred nuts [22] and is primarily produced in the United States, Iran, and Turkey, where nearly 1.24 million tons are annually obtained. Considering that the shell/pistachio ratio usually ranges 50–70%, a significant amount of pistachio shell arises after consuming the nut, and since they do not have any commercial use, most of the shells are finally disposed to landfills or burned [23]. On the other hand, *Jatropha curcas* has been recognized as an inexpensive, sustainable, and promising energy crop [24] that has been extensively studied as a source for biodiesel production. *Jatropha* oil has been investigated as a rejuvenator additive for increasing the life and performance of asphalt pavements [25]; nevertheless, references regarding the direct use of the biomass obtained from either pistachio shells or *Jatropha curcas* for asphalt modification are few.
Based on previous information, this work reports the modification of hot mix asphalt, using as modifiers pistachio and \textit{Jatropha curcas} shells. The main physical properties, such as ring and ball, phase separation, dynamic viscosity, and rheology, are evaluated. Furthermore, the dispersion of modifier particles by means of fluorescent microscopy are reported.

2. Materials and Methods

2.1. Materials and Methods

Materials

\textit{Jatropha curcas} seed shells and pistachio shells were used in this study. The shells were cleaned to remove undesired particles; they were subsequently pulverized using a domestic blender, and then sieved using a no. 25 mesh to obtain fine shell particles of uniform size (0.707 mm). Finally, the particles were dried at 60 °C for 24 h. The base asphalt binder used in this study was donated by Ergon Asfaltos México, Altamira, with the following SARA composition: saturates 2.26%, aromatics 64.42%, resins 18.95%, and asphaltenes 13.35%.

2.2. Preparation of Asphalt Binder

Modified asphalt blends were prepared using a heating device equipped with temperature control and an IKA WERKE RW16 basic mechanical stirrer. The temperature (180 °C) and mixing speed were kept constant. The following samples were prepared and identified: base asphalt (AB), modified asphalt with 2%, 4%, 6%, and 8 wt.% of \textit{Jatropha curcas} seed shell (J2, J4, J6, and J8, respectively), and modified asphalt containing 2%, 4%, 6%, and 8 wt.% of pistachio shell (P2, P4, P6, and P8, respectively).

2.3. Asphalt Binders Characterization

Dynamic viscosity was measured on a Fungilab EVO Expert viscosimeter according with ASTM 4401-02 using 10.5 g samples and a TR9 geometry. The measurements were performed at 135, 160, and 190 °C, establishing 30 min as thermal equilibrium time, the shear rate used was 68 s$^{-1}$ developing a torque resistance between 50% and 98%, the shear rate was maintained for a period of 5 min to establish the steady state. The softening point of the asphalt was determined according to the specifications of the ASTM D36/D36M-14e1 method. The phase separation or storage stability test was carried out based on the ASTM D5892-00/M-MMP-4-05-022/02 methods to identify the compatibility between the asphalt and the modifier particles since this is one of the main indicators revealing the efficiency of the asphalt modification process. This test consisted of pouring asphalt into a collapsible aluminum tube heated at 163 °C for 48 h. After the heating period, the sample was placed in a freezer at 0 °C for at least 4 h. The sample tube was then divided into three sections, discarding the intermediate portion, and the softening points of the top and bottom sections were measured. If the difference between the softening points of both sections was less than 2.5 °C, then the sample was considered to show good storage stability [26].

Fluorescence microscopy was used to evaluate how the modifier particles are dispersed into the asphalt matrix. This analysis was carried out using a Carl Zeiss Axiptech microscope, using a 20× magnification. The technique is based on the fluorescence phenomenon, which largely depends on the concentration of modifier in the asphalt, and it is a good method that allows the identification of the dispersion pattern of modifier particles in asphalt matrix; the absence of fluorescence reveals a homogenous dispersion attributed to a compatibility between modifier and asphalt matrix [27,28].

The rheological behavior of the asphalt blends was measured on an Anton Paar dynamic shear rheometer (DSR) MCR 301 model. Temperature sweeps on oscillatory mode were applied at a fixed deformation of 12% and a frequency of 10 rad/s, from 52 to 82 °C, at intervals of 6 °C. The behavior of the ratio of the complex modulus to the phase angle sine ($|G^*|/\sin \delta$) as a function of temperature was monitored since this parameter has been related to a traffic speed of about 100 km/h.
The thermal stability of the asphalt samples was investigated through thermogravimetric analysis, which is useful for revealing any possible intermolecular interactions between the asphalt fractions and the modifier components. For this purpose, a TA Instruments equipment, model SDT Q600, was used, with samples of 15 mg and a heating rate of 10 °C/min at temperatures ranging from room temperature to 700 °C.

3. Results and Discussion

3.1. Physical Properties

Table 2 shows the physical properties of the asphalt binder modified with *Jatropha* and pistachio shells. The softening point of all modified samples increased compared with that of the base asphalt; therefore, all modified asphalt blends are less susceptible to exhibit permanent deformations. The improvement in softening point makes the asphalt binder stiffer, which causes its straight-against mechanical damage to improve, and decreases susceptibility to permanent deformation [10,17]. This behavior is an indicator of the improved performance of the modified binder relative to the pure asphalt.

| Sample | Softening Point R and B (°C) | Phase Separation R and B (°C) | Rotational Viscosity @135 °C, (cP) | Rotational Viscosity @160 °C, (cP) | Rotational Viscosity @190 °C, (cP) |
|--------|-----------------------------|-----------------------------|-------------------------------|---------------------------------|-------------------------------|
| Asphalt | 48.25                        | 0                           | 383.2                         | 126.7                           | 47.2                           |
| J2     | 52.75                        | 1.8                         | 431.0                         | 140.1                           | 50.0                           |
| J4     | 50.75                        | 1.5                         | 447.6                         | 146.8                           | 54.6                           |
| J6     | 51.0                         | 2.0                         | 481.8                         | 152.6                           | 55.7                           |
| J8     | 53.5                         | 2.5                         | 434.5                         | 140.6                           | 52.2                           |
| P2     | 52.25                        | 0                           | 449.1                         | 144.7                           | 51.3                           |
| P4     | 50.5                         | 0.5                         | 456.5                         | 143.9                           | 52.3                           |
| P6     | 53.5                         | 1.0                         | 448.4                         | 141.7                           | 52.9                           |
| P8     | 51.0                         | 1.7                         | 433.8                         | 138.6                           | 51.2                           |

This behavior is similar to that reported previously when powder of waste crayfish shells is added to asphalt, increasing the softening point to 20% [21].

One of the basic rheological properties of asphalt binder is its viscosity, which can be regarded as a demonstrator of fluid resistance against shear. Another positive effect of the modification was detected as an increment of the rotational viscosity of the modified samples in the temperature range between 135 and 190 °C for modified asphalts compared with pure asphalt. The asphalt blends modified with *Jatropha* seed shells registered the maximum rotational viscosity at a concentration of 6 wt.%. Interestingly, the viscosity of the samples containing 2% and 8% of *Jatropha* shells was quite similar, which may be explained by the fatty acid content of the modifier that produces a softer asphalt at high concentrations of *Jatropha*; this behavior suggests the existence of a limit concentration of *Jatropha* particles for obtaining the optimum viscosity.

If the viscosity of the modified asphalt binder is too high, it causes the asphalt mixture to be too hard to compact during pavement construction; forming an eligible pavement surface would be difficult, leading to increased mixing and computation temperature, and higher construction costs. Mixtures with higher viscosity value would be harder to lay down and compact on the road [7].

The maximum viscosity of the asphalt mixtures modified with pistachio shells was observed for the 4 wt.% sample at 135 °C. The effect of varying the modifier content on the viscosity is less pronounced at 160 and 190 °C, which may reflect that the components of pistachio shells are not able to interact with the larger molecules of the asphalt.

The softening points measured in the phase separation test show that the greatest difference between the top and bottom sections of the collapsible tube corresponds to the asphalt blend containing 8 wt.% *Jatropha* shell. The other values are lower than 2.5 °C,
which reveals that both modifiers are efficient for avoiding phase separation. This behavior is a consequence of physical interactions established during the mixing process between the shell particles and the asphaltic matrix; a low difference, such as those observed in Table 1, evidences the presence of strong interactions between the modifier and the asphalt that avoid the separation between the asphalt components at the storage stability test conditions. The samples having the maximum difference in the phase separation tests of both *Jatropha*- and pistachio-modified asphalt correspond to the concentration of 8 wt.% of each modifier. This observation is consistent because, at high modifier concentrations, the particles are no longer uniformly spread throughout the asphaltic matrix. On the contrary, the minimum phase separation was shown by the 2 wt.% pistachio shell sample, which registered exactly the same softening point for the top and bottom sections of the test tube, indicating significant affinity between the modifier and the asphalt binder. The high lignin content of the pistachio shells [29] could be responsible for promoting this affinity due to the interactions between the aromatic rings present in the lignin’s chemical structure and the heavy asphaltic fractions.

3.2. Fluorescence Microscopy

Figure 1 shows micrographs of modified asphalt blends prepared with *Jatropha curcas* seed shell. The 2 and 4 wt.% micrographs, observed in Figure 1a,b, exhibit less fluorescent effect, which is a direct consequence of the homogeneous dispersion of the modifier into the asphalt. This result confirms what was previously discussed in the phase separation test, where compatibility between the asphalt and the *Jatropha* seed shells was observed at the same concentrations. Nevertheless, as the proportion of *Jatropha* increases in the tested samples, the modifier particles tend to coalesce and form aggregates that are not well dispersed in the asphaltic matrix, as observed in Figure 1c,d; this fact is also responsible for the greater phase separation of the samples containing 6 and 8 wt.% of *Jatropha*, compared with the results of the 2% and 4% samples. The elevated lignin content of *Jatropha* seeds [30], which is compatible with the polar compounds of the asphalt, may explain the good dispersion of the modifier particles. The compatibility between asphalt and modifier allow the integral transport of malting and highly polar fractions from the asphaltene-rich phase, causing a phase inversion that can be spotted in the fluorescent background of the micrographs [31].

Figure 2 shows the fluorescence micrographs of the asphalt blends modified by pistachio shells. The sample containing 2 wt.% pistachio shells is depicted in Figure 2a, which is the most homogeneous sample. The 4 wt.% sample is also homogeneous, as shown in Figure 2b. The effect discussed in Figure 1 for *Jatropha*-modified asphalt is also valid in Figure 2 for pistachio shell as a modifier; the more concentrated the modifier in the asphaltic preparation, the more agglomerated the particles become; however, the aggregation of pistachio shell particles is less pronounced than that of *Jatropha* seed shells, as noticed by comparing Figure 1c,d with Figure 2c,d. These results are also consistent with the previous observation that the phase separation is more evident in the asphalt samples modified by *Jatropha* than those modified by pistachio shells. Given that the lignin content is proportionally lower in pistachio shells than in *Jatropha* seed shells, an excess of lignin in the modified asphalt could be related to greater phase separation.
Figure 1. Fluorescence microscopy of asphalt binder with *Jatropha curcas* shell particles: (a) J2, (b) J4, (c) J6, and (d) J8.

3.3. Rheology

The evolution of $|G^*|/\sin \delta$ as a function of the temperature of the asphalt blends containing *Jatropha* particles is shown in Figure 3. The complex modulus $|G^*|$ is related...
to the rigidity of the asphalt samples, and the $|G^*|/\sin \delta$ parameter is associated with the binder’s rutting or permanent deformation resistance. The failure temperatures of the asphalt blends modified by *Jatropha* seed shells are 79.6 °C (J2), 75.3 °C (J4), 75.9 °C (J6), and 75.1 °C (J8), while the failure temperature of the unmodified asphalt is 74.3 °C. The failure temperature, also known as $T_{	ext{SHRP}}$, is the temperature where $|G^*|/\sin \delta = 1 \text{kPa}$. All the modified asphalt curves in Figure 3 are located above the reference asphalt curve, which implies that adding *Jatropha* seed shells as an asphalt modifier improves its rheological properties [6]. Furthermore, Figure 3 also evidences that the asphalt sample modified by 2 wt.% *Jatropha* particles has significantly improved its rheological behavior relative to the pure asphalt throughout the complete domain of examined temperatures. However, the behavior of the rheological parameter plotted in Figure 3 approaches that of the base asphalt when the proportion of *Jatropha* modifier grows in the asphalt blends, which suggests that the shell components act as the lighter fraction of the asphalt when they are present in significant proportions. Additionally, the saturation of the highly concentrated samples may prevent the interactions between the lignin and the polar groups of the asphalt; therefore, the 2 wt.% content appears to be the critical point where the $|G^*|/\sin \delta$ parameter reaches its maximum value.

![Figure 3. Isochronal plots of $|G^*|/\sin \delta$ vs. temperature of asphalt binder modified by *Jatropha curcas* seed shell particles.](image)

Figure 4 shows the parameter $|G^*|/\sin \delta$ as a function of the temperature of the asphalt modified by pistachio shells. The failure temperatures of the pistachio-modified asphalt blends are 75.5 °C (P2), 80.9 °C (P4), 74.9 °C (P6), and 80.4 °C (P8), which are also higher than the corresponding failure temperature of the unmodified asphalt, and reveal that pistachio shell particles enhance the mechanical resistance of the asphalt binder. The highest values of $|G^*|/\sin \delta$ in this experiment correspond to a concentration of 4 wt.% of the modifier, which has already been attributed to the interaction between the lignin of the shells and the polar groups of the asphalt binder. The P4 failure temperature (Figure 4) is close to that of J2 (Figure 3), which is coherent with the fact that the lignin in pistachio shells is not as abundant as it is in *Jatropha* seed shells; therefore, a relatively greater amount of pistachio modifier produces almost the same rheological response as a lower concentration of *Jatropha* particles. The sample modified with 6 wt.% of pistachio shells presents a rheological behavior similar to that of the base asphalt, but a concentration of 8 wt.% increases the $|G^*|/\sin \delta$ values to a level close to that of the P4 sample. This behavior may be a consequence of the pistachio shell’s stiffness, which results in forming strong modifier aggregates, like those revealed by the fluorescence microscopy analysis (Figure 2d), which act not only as a filler but also as a reinforcement agent of the modified binder.
analysis (Figure 2d), which act not only as a filler but also as a reinforcement agent of the modified binder.

![Figure 4](image)

**Figure 4.** Isochronal plots of \(|G^*/\sin \delta|\) vs. temperature of asphalt modified by pistachio seed shell particles.

The improvement in rutting resistance within high temperatures when particles modifiers were added can be attributed to its reinforcing factor, which enhanced the bond strength between asphalt binder particles due to its high surface area [1].

The tan δ measurement expresses the ratio of the viscous to the elastic modulus and is useful for detecting the physical changes experienced within a temperature range. Figure 5 shows the isochronal curves of tan δ for the samples of asphalt modified with *Jatropha* particles. These curves were constructed at the same angular frequency as the experiments presented in Figures 3 and 4. The elastic response of the *Jatropha*-modified samples is better than that of the unmodified asphalt since all the curves lie below the reference asphalt curve. The increasing tendency of tan δ, particularly at high temperatures, reflects that the elastic behavior of the asphalt decreases as the temperature increases, which implies that the phase angle \(\delta\) takes values closer to 90°. The mechanical implication of this fact is that the asphalt is suffering a transition from a solid like behavior to a predominantly Newtonian-viscous nature. Figure 5 shows that the lowest tan δ values correspond to the J2 sample; although the J2 curve increases at every point with the other curves; its slope is the least steep and increases smoothly even in the high-temperature region, where the tan δ of the other samples, especially that of the unmodified asphalt, steps up abruptly. As a result, the best elastic response before flowing at high temperatures corresponds to the 2 wt.% *Jatropha*-modified asphalt, while the J4, J6, and J8 samples would be more prone to suffer mechanical failures such as rutting, cracking, or fractures due to thermal changes.

The phase angle is very sensitive to the physical and chemical structure of modified asphalt binders. Figure 6 shows the isochronal curves of tan δ of the modified asphalt blends with pistachio shells at an angular frequency of 10 rad/s. The addition of pistachio particles improves the elastic response of the asphaltic binder since all of the modified asphalt curves are lower than the base binder. However, the comparison between Figures 5 and 6 suggests that the elastic effect at high temperatures that arises from the incorporation of pistachio particles is not as good as its corresponding analog containing *Jatropha* particles for a fixed modifier concentration. However, the behavior of P4 and P8 samples (Figure 6) is comparable to that of J2 (Figure 5), which indicates that a content of 4% or 8% pistachio shell particles produces the best elastic behavior before flowing at high temperatures; contrarily, the P6 sample would be more susceptible to suffer the most common asphaltic failures.
3.4. Thermal Properties

Figure 7 shows the Thermogravimetric Analysis (TGA) thermograms for asphalt, Jatropha curcas particles, and Jatropha-modified asphalts. The Jatropha shows two main steps of decomposition, first around 290 °C and the second at 335 °C; these correspond to cellulosic materials and lignin compounds, respectively [32]. The asphalt blends modified by Jatropha shell presented one weight loss step in the temperature range from 250 °C to 500 °C, with a residue represented near 20 wt.%. The thermal degradation of resins, aromatics, and some asphaltenes has previously been reported in the same temperature interval [4]. The thermograms of modified asphalt blends with Jatropha seed shells are shown in Figure 7. The incorporation of modifiers to the binder reduces its thermal decomposition susceptibility, as especially shown by the J4 sample. The asphalt blends modified with 2, 6, and 8 wt.% behave similarly so that the concentration of 4 wt.% Jatropha particles is the critical value for achieving better thermal stability. The shift to high temperatures observed in the J4 thermogram could be a consequence of the interactions between the polar compounds of the Jatropha seed shells and the polar fractions of the
asphalt, which establish forces that prevent the thermal rupture of bonds at relatively lower temperatures. Similar results were reported by Nciri et al. 2020 [33], who reported that more than 6% of waste pig fat improved the thermal stability, which was attributed to the high unsaturated fatty acid content that made the asphalt binder more susceptible to an insignificant thermal decomposition.

![Thermogravimetric Analysis (TGA) thermograms](image)

**Figure 7.** TGA thermograms of asphalt, *Jatropha curcas*, and modified asphalt mix with *Jatropha curcas* seed shells.

The thermograms of pistachio-modified asphalt blends with pistachio shells are presented in Figure 8. Pistachio and *Jatropha* show two main decomposition steps: the first around 270 °C and second around 350 °C; however, the first is more significant compared with *Jatropha* and at a lower temperature; those steps are attributed to hemicellulose and cellulose decomposition for the first and lignin for the second [34]. The P2, P4, and P6 samples behave quite similarly and exhibit less susceptibility to suffering from thermal decomposition than the unmodified binder. On the other hand, the P8-sample thermogram overlaps that of the pure asphalt, which indicates that at elevated concentrations of pistachio shell particles, the modifier provides excessive amounts of light components that cause the adverse effect on thermal susceptibility of the modified asphalt blend. However, as previously discussed, this effect was not observed in the *Jatropha*-modified asphalt samples due to the more predominant lignin presence in *Jatropha* compared with pistachio shells. Since lignin is a biopolymer of elevated molecular weight and high degradation temperature [5], the thermal stability of *Jatropha*-modified asphalts is improved more significantly than their corresponding samples modified by pistachio shells. However, the thermograms in Figure 8 still exhibit that pistachio shell particles reduce the degradation susceptibility of the asphalt binder by a maximum concentration of 6 wt.%. 
According to the results of this study, we demonstrated that waste shells of pistachio and *Jatropha curcas* shells can be used as efficient additives for asphalt modification. The results show that pistachio particles can act as a modifier. *Jatropha curcas* particles act more like a filler when there is a high content of particles; it has an inverse effect of a modifier. The microscopy results show that the modifier particles are better dispersed in the asphalt matrix when their concentration is 2 or 4 wt.% because at higher concentrations some modifier agglomerates were detected.

The rheological analysis revealed that all of the shell-modified formulations presented higher failure temperatures than the pure asphalt, which is an indicator of better resistance to rutting, cracking, and permanent deformation, because the modified asphalt blends were tested at conditions that simulate a traffic speed of 100 km/h. The thermal analysis was useful for proving that the pistachio shells acted as a thermal stabilizer when they were introduced to the asphalt up to a concentration of 6 wt.%, which increased the degradation temperature of the modified asphalt blends in comparison with that of the base asphalt. On the other hand, when *Jatropha* particles were used as a modifier, better thermal behavior was observed for the sample containing 4 wt.% of the modifier. The overall interpretation of the results suggests that the presence of lignin and other polar compounds in the shells is responsible for inducing the physical, rheological, and thermal improvements registered by the modified asphalt binder.

**Figure 8.** TGA thermograms of asphalt, pistachio shells and modified asphalt mix with pistachio seed shells.

**4. Conclusions**

According to the results of this study, we demonstrated that waste shells of pistachio and *Jatropha curcas* shells can be used as efficient additives for asphalt modification. The results show that pistachio particles can act as a modifier. *Jatropha curcas* particles act more like a filler when there is a high content of particles; it has an inverse effect of a modifier. The microscopy results show that the modifier particles are better dispersed in the asphalt matrix when their concentration is 2 or 4 wt.% because at higher concentrations some modifier agglomerates were detected.

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