Analysis of Reclaimed Asphalt Pavement Heating with Microwave Radiation

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Abstract

The research focuses on the analysis of potential use of microwave radiation as alternative Reclaimed Asphalt Pavement (RAP) heating method. Material characteristics and the microwave heating possibility for the production of Hot Mix Asphalt (HMA) were verified. The research focused on testing HMA with different content of RAP and RAP of different moisture containing unmodified bitumen and modified bitumen with styrene-butadiene-styrene (SBS) polymer. Tests for density, bulk density, air void content and the Indirect Tensile Strength were carried out.

The test results confirmed the possibility of using microwaves to heat the HMA without adversely affecting its basic properties. The research also shows the possibility of heating the RAP in the process of HMA production, especially with the RAP of a moisture content above 3%. In addition, the tests of HMA did not reveal any negative impact of microwave heating in the case of using moist RAP for the production of HMA. The susceptibility of the SBS polymer to microwave radiation was indicated by comparing the behavior of the two HMA types under its influence. HMA containing modified bitumen appears to achieve higher temperatures than HMA with unmodified bitumen after the same time of microwave heating.

1. Introduction

Reduction of the air pollution is one of the most current challenges of densely populated areas. The efforts made to keep the air clean are visible in many fields e.g. in the automotive industry where exhaust system gases are being analyzed, leading to advances in technology in order to become less harmful for both people and the environment (Lozhkin et al., 2018). To improve the air quality in urban areas, all fields of industry should contribute to limitation of air pollution. In the field of road engineering, production of raw materials requires significant amounts of energy, which may be delivered directly from combustion at location of the factory/plant or in some cases it may be delivered to the factory/plant as electric energy which may be obtained from renewable energy sources.

Building materials such as cement or hot mix asphalt (HMA) are produced at high temperatures. For cement it is over 1000°C and for HMA it is usually up to 200°C, which leads to different influences on the air quality (Zhou et al., 2022). Those temperatures are usually achieved in the process of fuel burning in place, making the air surrounding the plant affected by the products of burning. Depending on the fuel used, those products may significantly affect air quality and consequently have an impact on people's health (Cohen et al., 2017; Edwards et al., 2022; Liu et al., 2019; Qu et al., 2021). Turning into electrical heating enables to use renewable sources of energy and concentrate the air pollution only on a few power plants focusing all of pollution around uninhabited areas.

One of the effective ways to heat some materials (e.g. water) are microwaves. Microwave radiation is part of the spectrum of electromagnetic waves. Its existence was found out by Clark James Maxwell and confirmed experimentally by Heinrich Herz. Microwaves are electromagnetic waves with a wide frequency range of 300 MHz-300 GHz. The most popular is, however, a much narrower range of frequencies between 915 MHz and 2450 MHz (Gwarek and Celuch-Marcysiak, 2003). The assignment of electromagnetic waves to microwaves does not only result from the frequency range but also from the impact on other materials and objects. The majority of these interactions make the molecules of dipole materials (including water) vibrate (Metaxas and Meredith, 1993).

Due to this property and the phenomenon of dielectric loss, microwave heating is a more effective method compared to conventional heating for selected materials (Shukla et al., 2016; Zhu et al., 2009) where heat is transferred by radiation, conduction or convection (Jin et al., 2017). High efficiency of microwaves in heating and evaporating water was proven (Al-Ohaly and Terrel, 1988; Feng et al., 2012).

Some researchers report the possibility of microwave radiation use for the purpose of heating materials for HMA production (Benedetto and Calvi, 2013; Gulisano and Gallego, 2021). However, the influence of microwave radiation on the individual components of the HMA has not been fully investigated. According to some sources, aggregates are a material susceptible to polarization and microwave heating (Trigos et al., 2020a), also dependent on the moisture content of the material and the aggregate origin (Al-Ohaly and Terrel, 1988). Some studies mark that only some aggregates are susceptible to the microwave influence (Gulisano and Gallego, 2021) and among them we can point out andesite, ophite, blast furnace slag (Trigos et al., 2020b) and diorite (Sun, 2013). Research describing influence on basaltic and siliceous-calcareous aggregates showed their susceptibility to microwave heating with slightly higher influence on basalt (Benedetto and Calvi, 2013). On the basis of other studies, there was no effect of the increasing temperature of the aggregate by microwave radiation, e. g. quartzites and limestones (Sun, 2013; Trigos et al., 2020b), while heating of the bitumen containing polar fractions was observed (Norambuena-Contreras and Garcia, 2016). It is worth mentioning that the lower microwave frequency was used the greater penetration of heated materials was observed (Sun et al., 2016).

The researchers have recently made significant advances in the field of aggregate, bitumen and asphalt mix heating and testing with the use of microwave radiation. Microwave heating were widely used to heal asphalt layers (Gulisano et al., 2020; Lizárraga and Gallego, 2020; Lou et al., 2021; Norambuena-Contreras and Garcia, 2016; Sun et al., 2014; Tabaković et al., 2019; Xu et al., 2021). In numerous papers it was verified that the addition of special ferrite materials (especially containing iron) enhances the heating effect of the microwaves on the HMA (Baowen et al., 2020; Yalcin, 2021). In laboratory microwaves were found to be useful to imitate bitumen aging (Bishara and McReynolds, 1995; Li et al., 2019; Mitchell et al., 2013). In the field of road engineering microwaves were applied in order to synthesize polymers for bitumen modification (Alonso-Buenaposada et al., 2016; Ergan et al., 2015) and devulcanization of rubber (Garcia et al., 2015; Xu et al., 2020; Yu et al., 2011). However, the technology of HMA microwave heating is currently being analysed, it was once applied in practice in one of the plants in Los Angeles developed by CYCLEAN, Inc. of Austin, Texas (CYCLEAN, 1992). The microwave radiation was used as the way of heating virgin aggregate, reclaimed asphalt pavement (RAP) and rejuvenating agent mix, prior to introducing the mix to the storage silo.

Considering the need for broadening the knowledge of influence of microwaves on HMA and results of its laboratory testing methods mentioned in the research (Gulisano and Gallego, 2021). This study aimed at verification of microwave use in HMA production with the focus on RAP heating in a potential second drum heated by microwaves.

2. Materials And Methods

The goal of the research was to verify possibility of microwave heating of RAP in order to produce HMA containing significant (ranging 50%) amounts of recycled materials. It was planned to imitate the production process of standard asphalt batch plant like Ammann Uniglobe 200 described in (Zaumanis et al., 2019) with additional installation for microwave RAP heating. Second stage of the research focuses on the influence of microwave heating on properties of HMA containing SBS modification of the bitumen.

2.1. First stage

For the purpose of the first stage of the research an asphalt mix design was chosen. It is one of the widely used asphalt concrete mix designs within one of the leading asphalt production companies in Europe. The mix was modified, without changing bitumen content and grain size distribution (Fig. 2.1), in order to introduce different amounts of RAP – 15% and 50%. Three ways of RAP treatment are presented – unheated, heated in a traditional method in laboratory oven and with use of microwaves (according to Table 2.1). RAP was obtained from homogenous stockpile from the mixing plant, prepared for industrial use. RAP’s sieve analysis results are presented in Fig. 2.2. To reflect the HMA production in a more detailed way it was also verified if the moisture content (usually present in RAP during full scale production) affects the process using microwaves and how it changes final product (HMA) parameters.

For all types of HMA, RAP with the sieve curve presented in Fig. 2.2 was used. In order to unify all types of HMA used for the research, the aggregate fractions content was adjusted to the content of RAP (15% or 50%) so that the sieve curves of these HMAs were possibly identical. Bitumen content of the RAP was 4,4% and for the final HMA it was 4,3% for all HMA types.

Due to the fact that the RAP addition affected the temperature in the final mix, the experiment was designed to ensure one, equal final temperature of the HMA regardless of RAP content and heating method, similarly to the full scale process at mixing plant. All tested mixes with different RAP content with different heating methods together with information about HMA ingredients temperatures are listed in Table 2.1.

Table 2.1
Description of the types of HMA used in the tests

HMA type	RAP content [%]	RAP moisture content [%]	Aggregate temperature [°C]	Bitumen temperature [°C]	RAP temperature [°C]	HMA compaction temperature [°C]	RAP heating method
1	15	0	175	150	20	150	None
2	15	3	175	150	20		None
3	15	3	160	150	100		Microwave
4	15	0	150	150	150		Drying Oven
5	50	3	200	150	100		Microwave
6	50	0	150	150	150		Drying oven

The differences between temperature of every HMA ingredient were necessary to achieve equal compaction temperature. In case of HMA type 1 and 2, the RAP was added in the “cold” method (at room temperature). The RAP of the HMA 4 and 6 was heated to the desired temperature by the conventional method in a laboratory oven with air circulation, while for HMA 3 and 5 using microwave radiation. For each series, 4 cylindrical samples were made according to PN-EN 12697-30: 2019-01 (“PN-EN 12697-30:2019-01. Mieszanki mineralno-asfaltowe - Metody badań. Część 30: Przygotowanie próbek zagęszczonych przez ubijanie,” n.d.). All samples were compacted in Marshall compactor with 75 blows on each side.

In terms of RAP addition, in the full scale HMA production it often has various moisture content throughout the season. Based on data from one of the leading producers of HMA, the average moisture content of RAP stored without roofing varies between 2–4%, but temporarily its moisture content can raise to over 10% during the rainfall period. For this stage of research, the used RAP moisture content was 0% and 3% for microwave heated and not heated RAP. Verification of different moisture content enabled verification of the negative impact of water on the properties of the final HMA.

All types of HMA were tested in terms of density (“PN-EN 12697-5:2019-01. Mieszanki mineralno-asfaltowe - Metody badań - Część 5: Oznaczanie gęstości,” n.d.), bulk density (“PN-EN 12697-6:2020-07. Mieszanki mineralno-asfaltowe - Metody badań - Część 6: Oznaczanie gęstości objętościowej próbek mieszanki mineralno-asfaltowej,” n.d.), air void content(“PN-EN 12697-8:2019-01. Mieszanki mineralno-asfaltowe - Metody badań - Część 8: Oznaczanie zawartości wolnej przestrzeni,” n.d.) and indirect tensile strength (“PN-EN 12697-23:2017-12. Mieszanki mineralno-asfaltowe – Metody badań. Część 23: Oznaczanie wytrzymałości mieszanki mineralno-asfaltowej na rozciąganie pośrednie,” n.d.).

2.2. Second stage

The second stage of the research was independent from the first one. It verified the influence of polymer modification on the mix containing RAP heated with traditional oven and with microwaves. For this purpose, two mixes with different bitumen were chosen – unmodified (50/70) and Highly Modified Asphalt (HiMA) containing SBS polymer (45/80–80).

Asphalt PMB 45/80–80 contains 6–8% of the SBS polymer. Currently, the most frequently used polymer for this type of bitumen is Kraton D0243. Samples were prepared according to PN-EN 12697-30: 2019-01 ("PN-EN 12697-30:2019-01. Mieszanki mineralno-asfaltowe - Metody badań. Część 30: Przygotowanie próbek zagęszczonych przez ubijanie," n.d.). In order to standardize the test procedure, all samples were compacted with 75 blows on each side with a Marshall compactor. Compaction temperature was 150°C for both heating methods (laboratory oven with air circulation and microwave radiation). The reason for unification the procedure was to maintain the same level of aging processes of both mixes and use the same samples for the density and indirect tensile strength tests.

This stage of the study is referred to the comparison of microwave radiation effect on the HMA containing unmodified bitumen and highly modified bitumen with the SBS polymer. For both types of HMA, one part was heated to the desired temperature of 150°C in a laboratory oven before forming them in a Marshall compactor. The other part was subjected to microwave radiation of frequency around 2,45 GHz. Marshall specimens preheated by microwaves were stored in a laboratory oven for a short time before compaction to maintain stable temperature.

For both types of HMA and both methods of heating, compacted samples were tested in terms of bulk density and indirect tensile strength ("PN-EN 12697-23:2017-12. Mieszanki mineralno-asfaltowe – Metody badań. Część 23: Oznaczanie wytrzymałości mieszanki mineralno-asfaltowej na rozciąganie pośrednie," n.d.). Based on density ("PN-EN 12697-5:2019-01. Mieszanki mineralno-asfaltowe - Metody badań - Część 5: Oznaczanie gęstości," n.d.) and bulk density ("PN-EN 12697-6:2020-07. Mieszanki mineralno-asfaltowe - Metody badań - Część 6: Oznaczanie gęstości objętościowej próbek mieszanki mineralno-asfaltowej," n.d.) test calculations of the air void content were made ("PN-EN 12697-8:2019-01. Mieszanki mineralno-asfaltowe - Metody badań - Część 8: Oznaczanie zawartości wolnej przestrzeni," n.d.).

3. Results And Discussion

3.1. First stage

At the beginning of the research, it was essential to confirm possibility of RAP heating with use of microwaves. The RAP chosen for the test was subjected to microwaves having various moisture content ranging from 0–5%. The results of 60 second microwave heating of 500 g of the RAP are presented in Fig. 3.1.

First tests confirmed efficiency of microwave heating, suggesting that the increase of moisture content in the RAP does not have a negative impact on the heating process to the contrary to standard RAP heating methods. According to the results it may even strengthen the heating capabilities. Higher moisture content increased efficiency of microwave heating, leading to achievement of higher RAP temperatures after 60 seconds of heating in moisture range of 0–3%. Higher amounts of moisture did not reveal any significant changes in heating efficiency.

Further the mixes were prepared according to the plan presented in Table 2.1. Air void content was checked in order to determine the changes in the HMA with the changes of heating method, RAP content and its moisture. Results of the air void content are presented in Fig. 3.2 and Fig. 3.3.

The air void value shown by HMA 3 with a 15% RAP content (w/w) heated by microwave radiation is significantly lower than HMA 4 containing RAP heated by conventional method. The same observation refers to samples containing 50% of RAP – HMA 5 heated by microwaves shows lower air void content than HMA 6 heated in oven. Samples with a moisture content of 3% (w/w) (HMA 2, 3 and 5) reveal lower air void content than samples with 0% moisture content. Laboratory oven heating appears to have caused higher air void content due to more intense ageing process.

Figure 3.4 and Fig. 3.5 summarize the average Indirect Tensile Strength results of the samples. The highest ITS are obtained by samples containing 50% RAP (w/w) (HMA 5 and 6). Higher ITS values are shown by series of specimens containing RAP heated by microwave radiation (HMA 3 and 5) in relation to specimens containing RAP heated in the laboratory oven (HMA 4 and 6). Both HMAs with the addition of cold RAP (HMA 1 and 2), despite different air void content showed on Fig. 3.2, show similar ITS results.

3.2. Second stage

Initial tests, in order to define the length of microwave heating, were performed. Large part of the tested specimens reached temperature of 150°C after 120 seconds of heating (Fig. 3.6). Asphalt containing unmodified bitumen requires more time for heating, which indicates different impact of the microwaves on these two materials. As each of these materials shows slightly different microwave heating efficiency it suggests that presence of SBS polymer causes differences in HMA behavior.

During microwave heating of a HMA with bitumen containing the SBS polymer, the material showed a tendency to fume or spark. The temperature measurement during the phenomenon showed values significantly below the flash point temperature of the bitumen, moreover, the characteristic smell of sulfur was observed, which may be caused by a cross-linking additive to the polymer (Rybiński et al., 2014).

Figure 3.7 summarizes the air void content of both HMA. The HMA containing highly-modified bitumen has a much higher air void content compared to the HMA with unmodified asphalt. Microwave radiation does not significantly affect air void content of HMA samples in comparison to HMA heated in laboratory oven. No change was observed both in case of HMA with unmodified bitumen and bitumen modified with SBS polymer.

Figure 3.8 summarizes the results of the Indirect Tensile Strength of both HMA. Microwave heating affected samples with unmodified bitumen more, as difference in ITS values between the two heating methods were visible just for samples with unmodified bitumen. Microwave heating caused visible decrease of ITS parameter, however, the values are within the range of expected HMA parameters.

4. Conclusions

This study was designed to determine possibility of microwave radiation application during Hot Mix Asphalt production. It was assumed that it may be used for the purpose of RAP heating during production of high RAP content asphalt mixes. The research consisted of two stages of tests carried out with use of different RAP content and different bitumen present in the RAP (with and without the SBS polymer modification). The results lead to the following observations:

- It was confirmed that there is a possibility to use microwaves for RAP heating, especially with the RAP containing real water content present in the full-scale HMA plant,
- More effective microwave heating occurs for RAP moisture exceeding 3%,
- Use of microwave heated RAP with water content of 3%, for production of HMA, leads to improved compactability and lower HMA air void content in comparison to using RAP heated in traditional way,
- HMA containing RAP heated by microwave radiation reveals differences of Indirect Tensile Strength values in comparison to the HMA containing RAP heated in laboratory oven,
- Microwave heating of HMA containing polymer modified bitumen appears to be more effective in comparison to HMA containing unmodified bitumen,
- Heating and compacting HMA fully by microwaves leads to acceptable in terms of HMA production differences of HMA parameters.

The observations not only confirm the possibility of microwave use during HMA production but also focuses on specific use which may bring benefits from heating technology change. In case of wet RAP material use, which is difficult to handle in traditional way, it may be not only environmentally friendly to switch to electric heating but it may also be financially reasonable. Such in-depth analysis is planned for future research.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. All authors read and approved the final manuscript.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

References

1. Al-Ohaly, A.A., Terrel, R.L., 1988. Effect of microwave heating on adhesion and moisture damage of asphalt mixtures. Transportation Research Record.
2. Alonso-Buenaposada, I.D., Menéndez, J Angel, Calvo, E.G., Menéndez, J A, Arenillas, A., 2016. 189–191.
3. Baowen, L., Aimin, S., Yupeng, L., Wentong, W., Zhuangzhuang, L., Wei, J., Xin, C., 2020. Construction and Building Materials 246, 118510.
4. Benedetto, A., Calvi, A., 2013. Construction and Building Materials 44, 351–359.
5. Bishara, S.W., McReynolds, R.L., 1995. Transportation Research Record.
6. Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. The Lancet 389, 1907–1918.
7. CYCLEAN, Inc. of A., 1992. Microwave Process for Asphalt Pavement Recycling.
8. Edwards, L., Wilkinson, P., Rutter, G., Milojevic, A., 2022. Environmental Pollution 292.
9. Ergan, B.T., Bayramo□lu, M., Özcan, S., 2015. European Polymer Journal 69, 374–384.
10. Feng, H., Yin, Y., Tang, J., 2012. Food Engineering Reviews 4, 89–106.
11. Garcia, P.S., de Sousa, F.D.B., de Lima, J.A., Cruz, S.A., Scuracchio, C.H., 2015. Express Polymer Letters 9, 1015–1026.
12. Gulisano, F., Crucho, J., Gallego, J., Picado-Santos, L., 2020. Applied Sciences (Switzerland) 10.
13. Gulisano, F., Gallego, J., 2021. Construction and Building Materials 278, 121993.
14. Gwarek, W.K., Celuch-Marcysiak, M., 2003. IEEE Transactions on Microwave Theory and Techniques 51, 1920–1928.
15. Jin, S., Guo, C., Lu, Y., Zhang, R., Wang, Z., Jin, M., 2017. Polymer Degradation and Stability 140, 32–41.
16. Li, B., Zhou, J., Zhang, Z., Yang, X., Wu, Y., 2019. Materials 12.
17. Liu, C., Chen, R., Sera, F., Vicedo-Cabrera, A.M., Guo, Y., Tong, S., Coelho, M.S.Z.S., Saldiva, P.H.N., Lavigne, E., Matus, P., Ortega, N.V., Garcia, S.O., Pascal, M., Stafoggia, M., Scortichini, M., Hashizume, M., Honda, Y., Hurtado-Díaz, M., Cruz, J., Nunes, B., Teixeira, J.P., Kim, H., Tobias, A., Íñiguez, C., Forsberg, B., Åström, C., Ragettli, M.S., Guo, Y.L., Chen, B.Y., Bell, M.L., Wright, C.Y., Scovronick, N., Garland, R.M., Milojevic, A., Kyselý, J., Urban, A., Orru, H., Indermitte, E., Jaakkola, J.J.K., Ryti, N.R.I., Katsouyanni, K., Analitis, A., Zanobetti, A., Schwartz, J., Chen, J., Wu, T., Cohen, A., Gasparrini, A., Kan, H., 2019. The New England Journal of Medicine 381, 705–715.
18. Lizárraga, J.M., Gallego, J., 2020. Materials 13.
19. Lou, B., Sha, A., Barbieri, D.M., Liu, Z., Zhang, F., Jiang, W., Hoff, I., 2021. Journal of Cleaner Production 320, 128823.
20. Lozhkin, V., Lozhkina, O., Dobromirov, V., 2018. Transportation Research Procedia 36, 453–458.
21. Metaxas, R.C., Meredith, R.J., 1993. Industrial microwave heating. P. Peregrinus on behalf of the Institution of Electrical Engineers, London UK.

22. Mitchell, R., Woodward, D., Ryan, D., 2013. Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements - Proceedings of the 2013 Airfield and Highway Pavement Conference 1211–1218.
23. Norambuena-Contreras, J., Garcia, A., 2016. Materials and Design 106, 404–414.
24. PN-EN 12697-5:2019-01. Mieszanki mineralno-asfaltowe - Metody badań - Część 5: Oznaczanie gęstości.
25. PN-EN 12697-6:2020-07. Mieszanki mineralno-asfaltowe - Metody badań - Część 6: Oznaczanie gęstości objętościowej próbek mieszanki mineralno-asfaltowej.
26. PN-EN 12697-8:2019-01. Mieszanki mineralno-asfaltowe - Metody badań - Część 8: Oznaczanie zawartości wolnej przestrzeni.
27. PN-EN 12697-23:2017-12. Mieszanki mineralno-asfaltowe – Metody badań. Część 23: Oznaczanie wytrzymałości mieszanki mineralno-asfaltowej na rozciąganie pośrednie.
28. PN-EN 12697-30:2019-01. Mieszanki mineralno-asfaltowe - Metody badań. Część 30: Przygotowanie próbek zagęszczonych przez ubijanie.
29. Qu, S., Fan, S., Wang, G., He, W., Xu, K., Nie, L., Zhao, Y., Zhu, Q., Li, T., Li, G., 2021. Journal of Environmental Sciences 109, 57–65.
30. Rybiński, P., Kucharska-Jastrza̧bek, A., Janowska, G., 2014. Polymer Science - Series B 56, 477–486.
31. Shukla, M., Ghosh, S., Dandapat, N., Mandal, A.K., Balla, V.K., Shukla, M., Ghosh, S., Dandapat, N., Mandal, A.K., Balla, V.K., 2016. Journal of Materials Science and Chemical Engineering 4, 71–78.
32. Sun, J., Wang, W., Yue, Q., 2016. Materials 9.
33. Sun, T., 2013. International Journal of Applied Electromagnetics and Mechanics 43, 353–363.
34. Sun, Y., Liu, Q., Wu, S., Shang, F., 2014. Key Engineering Materials 599, 193–197.
35. Tabaković, A., O’Prey, D., McKenna, D., Woodward, D., 2019. Case Studies in Construction Materials 10, e00233.
36. Trigos, L., Gallego, J., Escavy, J.I., 2020a. Construction and Building Materials 230, 117035.
37. Trigos, L., Gallego, J., Escavy, J.I., 2020b. Construction and Building Materials 230, 117035.
38. Xu, J., Li, R., Liu, T., Pei, J., Li, Y., Luo, Q., 2020. 1–13.
39. Xu, S., Liu, X., Tabaković, A., Schlangen, E., 2021. Processes 9.
40. Yalcin, E., 2021. Construction and Building Materials 286, 122965.
41. Yu, G.X., Li, Z.M., Zhou, X.L., Li, C.L., 2011. Petroleum Science and Technology 29, 411–417.
42. Zaumanis, M., Boesiger, L., Kunz, B., Cavalli, M.C., Poulikakos, L., 2019. Construction and Building Materials 198, 368–378.
43. Zhou, X., Zhang, X., Zhang, Y., Adhikari, S., 2022. Construction and Building Materials 315, 125738.
44. Zhu, H., Han, X., Tao, Y., Nai, S.M.L., Kuma, J.V.M., Gupta, M., 2009. J. Phys. D: Appl. Phys 42, 8.

Figures

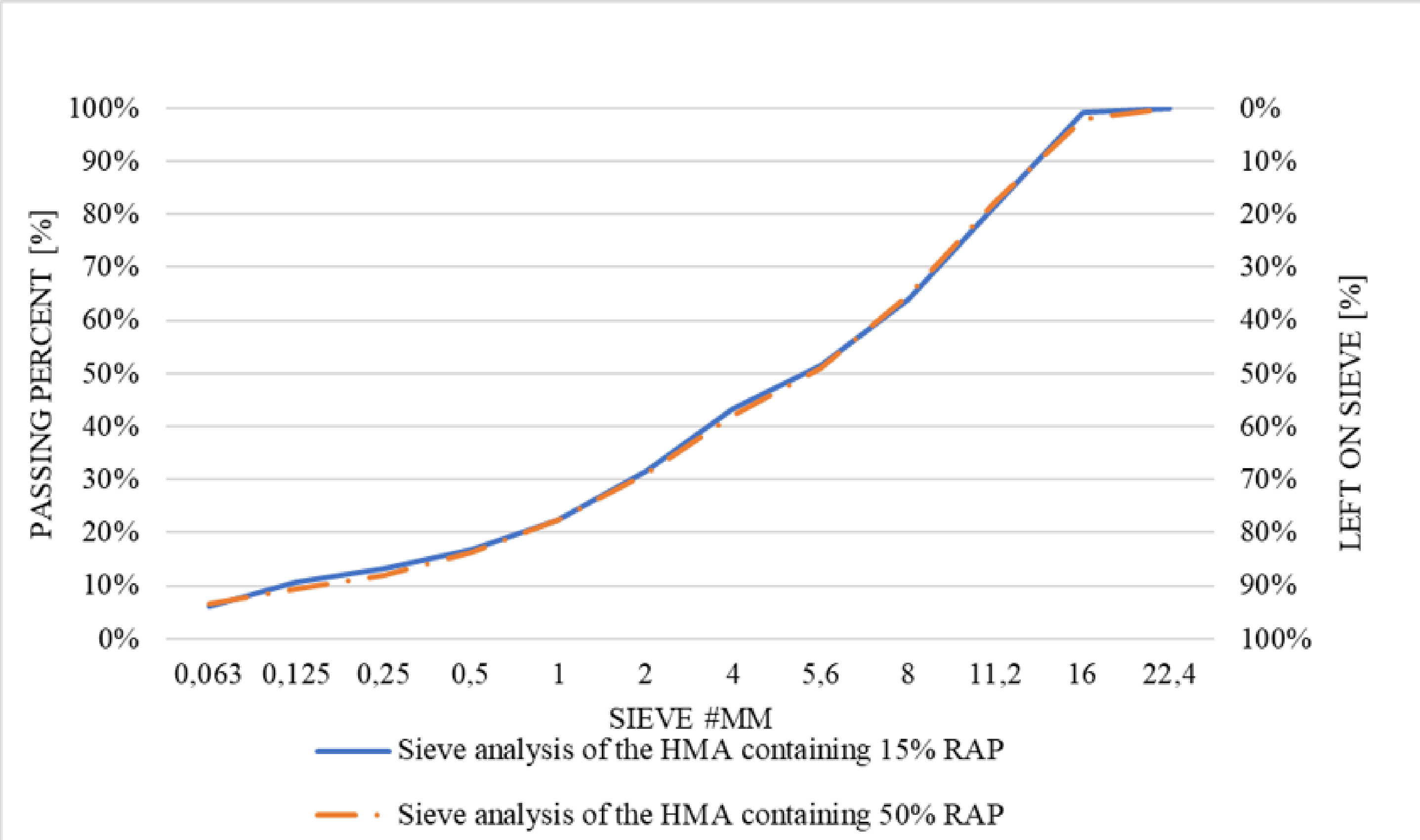

Figure 1

Fig. 2.1 Comparison of the sieve analysis of the HMA containing 15% and 50% RAP

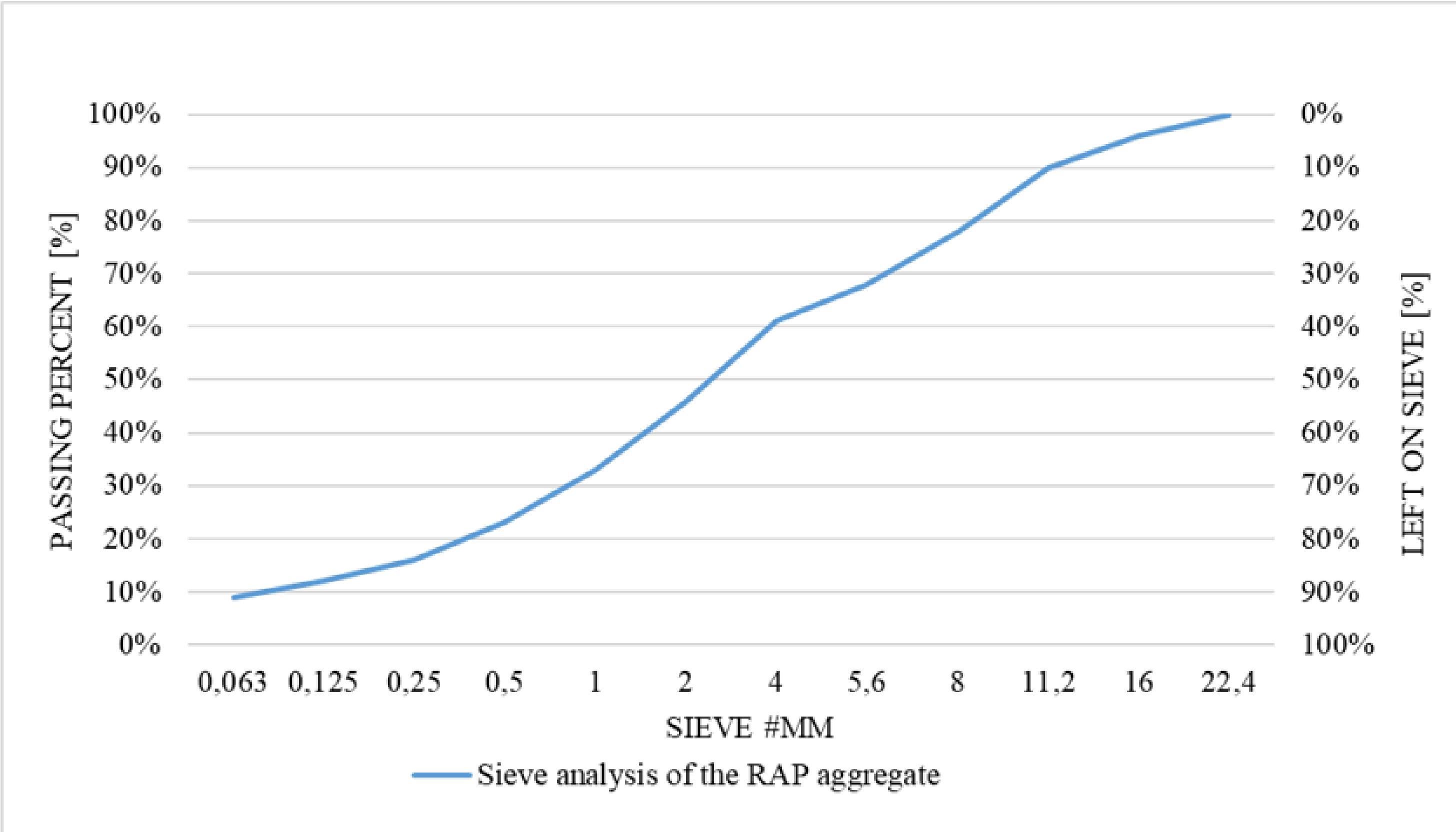

Figure 2

Fig. 2.2 Sieve analysis of the RAP aggregate

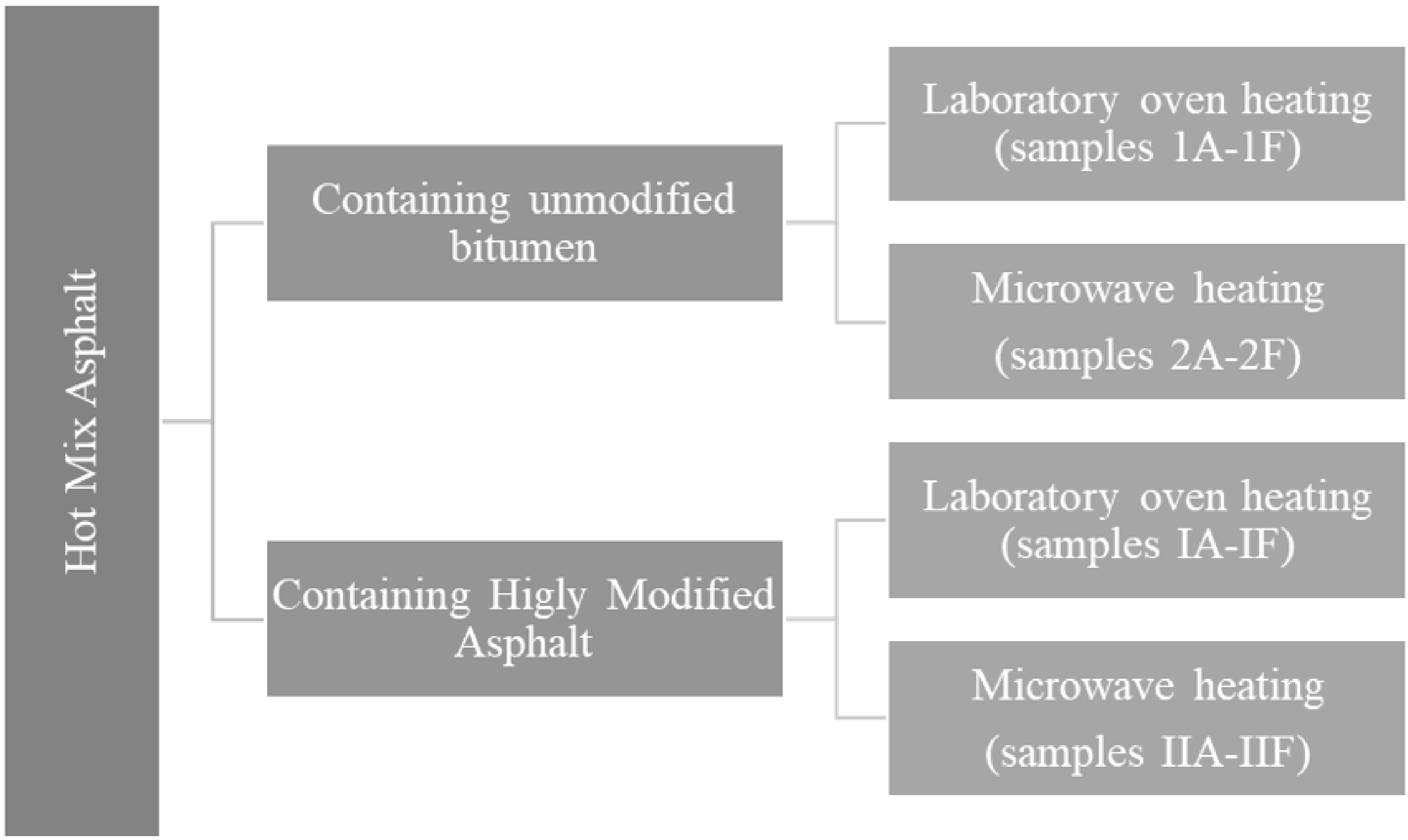

Figure 3

Fig. 2.3 Numeration of compacted samples preheated by laboratory oven and microwave radiation

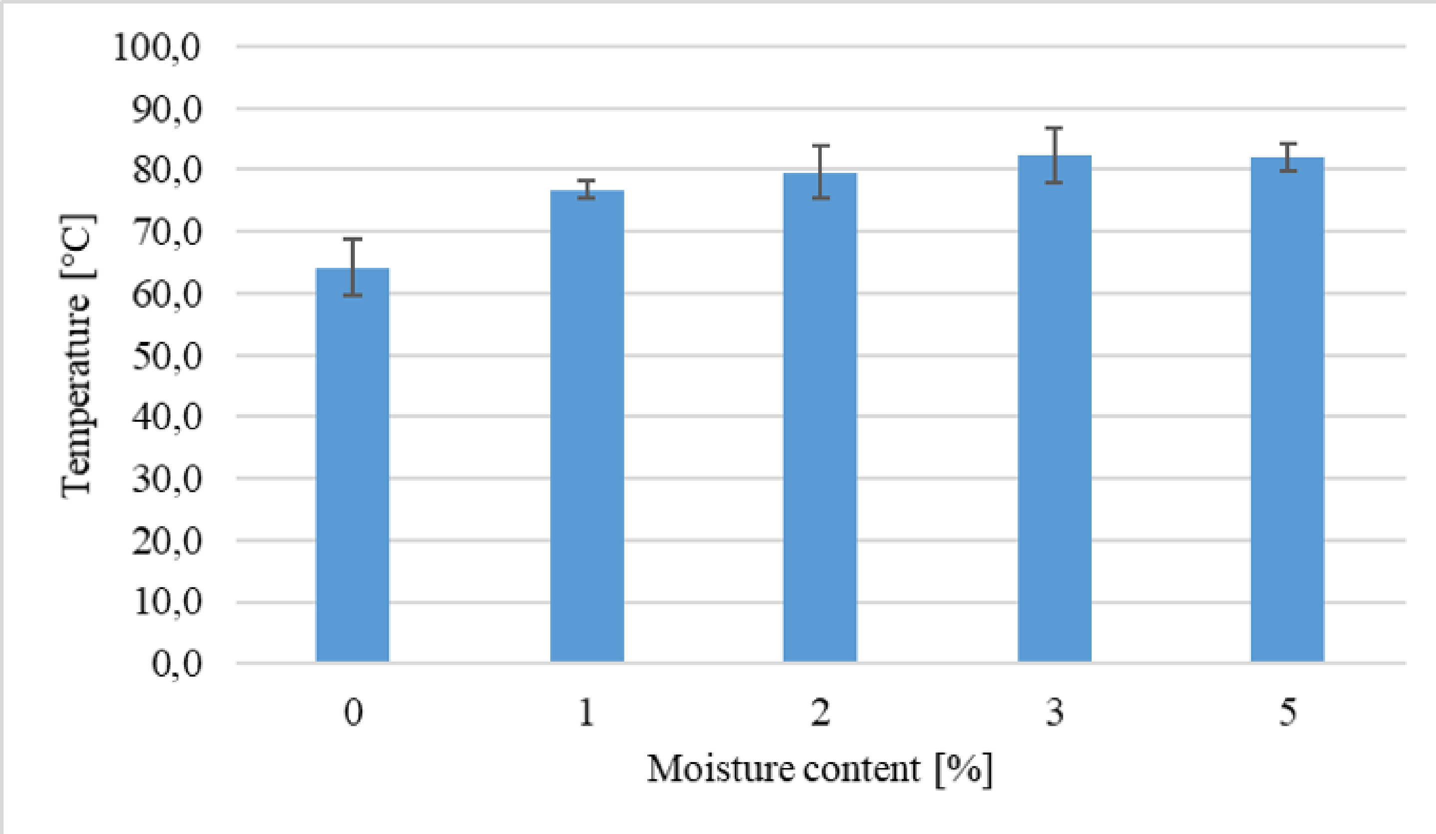

Figure 4

Fig. 3.1 Average temperature measurement with standard deviation for variable moisture content after 60 seconds of microwave heating 500 g of HMA

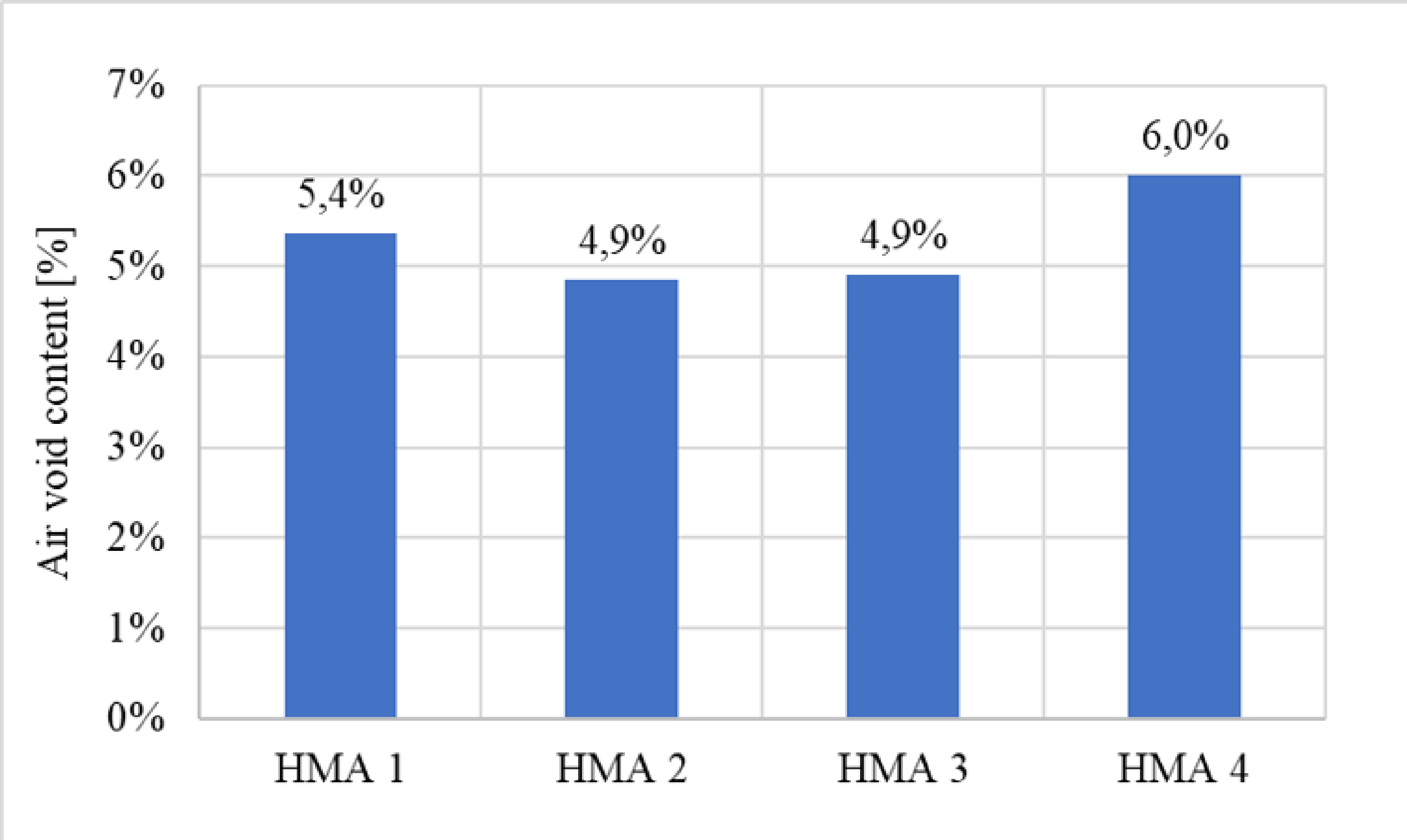

Figure 5

Fig. 3.2 Air void content of the mixes containing 15% of RAP

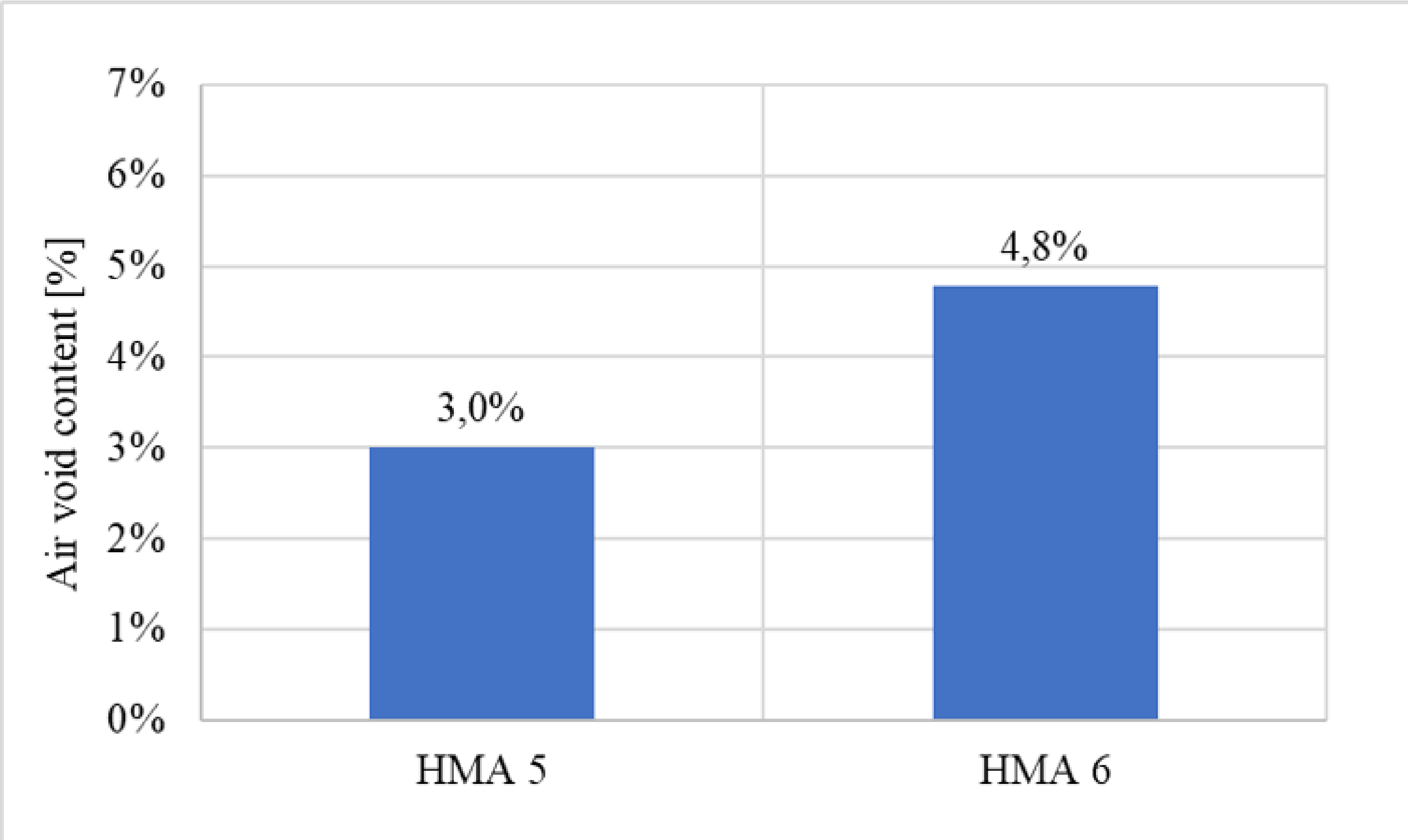

Figure 6

Fig. 3.3 Air void content of the mixes containing 50% of RAP

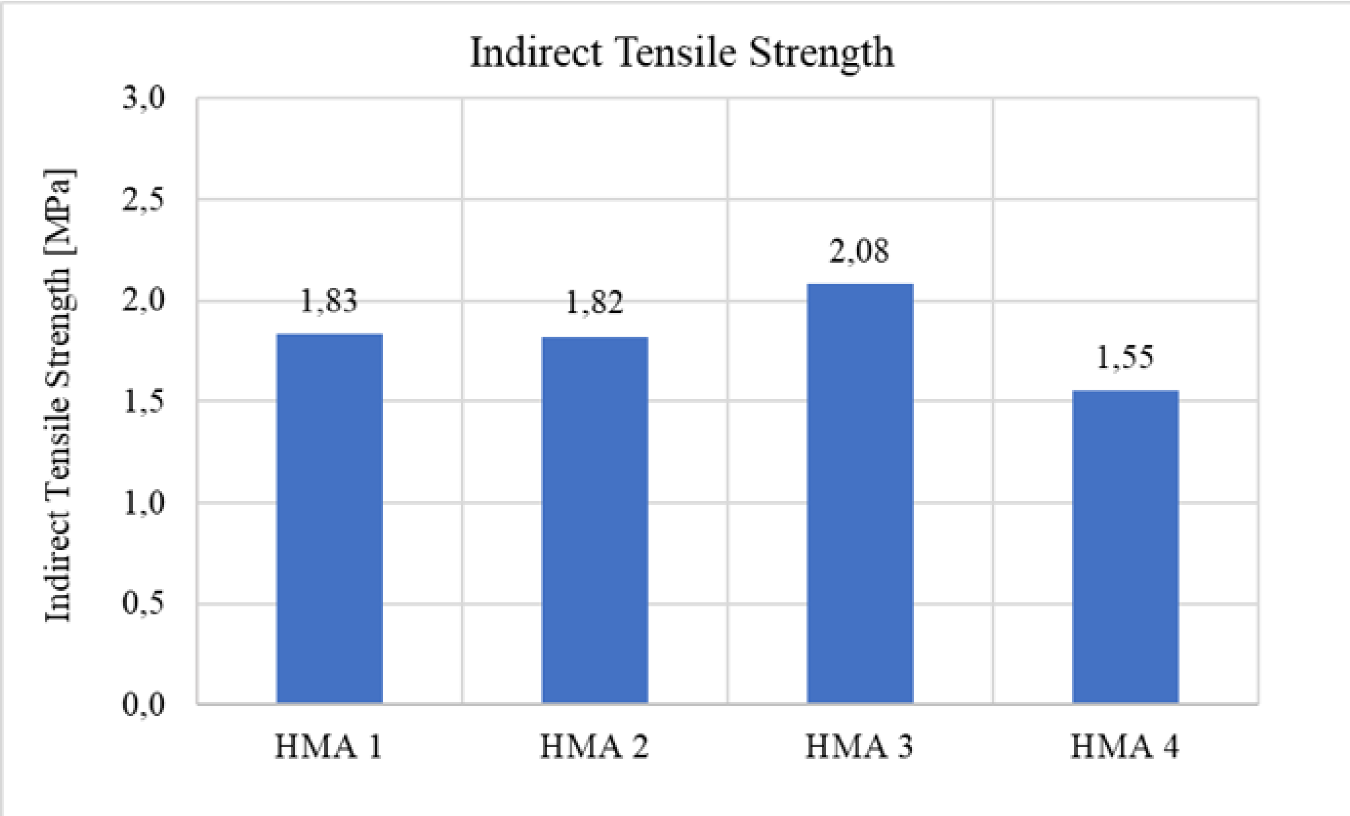

Figure 7

Fig. 3.4 Average ITS results for mixes containing 15% RAP

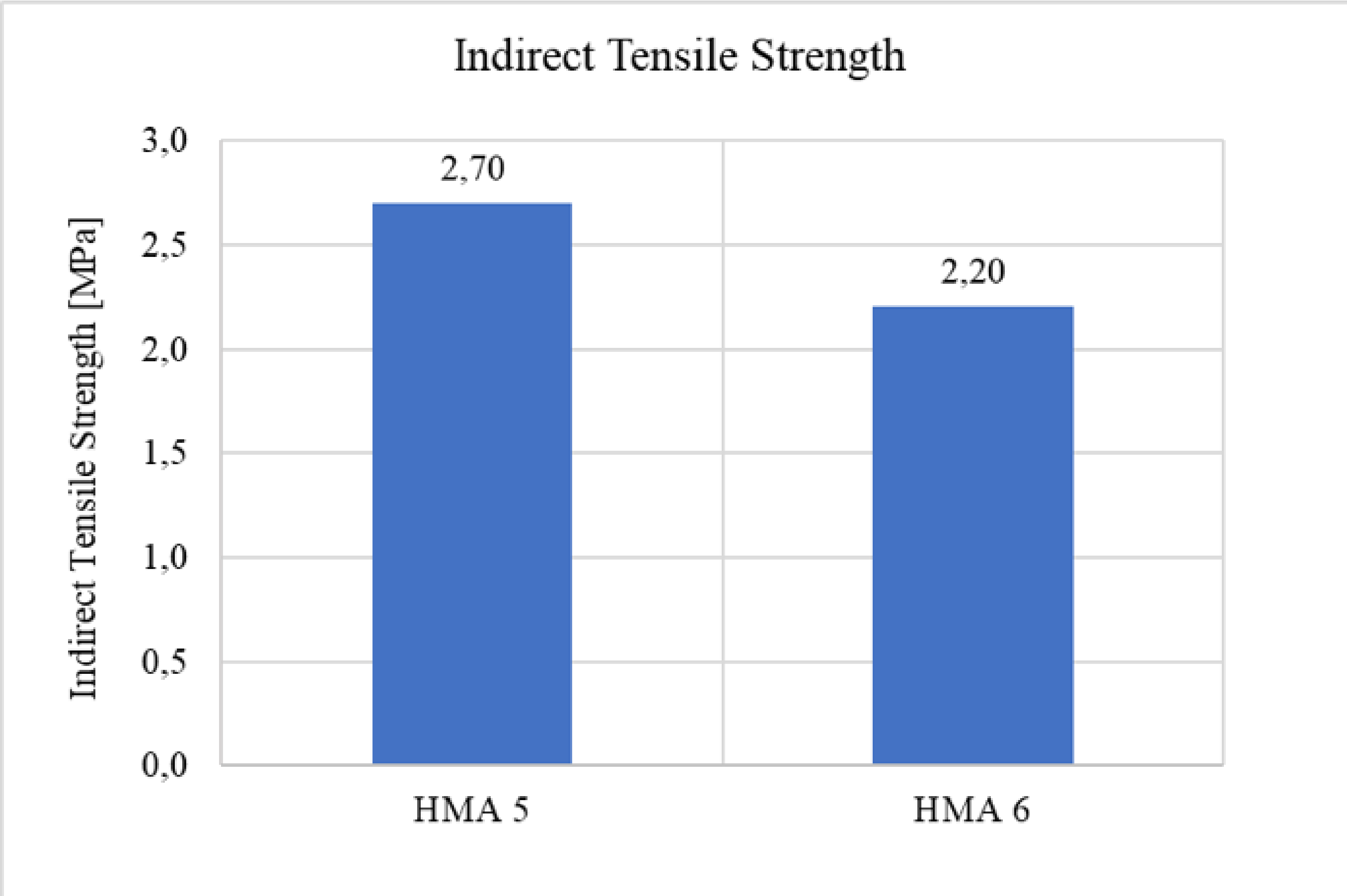

Figure 8

Fig. 3.5 Average ITS results for mixes containing 50% RAP

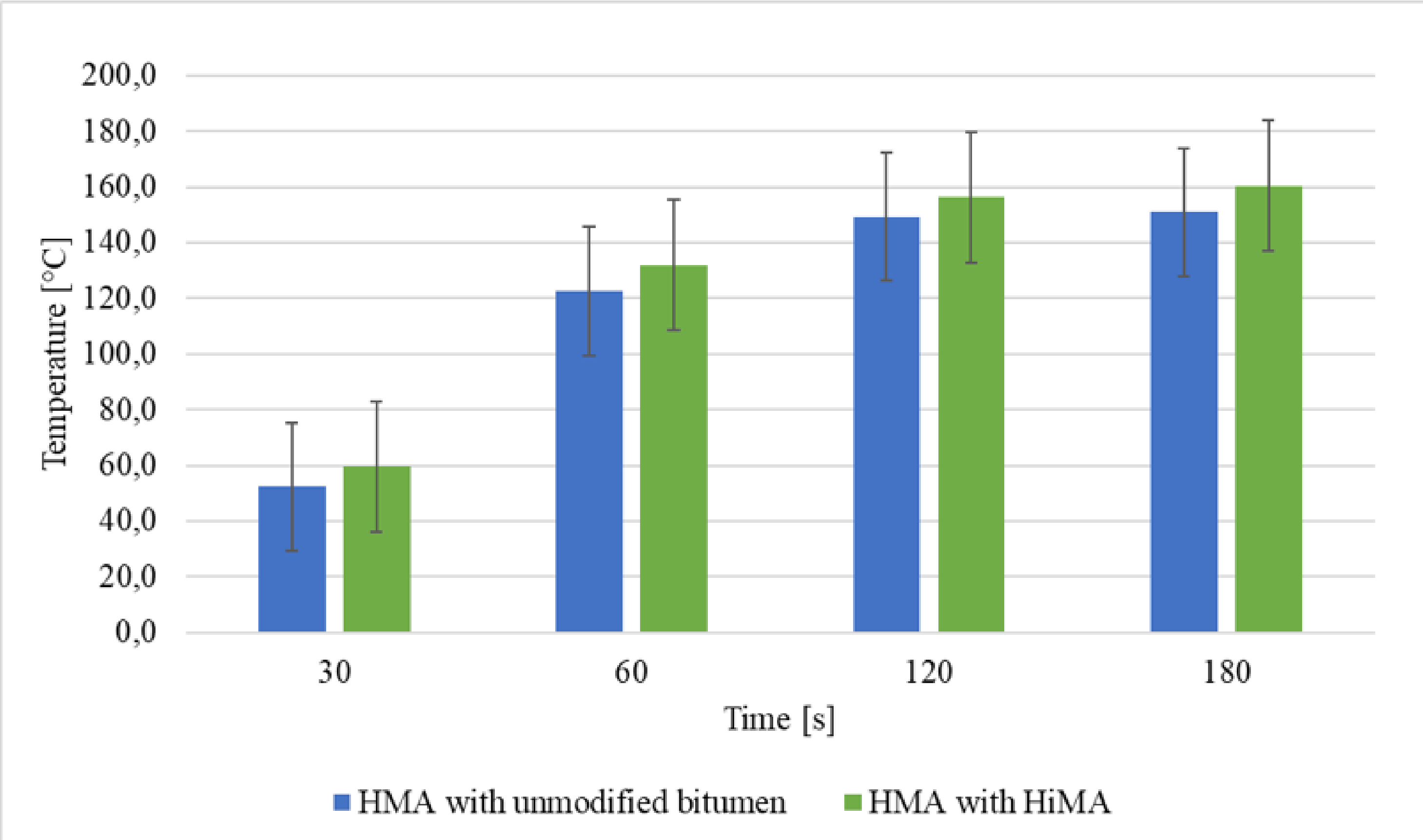

Figure 9

Fig. 3.6 Average temperature and standard deviation after each microwave heating cycle for two different HMA

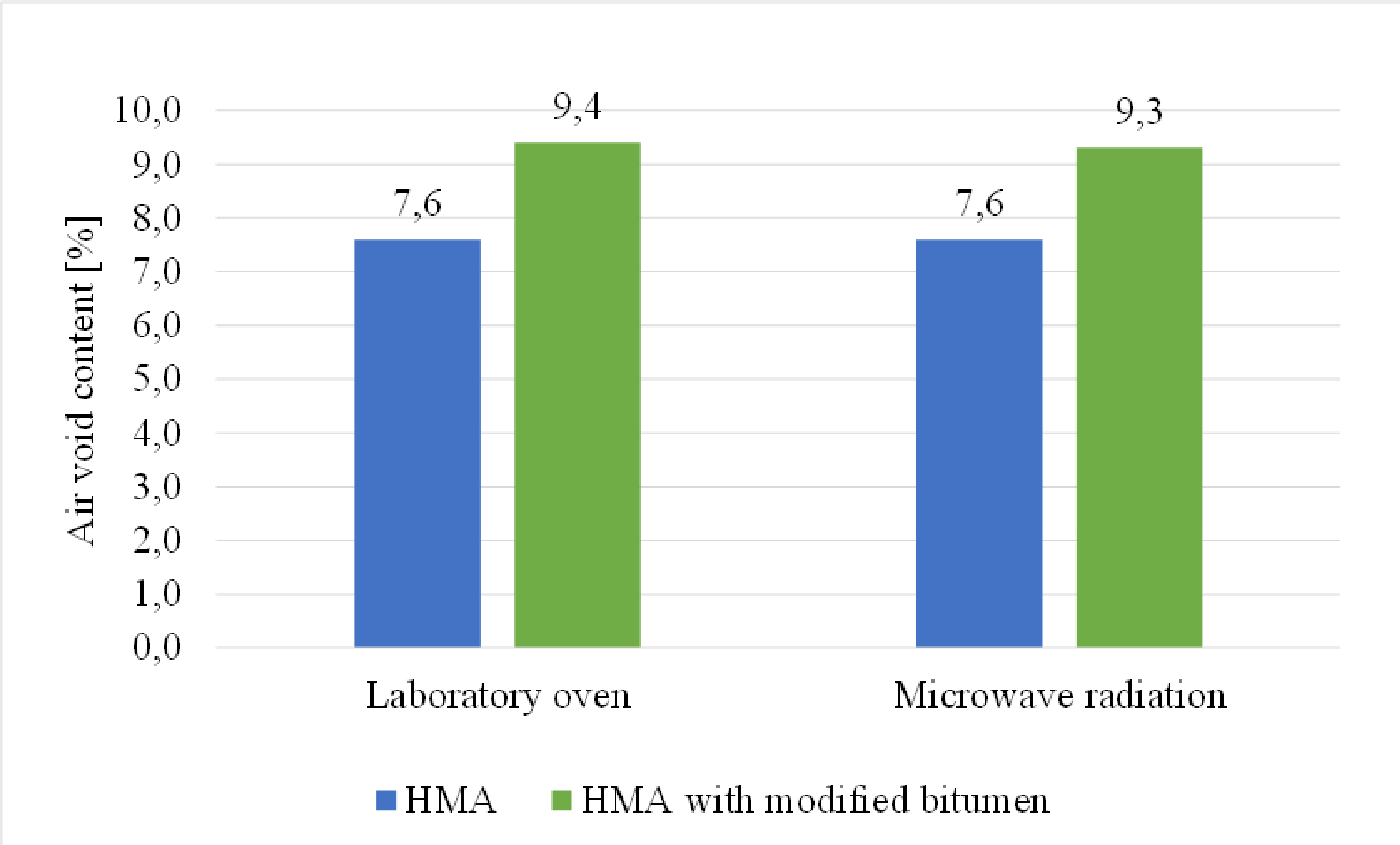

Figure 10

Fig. 3.7 Summary of the air void content for HMA and HMA with modified bitumen

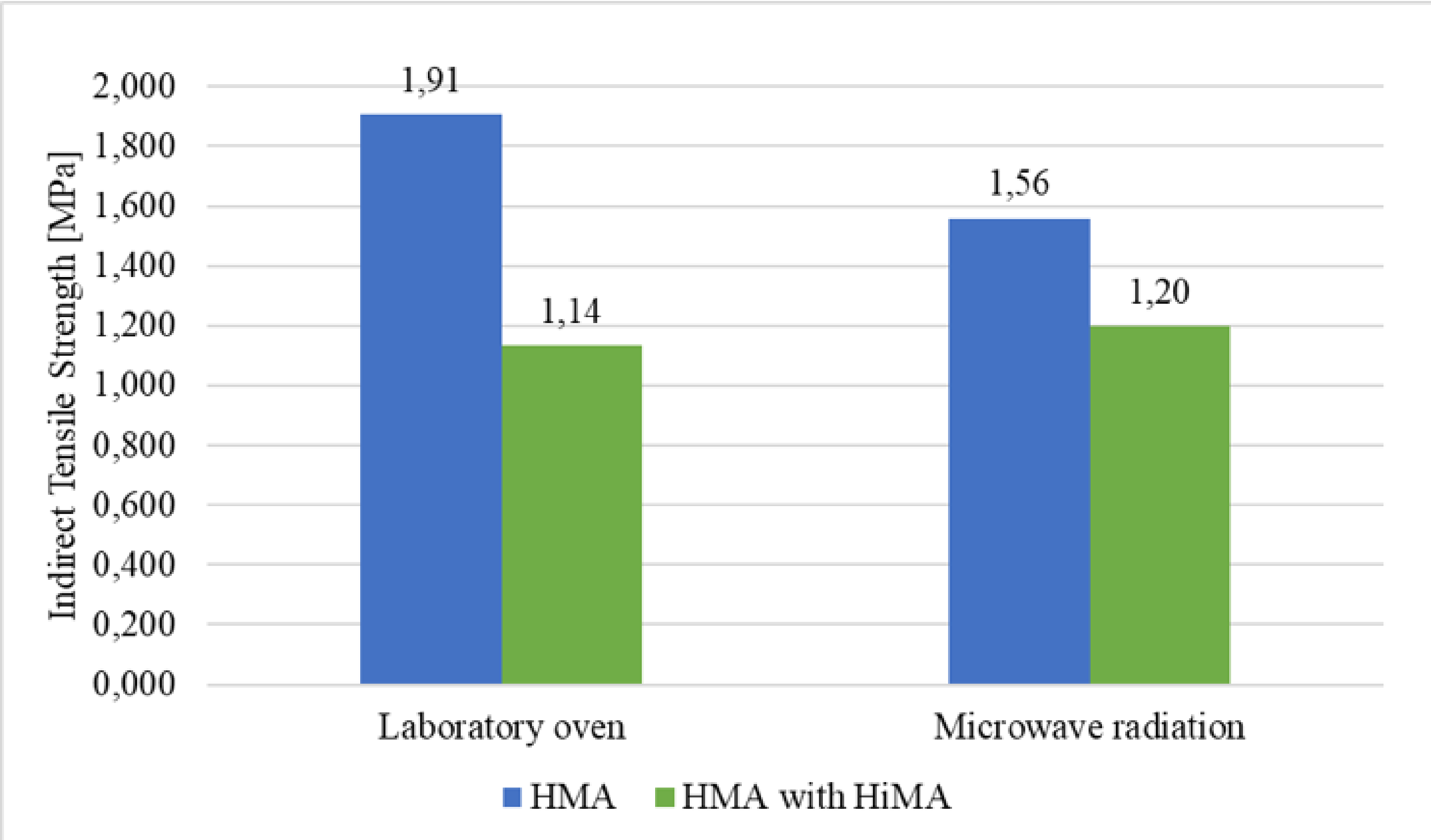

Figure 11

Fig. 3.8 Summary of average Indirect Tensile Strength for both HMA