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Waste Silt as Filler in Hot Mix Asphalt: A Laboratory Characterization

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Abstract: Several studies aimed to improve both the performance and environmental impact of asphalt pavements using waste and recycled materials as fillers. This study focused on the effect of untreated and thermally treated silt as a filler in hot mix asphalt (HMA). The silt used in the study was a byproduct from a local aggregate production plant in Bologna, Italy. Mineral and chemical analyses revealed that the waste silt required thermal treatment at 750 °C for 2 h. The study compared the use of calcined silt, untreated silt, and a common limestone filler in the production of asphalt mastics and HMA specimens. The rheological properties of the mastics were analyzed using frequency sweep and multiple stress creep recovery tests. The physical and mechanical characteristics of the HMAs were evaluated through the air voids content, Marshall stability and indirect tensile strength tests. Additionally, the water susceptibility and thermal sensitivity of the HMAs were evaluated through the indirect tensile strength ratio and indirect tensile stiffness modulus at different testing temperatures. The results showed that the addition of calcined silt had no significant effect on the rheological properties of the mastic or the optimal binder content. However, the samples produced with thermally treated silt showed the highest stiffness and resistance to rutting compared with the other samples. On the other hand, the addition of untreated silt slightly decreased the stiffness value of the samples. In conclusion, the use of waste silt as a filler has potential as a sustainable and eco-friendly solution for HMAs.

Keywords: waste silt; calcined silt; filler; silt thermal treatment; recycled fillers

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1. Introduction

Aggregate plants and quarries are providing a daily supply of aggregates for use in civil engineering projects, which require the extraction and production of approximately 3000 million tons of non-renewable natural aggregates each year [1]. During this process, various waste powders are generated that have hidden value and could serve as a potential substitute for traditional aggregate and fillers in construction materials. The type of by-product produced depends on the stone being processed and the extraction and production methods used at the plants. As a result, the asphalt pavement sector is facing new challenges that require the improvement of pavement performance to meet user needs and provide more sustainable solutions. Waste and recycled materials were successfully added to asphalt concrete to enhance their properties and provide additional capabilities and functionalities [2–6]. For example, replacing some mineral aggregates with crumb rubber from tires can reduce the stiffness of asphalt layers and make the environment safer for pedestrians [7].

Other approaches require the total or partial substitution of hot mix asphalt (HMA) fillers with waste mineral fillers [8–12]. Fillers occupy between 5 and 12% of asphalt mixture and are very fine materials that mostly pass sieve sizes 0.063 mm (EN 13043) or 0.075 mm (ASTM D242) depending on the standard used. In contrast to its little amount in a bituminous mixture, its contribution to the physical and chemical properties of the material is significant. For instance, fillers complete and satisfy gradation curves and can alter the strength and volumetric properties of mixtures [13]. A study evaluated the effect of different filler types and ratios on various HMA mechanical properties. It was concluded that an increase in filler content led to a decrease in the optimal binder content. Furthermore, a drop in the moisture damage resistant value was observed [14]. A similar study indicated that the amount and type of filler dramatically affected the indirect tensile strength (ITS) of HMA specimens. The authors showed that the addition of hydrated lime or cement bypass dust could improve the ITS values of pavements and were superior to common limestone dust [15]. According to the literature, fillers could influence the thermal sensitivity, aging and thermal performance of asphalt mixtures [12]. In addition, HMA samples composed of calcium carbonate and hydrated lime fillers exhibit higher ITS values compared with limestone fillers [16].

Excessive usage of common filler could produce several environmental risks, such as the depletion of natural resources. For this reason, finding an affordable and sustainable alternative to replace common fillers in asphalt pavements seems necessary. Various waste materials were used as fillers to produce sustainable asphalt pavements. For instance, the possibility of using fly ash, brick powder, and construction and demolition (C&D) waste in asphalt pavement as a filler was investigated [8]. Limestone filler was used as the reference filler and the results were compared with the control samples. The authors claimed that the waste fillers showed strong water damage resistance. Moreover, the fly ash presented acceptable binding with the bitumen, whereas the C&D waste had high CaO content, which is one of the main attributes for using limestone filer. Ceramic waste and marble waste dust were partially introduced into HMA, whereas limestone dust was used as the control sample [9]. The recommended substitution rates of ceramic waste and marble dust with the limestone filler were reported as 35 and 15%, respectively. In a similar approach, ceramic waste was applied as the filler in asphalt mixtures [11]. The waste powder was replaced with limestone filler from 25 to 100%. In all cases, the samples containing waste ceramic had better Marshall stability. Moreover, samples produced with 100% ceramic waste had improved moisture damage resistance and better fatigue life performance when compared with the control sample.

The influence of several waste filler types on different properties of asphalt pavements was reviewed by various authors [6,17,18]. In line with the same trend, the effect of clay materials as filler replacements was studied regarding pavement properties. For example, natural filler was substituted with 15% bentonite clay [19]. The partial substitution led to an increased indirect tensile strength and flow values of the HMA mixtures. Similarly, bentonite clay was used as a filler in hot mix asphalt samples [20]. However, the clay was used in both normal and thermally treated conditions. The clay was calcined at different temperatures ranging from 400–800 °C, where the best treatment was selected based on Atterberg limits while aiming for minimized plasticity and swelling of the bentonite clay. Overall, the 100% substitution of the natural filler with the thermally treated bentonite clay showed an increase in several mechanical properties of HMA.

The results from the two different studies show that the thermal treatment of the waste filler could result in better performance of HMA mixtures. A similar trend was observed when the use of normal kaolin and thermally treated kaolin clay as filler in the HMA mixture was investigated [21]. Samples produced with 100% thermally treated clay were shown to have better performance in terms of Marshall stability and indirect tensile strength (ITS) compared with those of normal kaolin.

The current study aimed at recycling waste silt obtained from a local aggregate production plant in Bologna (Italy). The waste silt will be used in two different forms, namely, untreated and thermally treated as a filler, totally replacing limestone. Such an application would be beneficial for a company contributing to a circular economy.

2. Materials

Società Azionaria Prodotti Asfaltico Bituminosi Affini (S.A.P.A.B.A. s.r.l.) is an asphalt production company located near Bologna, Italy. The company uses mainly limestone aggregates, which are obtained from local quarries and are fed to the company's asphalt production plants. The dirt and mud that result from the aggregate washing process are pumped out to special sedimentation lakes, which have the sole purpose of storing the waste material. Consequently, the sedimentation lakes are filled up with waste silt, which was the main material tested and applied for the current study. The silt was extracted from the sedimentation lakes, oven-dried, sieved and crushed to a very fine powder passing the 0.063 mm sieve. The silt obtained at this stage is referred to as untreated or normal silt. The complete characterization of the raw silt was fully described in our previous investigation [22].

In addition to the normal state, the waste silt was thermally treated using a static furnace. For this purpose, the silt was calcined at 750 °C for 2 h [22]. Calcination is the process of heating materials to high temperatures with no or limited air supply. The basic purpose of calcination is to remove impurities and increase the reactivity of compounds. Calcined silt is also referred to as thermally treated silt. The normal and calcinated silts are coded as SN and SC, respectively, throughout the manuscript. The untreated and treated silts are shown in Figure 1. These two alternative fillers were compared with a control limestone filler (named C).

Figure 1. Untreated (**left**) and thermally treated (**right**) silts.

The untreated and thermally treated silts, along with conventional limestone filler, were used to produce different bituminous mastics and HMA mixtures. The aggregates, including sand (0–4 mm) and gravel (4–8 mm), were provided by S.A.P.A.B.A. [23]. A neat 50/70 penetration grade bitumen (PEN 50/70) was used in the present study. The rheological properties of the PEN 50/70 were determined and the specific values are given in Table 1.

Table 1. Rheological properties of neat bitumen.

Test	Unit	Value	Standard
Penetration @ 25 °C	dmm	53	EN 1426
Softening point	°C	50	EN 1427
Dynamic viscosity @ 60 °C	Pa.s	327	EN 13702

3. Methods

The current study is comprised of two distinct experimental phases. The first phase focused on the examination of the rheological characteristics of the mastics, while the second phase was dedicated to evaluating the mechanical performance of the HMA samples.

3.1. Phase I

In brief, the rheological tests included amplitude sweep (AS), frequency sweep (FS) and multiple stress creep recovery (MSCR) tests.

The rheological studies were carried out on binder mastics that were prepared based on the mix design of the HMA (5.5% of bitumen and 7% of filler) [24]. Accordingly, three different mastics (44% bitumen and 56% filler) were prepared: the control mastic (M-C), the mastic with normal silt (M-SN) and the one with calcined silt (M-SC).

An Anton Paar MCR302 Dynamic Shear Rheometer using 8 mm parallel plate settings (2 mm gap) was used to study the rheological behavior of the produced mastics. An amplitude sweep (AS) test was performed to determine the linear viscoelastic (LVE) range of the mastics (EN 1477). The samples were tested at a constant frequency of 1.59 Hz at 10 °C.

A frequency sweep (FS) test was then applied considering the lowest linear viscoelastic limit obtained using the AS test on the three mastics. The FS test allows for the evaluation of the mastics' behavior and strength under various loading conditions. The samples were tested at different temperatures of 10, 20, 30, 40, 50 and 60 °C for frequencies ranging between 0.01 and 10 Hz. For each mixture, the complex shear modulus (G*) and phase angle (δ) were calculated.

The permanent deformation of each mastic was determined using the multiple stress creep recovery (MSCR) test (ASTM D7405). The MSCR tests were performed at 60 °C on mastic samples loaded at constant creep stress for 1 s followed by a zero-stress recovery of 9 s. The samples underwent shear creep loading and recovery at two stress levels, namely, 0.1 kPa and 3.2 kPa. Two cycles, each having 20 runs at 0.1 kPa and 10 runs at 3.2 kPa, were performed on the mastics. The non-recoverable creep compliance (Jnr) and the percent recovery after the latest ten runs at 0.1 and the ten runs at 3.2 kPa were assessed. The Jnr values were determined as the ratio between the average non-recoverable strain for 10 creep and recovery cycles and the applied stress for those cycles. On the other hand, the percent recovery was evaluated by considering the recoverable strain, as the ratio between the average recoverable strain after 10 cycles and the applied stress.

3.2. Phase II

The mechanical properties of the produced HMA samples were determined using various tests, including the optimal binder content (OBC), Marshall stability, ITS and indirect tensile stiffness modulus (ITSM).

The experimental HMA specimens contained 5.5% binder, 7% filler (C, SN or SC) and 87.5% aggregates (38% sand (0–4 mm) and 62% gravel (4–8 mm)). To evaluate the effect of filler type on the mechanical properties, HMA samples were prepared according to the Marshall method. The aggregate gradation was kept constant for all mixture types.

The optimal binder content (OBC) of the mixtures containing untreated silt (labeled HMA-SN) and thermally treated silt (labeled HMA-SC) were determined (EN 12697-30). A total of 9 mixtures for each set was produced and the OBC was determined based on the highest Marshall stability (EN 12697-34).

The mechanical characterization of the samples was conducted on specimens produced with the optimal binder content. The air voids content of the Marshall samples was calculated based on the EN 12697-8 standard. To study the resistance of the mixtures against moisture, a total of six samples (for each set) were produced using the Marshall method. Three samples were tested with dry conditions (25 °C) and the remaining three were tested after being submerged in water at 40 °C for 72 h. The indirect tensile strength (ITS) (EN 12697-23) test was then conducted on the 6 samples. The susceptibility of the mixtures to moisture was evaluated by comparing the ITS of wet and dry samples based on EN 12697-12. Moreover, all samples were tested in terms of indirect tensile stiffness modulus (ITSM, EN 12697-26 Annex C) at three different temperatures of 10, 20 and 30 °C to evaluate the possible change in the thermal sensitivity of the mixtures given by the addition of the waste fillers.

4. Results

4.1. Bituminous Mastic Analysis

4.1.1. Frequency Sweep Analysis

The complex shear modulus and phase angle master curves of the three mastics are presented in Figure 2. The linear viscoelastic analysis indicated similar behavior for the M-C and M-SC samples in terms of the complex shear modulus. Thus, samples produced with calcined silt provided a similar stiffness to the control samples produced with limestone filler. The same trend was followed for all tested frequencies. However, lower stiffness was observed for the M-SN samples, which were produced with normal silt.

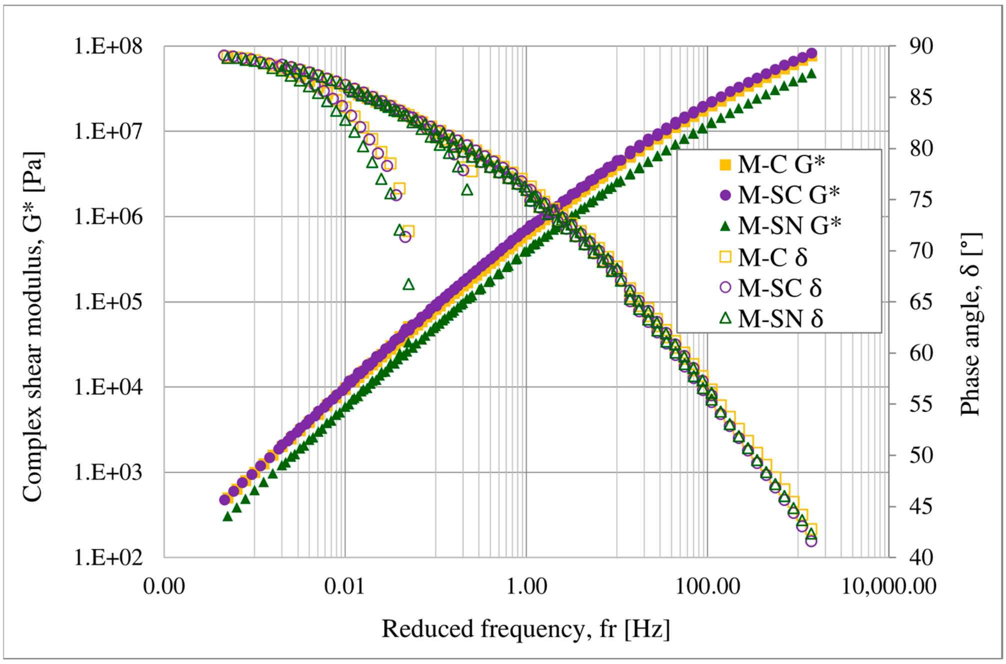

Figure 2. Complex modulus and phase angle master curves for all mastic samples.

The elastic responses of the three mastics were found to be similar throughout the range of frequencies and/or temperatures. With an increase in temperature and loading (lower frequency values), all three mastics showed fully viscous behavior (i.e., the phase angle was approx. 90°). In the opposite conditions, the three mastics behaved more like an elastic material.

Overall, the addition of the experimental fillers did not alter the rheological trend of the complex shear modulus and phase angle of the tested mastics. On the other hand, the addition of normal silt led to a general reduction of the complex shear modulus at all frequencies and temperatures when compared with the control mastic.

4.1.2. Multiple Stress Creep Recovery

The accumulated strain obtained from the MSCR test at 60 °C versus the test time is shown in Figure 3. The addition of untreated silt (SN) to the bitumen resulted in an important increase in the accumulated strain when compared with M-C and M-SC. However, the samples produced with thermally treated silt as a filler (M-SC) had the lowest values for accumulated strain and performed slightly better than the control sample (M-C). The rate of change in strain values started to increase when the 3.2 kPa loading was applied after the 20th cycle and significantly increased after the 200th second, showing a stress-dependent behavior of all mastics.

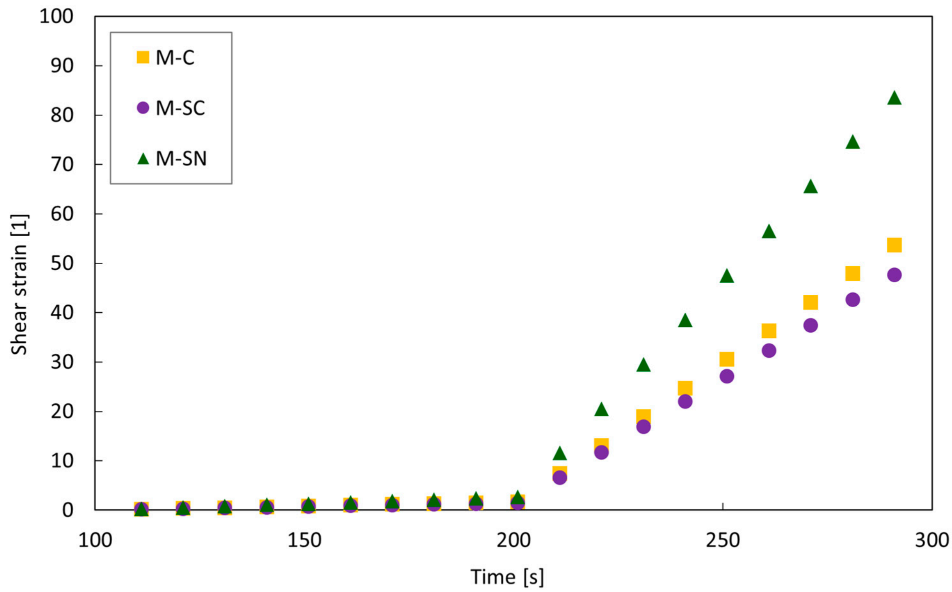

Figure 3. The results of the MSCR tests at 60 °C for all mastic samples.

The resistance of bituminous mastics to permanent deformation (rutting) can be studied through the Jnr parameter. Higher susceptibility toward permanent deformation is related to higher Jnr values. The average Jnr value for M-SC was the lowest compared with the remaining samples at both stress creep levels. The inclusion of thermally treated silt (SC) showed an improved performance in terms of rutting reducing the non-recoverable creep compliance by 0.90 times at both stress creep levels compared with the M-C sample. However, the use of untreated silt (SN) rather than the control one increased the Jnr parameter by 1.58 and 1.54 times at the lowest and highest creep loads, respectively.

The recovered strain can also be estimated by performing the MSCR test in terms of the percent recovery parameter. The average values of the percent recovery and Jnr of the three mastics recorded at the two stress levels are reported in Table 2. The percent recovery of all samples, regardless of filler type, was close to zero when applying a shear creep load equal to 0.1 kPa, and it was equal to zero at 3.2 kPa. However, the Jnr values were greater than zero for all mastics regardless of the stress load. The results of the two MSCR parameters indicated a viscous behavior of the analyzed mastics at high temperatures, which deformed under the application of shear loads without recording any significant strain. This response can be ascribed to the base bitumen used in the present study, i.e., PEN 50/70. The percent recovery and the Jnr values backed up the rheological data collected during the FS test at the highest temperature. Moreover, the mastic produced with the thermally treated silt behaved similarly to the mastic with standard limestone filler. Thus, the M-SC and M-C showed similar rutting resistance.

Table 2. Average recoverable strain and non-recoverable compliance at the two stress levels.

Sample	Stress Creep 0.1 kPa		Stress Creep 3.2 kPa	
	Percent Recovery (%)	**Jnr (%)**	**Percent Recovery (%)**	**Jnr (%)**
M-C	1.440	1.740	0.000	1.880
M-SC	0.294	1.570	0.000	1.699
M-SN	0.000	2.740	0.000	2.896

4.2. Hot Mix Asphalt Results

4.2.1. Optimal Binder Content and Air Voids

The control mix design (HMA-C) obtained from the previous analysis had an OBC of 5.5% on the mass of aggregates. However, the samples produced with untreated (HMA-SN) or calcined silt (HMA-SC) could require a different amount of binder depending on the possible different absorption properties of the powders. Thus, the optimal binder content of the experimental HMAs was calculated.

For each mixture, five different binder contents (5.0–6.0%) were selected, resulting in 15 Marshall samples for each HMA type. The samples were produced according to the EN 12697-34 standard by applying 75 blows to each side during the sample compaction. Samples were immersed in water for 30 min at 60 °C and were tested using the Marshall stability test. The average data for the Marshall stability and air voids content (Va, EN 12697-8) are summarized in Table 3 and presented in Figure 4.

Table 3. Marshall stability and air voids content for HMA mixtures.

Sample	Bitumen (%)	Stability (kN)	Va (%)
HMA-C	5.5	17.20	3.27
HMA-SN1	5.00	11.53 ± 0.12	4.03 ± 0.03
HMA-SN2	5.25	12.51 ± 0.29	4.01 ± 0.04
HMA-SN3	5.50	13.25 ± 0.37	3.89 ± 0.07
HMA-SN4	5.75	11.93 ± 0.15	3.88 ± 0.05
HMA-SN5	6.00	11.67 ± 0.30	3.81 ± 0.03
HMA-SC1	5.00	12.99 ± 0.22	3.76 ± 0.05
HMA-SC2	5.25	15.47 ± 0.14	3.82 ± 0.03
HMA-SC3	5.50	16.68 ± 0.19	3.91 ± 0.08
HMA-SC4	5.75	16.11 ± 0.25	3.95 ± 0.01
HMA-SC5	6.00	15.27 ± 0.10	3.93 ± 0.07

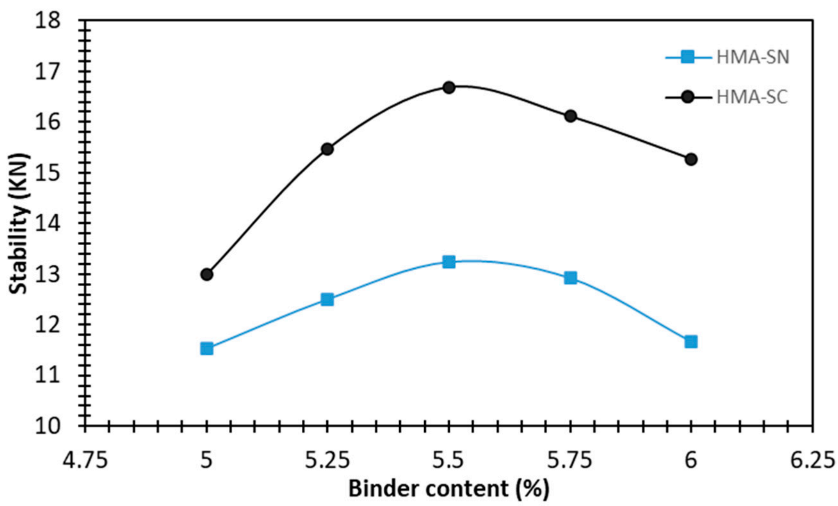

Figure 4. Marshall stability for the HMA samples.

The maximum Marshall stability of 17.20 kN was reported for the control sample (HMA-C). The mixtures produced with thermally treated silt followed closely behind with a maximum stability equal to 16.68 kN. The lowest Marshall stability value was obtained when untreated silt was used as filler in the mixtures. The performance of calcined silt was better in terms of stability when compared with untreated silt. A similar trend was observed when thermally treated and untreated bentonite clays were used as fillers in HMA mixtures [20]. However, the returned value for the optimal binder content was 5.5% for both mixtures. Thus, the substitution of the limestone filler with untreated or calcined silt did not affect the optimal binder content value. Moreover, the reported stability values were higher than the 11 kN suggest by the Italian technical specifications for this type of bituminous mixture.

The air voids content calculated for samples produced with the optimal binder content is also shown in Table 3. The highest compaction rate was related to the control sample.

The addition of waste silt to asphalt mixtures increased the air voids content regardless of the type of silt used. However, all values were within the range of 3–4.5% suggested by the Italian technical specifications taken as a reference.

4.2.2. Indirect Tensile Strength

The mechanical properties of the mixtures were further investigated by the means of the indirect tensile strength (ITS) in compliance with the EN 12697-23 standard. For each set of the mixture, 3 sets of samples were prepared with the Marshall compactor (75 blows on each side). Before testing, each specimen was conditioned at 25 °C for 4 h. The average ITS for each mixture is shown in Figure 5.

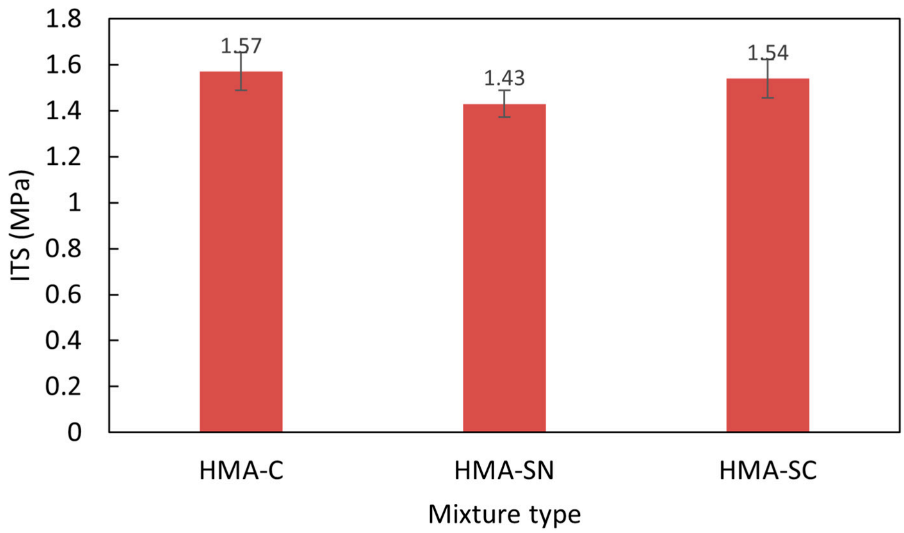

Figure 5. Average indirect tensile strength of the HMA mixtures at 25 °C.

The results of the one-way ANOVA indicated no significant difference ($p = 0.4598$) between the control, HMA-SN and HMA-SC mixtures. Thus, the inclusion of untreated or thermally treated asphalt mixtures did not affect the mechanical properties of the bituminous mixture. Overall, all three mixtures showed values higher than the 0.7 MPa suggested by the Italian technical specifications as the threshold value for this type of mixture.

4.2.3. Indirect Tensile Strength Ratio

The indirect tensile strength ratio (ITSR) measures the loss of strength due to the damage caused by moisture. For this purpose, a total of three samples were prepared for each set according to the Marshall method. The samples were kept in a water bath at 40 °C for 72 h (EN 12697-12). The ITSR is the ratio of the indirect tensile strength of wet (water-conditioned) specimens to that of dry specimens, expressed in percent (Figure 6).

The lowest indirect tensile strength ratio of 85% was recorded for the HMA-SN mixture. The inclusion of untreated silt led to an increase in the water sensitivity of the mixtures. This could be related to the natural behavior of silt and clay particles, which have higher water absorption rates than limestone filler. However, thermal treatment of waste silt at 750 °C was shown to be effective at reducing the moisture susceptibility of the mixtures and increased the ITSR by 5.0%. The best performance in terms of ITSR was reported for the control sample not containing any waste samples. The Italian specifications suggest that the ITSR values should be greater than 75%.

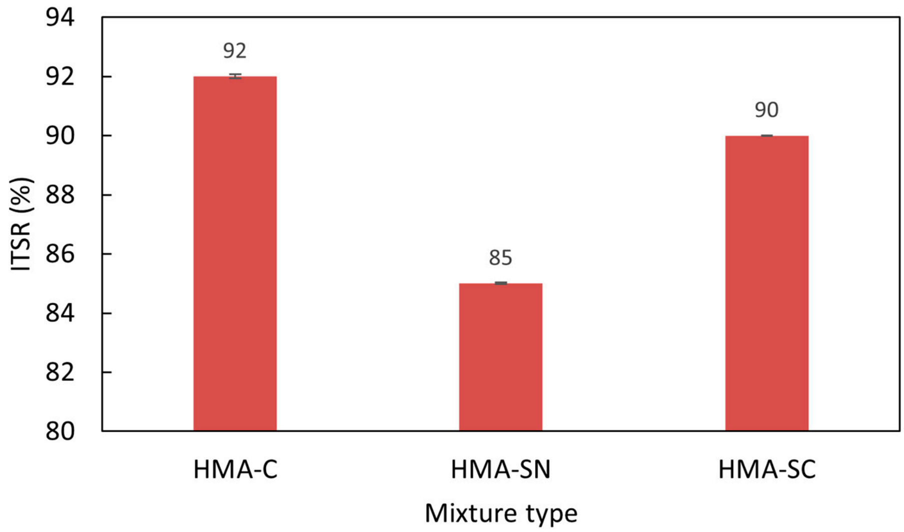

Figure 6. Indirect tensile strength ratio for HMA mixtures.

4.2.4. Indirect Tensile Stiffness Modulus

The ITSM values for the asphalt mixtures are shown in Figure 7. Each sample was tested at three different temperatures of 10, 20 and 30 °C. Overall, the control samples showed the highest modulus for all the tested temperatures. The lowest values were obtained for samples produced with normal silt. One-way ANOVA was conducted to further investigate the effect of the mixture type on the final ITSM value. No significant difference ($p = 0.1321$) was observed for the ITSM values of different samples measured at 10 °C. Thus, regardless of the filler used, all HMAs performed similarly at low temperatures. On the other hand, a significant difference ($p = 0.00005$) was observed for the samples tested at 20 °C. The addition of silt reduced the stiffness of the mixture, with a minor effect when the calcined silt was used. Finally, mixtures made with calcined silt and normal filler showed similar performances in terms of the ITSM at 30 °C. All in all, although the substitution of limestone filler with waste silt showed a detrimental effect in terms of stiffness, the ITSM values for the experimental mixtures were considerably high considering that a neat bitumen was used for the mixture.

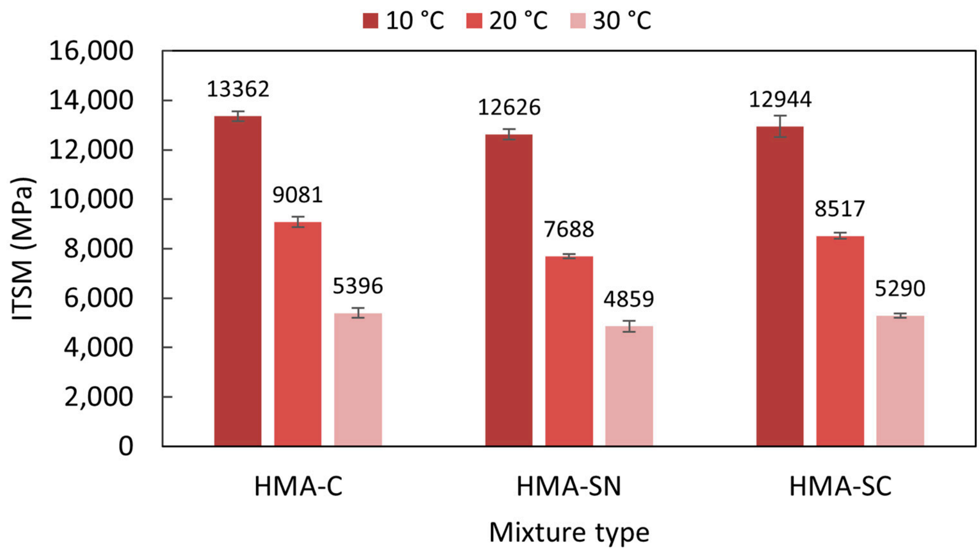

Figure 7. ITSM for the HMA mixtures.

5. Discussion

For the current study, silt was used in two forms, namely, untreated and thermally treated, as a filler to produce mastic specimens. According to our previous study [22], sharp peaks of calcite ($CaCO_3$) were observed from the semiquantitative X-ray powder diffraction (XRD) analysis of the waste silt. The data also indicated that the laboratory calcination of the waste silt at 750 °C led to the total collapse of the calcite peak, indicating its complete degradation into calcium oxide (CaO), which is also present in limestone filler [25–27].

According to the master curves, the addition of normal waste silt to bitumen produced a mastic with lower stiffness compared with M-C and M-SC. This was observable at all tested frequencies and/or temperatures. The higher potential for rutting was highlighted by the Jnr values, where M-SN was found to have the highest values amongst all mastics regardless of the load level. However, mastic produced with calcined silt demonstrated a similar rutting performance to M-C, which was produced with normal limestone filler. The Jnr values also indicated the best rutting performance for M-SC followed closely by M-C. Meanwhile, in terms of percent recovery, the M-C samples showed the best elastic behavior. The stiffness of the samples containing calcined silt could have been due to the higher CaO content compared with the M-SN samples [28]. The literature indicates that CaO content was shown to have a good correlation with rutting potential, meaning that higher CaO content could increase the rutting resistance of the samples. The binder used for all mastic samples was 50/70 unmodified bitumen. Thus, the percent recovery for all mastics was reported as zero. Moreover, this could also explain the fact that none of the mastics showed reduced stiffness at low temperatures, making them prone to low-temperature fatigue cracking. The mastic produced with normal silt had the lowest G* value at high-frequency values, indicating its better performance in terms of fatigue cracking. The lower stiffness of M-SN could be related to the lower CaO content. Moreover, studies suggested that the presence of Al_2O_3 and SiO_2 in filler could result in a stiffer binder mastic. Calcination usually increases the reactive aluminosilicate elements within fillers. Therefore, mastic produced with calcined silt had higher stiffness when compared with M-SN.

In addition to the mastic samples, HMA specimens were produced. The indirect tensile strength test can be considered an indicator of the cohesion properties between mastic and aggregates. The results demonstrated an insignificant difference in terms of performance between the mixtures. Thus, the inclusion of untreated or thermally treated silt in the mixture did not affect the cohesion properties of the samples when compared with the control mix [29]. However, the sample produced with untreated silt had the lowest strength, whereas HMA-SC performed similarly to the control samples produced with limestone as filler. The behavior of the calcined silt could have been due to its similarity to the limestone filler in terms of chemical composition [28]. Laboratory specimens containing thermally treated waste silt showed high resistance against moisture damage, as shown by the ITSR values.

Water-insoluble minerals present in fillers, such as calcite, portlandite and dolomite, can produce a strong filler-binder bond [30,31] and could have been responsible for the high moisture resistance of samples produced with calcined silt. The stiffness sensitivity of specimens to temperature was examined using an advanced dynamic test (ITSM). All three samples showed similar mechanical behavior toward temperature sensitivity and no significant difference was observed.

To sum up, the rheological and mechanical properties of the produced HMA specimens were in line with the Italian specifications, where the untreated silt and calcined silt showed similar performances to the control samples produced with limestone as filler. However, using untreated silt will further reduce costs and greenhouse gas emissions since it will not require any thermal treatment as common fillers do. A full life-cycle analysis (LCA) could further aid in determining the environmental and economic effects of using waste silt as a filler in flexible pavements. Nevertheless, the application of such waste as a filler was shown to be promising.

6. Conclusions

Untreated and thermally treated waste silts from a local aggregate production plant were used as a replacement for convenient limestone filler to produce HMAs. The evaluation of the effects given by the adoption of the waste fillers was studied in a two-stage laboratory analysis, which involved studying the binder–filler interaction and the HMA's physical and mechanical properties.

The following conclusions were drawn:

- The addition of thermally treated silt did not have a significant impact on the rheological properties of the resulting mastic, as measured using the complex shear modulus and phase angle. However, untreated silt slightly reduced the stiffness of the mastic, as evidenced by a decrease in the complex shear modulus. No significant changes were observed in the phase angle master curves.
- In terms of rutting performance, thermally treated silt had the highest resistance against permanent deformation. This was observable via lower accumulated strain and lower non-recoverable compliance values. Untreated silt showed the lowest resistance against rutting. However, the substitution of control limestone filler with waste silts influenced the elastic response of the final bituminous mastics, reducing the percent recovery parameters.
- The replacement of limestone filler with waste silt did not alter the optimal binder content of the mixture or the porosity of the produced samples. Thus, the presence of waste silt did not negatively affect the workability or compactibility of the bituminous mixture.
- The inclusion of untreated silt as filler resulted in a reduction in the ITS values. In contrast, thermally treated silt demonstrated a similar performance to the control sample. The same trend was recorded for the water susceptibility of the mixtures.
- The ITSM results were in line with the static mechanical characterization A slight reduction in stiffness was recorded for the HMA-SC mixture, while a clear drop in ITSM values occurred when untreated silt was adopted. However, the thermal sensitivity of the mixture was not influenced by the substitution of limestone filler with waste powders.

It can be stated that calcined silt exhibited comparable performance to the control samples, which can be attributed to its CaO content.

Based on the presented preliminary results, the use of waste silt as a filler could be a potential solution for sustainable and eco-friendly HMAs. Silt calcination was found to be beneficial since it reduced the influence of the waste material on the rheological and mechanical properties of the bituminous mixture. Partial substitution of limestone filler instead of the current total replacement could provide better mechanical performance. Further studies are needed to back up this assumption.

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