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Alternative Supply of the Mineral Raw Material Needs of the Asphalt Industry by Metallurgical Slags

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Abstract

With the growing demand for high-quality raw materials in the asphalt industry, finding sustainable alternatives to natural aggregates has become increasingly important. This study explores the potential of using metallurgical slags – specifically, blast furnace slag (BFS) and converter slag (CS) – as substitutes for traditional materials like basalt and andesite in asphalt mixtures.

Through a series of laboratory tests, we examined the performance of these slag-based mixtures in terms of stiffness, water resistance, deformation, and durability under thermal stress. The results were promising that both BFS and CS met or even exceeded standard technical requirements. CS showed superior stiffness and aging resistance, likely due to its alkaline properties that slow down bitumen degradation. Slag-based mixtures also demonstrated strong skid resistance and maintained their mechanical properties better than natural aggregates when exposed to extreme temperature changes.

These findings suggest that incorporating metallurgical slags into asphalt production could help address raw material shortages while offering environmental benefits, such as reducing CO_2 emissions and preserving natural resources. With comparable or even better performance than traditional aggregates, slag-based asphalt mixtures present a viable and sustainable option for the future of road construction.

Keywords

metallurgical slag, asphalt mixtures, blast furnace slag, converter slag, sustainable road construction

1 Introduction

According to the literature (Ézsiás et al., 2024; Fischer, 2025; SNAP-SEE, online), the demand for raw materials for infrastructure development is increasing. Based on specified surveys by researchers' predictions, consumption of mineral raw materials is estimated to increase further in the medium term, nowadays, at an EU average of 6 tons per capita per year due to economic development, with an estimated value of around 9–12 tons per capita per year in the near future, thus showing an increasing trend (SNAP-SEE, online). It is also evident from the research data that secondary raw materials and industrial by-products can replace 10–20% of primary raw material demand. Consequently, primary raw material resources, which represent finite supplies, remain an indispensable source for meeting the demand for raw materials in the construction industry.

This is no different in the asphalt industry, which typically requires the highest quality of mineral resources (EAPA, online). The asphalt industry's objectives align with European trends, aiming to implement technologies and processes that reduce CO_2 emissions and energy consumption (Fischer and Kocsis Szürke, 2023; Fischer et al., 2024; Kocsis Szürke et al., 2023; Kuchak et al., 2020). These efforts are further supported by research promoting energy-efficient practices and advanced materials use (Kuchak et al., 2021; Novytskyi et al., 2019; Oliskevych et al., 2022; Semenov et al., 2022). Additional studies have explored innovations in asphalt recycling and sustainability-enhancing solutions (Semenov et al., 2023; Szalai et al., 2024; Taran et al., 2023; Zöldy and Baranyi, 2023). Researchers have also emphasized the role of cognitive mobility and future-oriented infrastructure design in

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achieving climate goals (Zöldy, 2024; Zöldy et al., 2024). However, despite these ambitions, the volume of reclaimed asphalt does not exceed 35–40% of total asphalt production even in the most advanced Member States. On average in the EU, only 5–10% of the asphalt production is based on recovered materials, meaning that 90–95% still relies on primary raw materials (EAPA, online).

A recently done, not fully representative survey that the authors conducted among asphalt producers in Hungary (Colas Északkő users, 2025) showed that access to the necessary raw materials is somewhat uncertain, hindered and fraught with many difficulties, less so for AC mixes than for SMA mixes (because of differences of these requirements). The survey also showed that for most asphalt producers, there are only 3–5 quarries that can be suppliers by the quality of raw materials, which carry significant risks; it is enough to think that the supply chain could be paralyzed by the loss of one of these sources from the available ones. That is a highlighted risk, be it a technical problem of short duration, risk in the permits or an unplanned emergency event. These impacts can be mitigated by the inclusion of alternative sources of raw materials in the supplier chain, such as metallurgical slags, whose rock physics parameters can compete with the best quality crushed stone and, through their other properties, can be a preferred substitute for primary raw materials, helping to meet the raw material needs of the asphalt industry while also slowing the depletion of finite primary supplies. These metallurgical by-products also have a number of properties that deserve to be highlighted, such as road safety aspects due to their improved skid resistance (European Commission, 2009). Advances in digital sensing technologies have also contributed to the future viability of asphalt pavements. High-resolution 3D colored point cloud data, combined with machine learning methods, are proving to be highly effective for road surface segmentation and condition monitoring. Dowajy et al. (2025) demonstrated that using shallow neural networks (SNN) on point cloud datasets allows for precise road surface extraction, achieving an overall accuracy of nearly 99.9%. Such technologies enable improved maintenance scheduling and quality assurance, which are particularly beneficial when evaluating alternative materials like metallurgical slags. Alongside traditional materials, researchers have been investigating the incorporation of recycled polymers into asphalt mixes to promote sustainability. Kaya et al. (2025) explored the use of Polymethyl Methacrylate (PMMA), a plastic waste product, in Marshall asphalt samples. Their results showed that when applied in moderate concentrations, PMMA enhanced the mechanical and thermal properties of stone mastic asphalt mixtures. These modifications not only contribute to reducing environmental impact but also align with the goals of circular economy by reusing polymer waste.

One of the authors (L. Ézsiás) was involved in the development of a factory production control (FPC) system for metallurgical slag products at the Dunaújváros Steelworks more than a decade ago. The results of the regular tests carried out during FPC showed positive results for certain metallurgical slags, such as blast furnace slag (BFS) and "rested" converter slag (CS), so there was already a realistic possibility that these by-products could be used not only for pavement granular base layers but also for more demanding applications, such as aggregates for asphalt mixtures. At that time, as researchers at the Institute for Transport Sciences, the authors had the opportunity to lead a comprehensive research program to prove this. The results were not presented to a broader public at that time but were part of ongoing Ph.D. research on the supply difficulties of the asphalt industry by aggregates in Hungary. The authors were encouraged to re-evaluate the results of this research concerning the current situation and present them to a broader professional community.

Despite innovations in vehicle automation and transport informatics, road pavement structures have been relatively overlooked in the broader infrastructure system. Tóth and Fischer (2025) emphasized that while vehicles and drivers are becoming increasingly intelligent and integrated, the materials and layers beneath them remain largely unchanged. Their study advocates for re-centering research focus on road pavements as critical components of transport systems, especially under the looming challenges of climate change and the increasing need for resilient infrastructure.

Investigations into the potential uses of industrial by-products, such as metallurgical slags for road construction, go back several decades. There are examples of applications in the national and international literature, both for earthworks and for asphalt and concrete, and many success stories (Airey et al., 2004; Ács, 1960; Bencze, 2006). There is further literature directly related to the mentioned topic (Chuaychoo and Witayakul, 2003; Csontos, 2004; Esmaeili Kalalagh et al., 2005; Fistric et al., 2010), as well as Gáspár (1990; 2005), and Hamzah and Yi (2008). Last but not least the following items should also be cited (Karsainé, 1999; Kubányi, 2004; Mózes, 2004a; 2004b; Wittayangkoon, 2007).

In Hungary, despite the positive experience with the application of metallurgical slags, no large-scale (routine) application in the asphalt industry has taken place to date, one of the main reasons being the general professional prejudice against the application, the lack of state involvement and the resulting lack of market competition. These materials could only compete to a limited extent on a purely market basis with crushed aggregates of known quality and behavior, which are better known and accepted on the market. The previous experiences of secondary raw materials in the past have also cast a significant shadow on slags, which has not encouraged large-scale use and has significantly contributed to the current unfavorable professional prejudices.

In the last two decades, European standards have also been introduced in Hungary, which have had a significant impact on both professional thinking and the conditions of use of secondary raw materials. During the construction of the first section of the M6 motorway (2005), the embankment was built using a large amount of slag-mix from Dunaújváros Steelworks. During construction, it was found that in addition to the favorable technical characteristics – good compaction, high load-bearing capacity, low water sensitivity – the quality of the slag used at that time was rather inhomogeneous, both in terms of grain structure and physical characteristics. It is important to note, however, that the BFS used at that time was a mixture of slag (BFS, martin slag, CS) that had accumulated over several decades in the slag heap at Dunaújváros and had not yet been stored in a sliced form, and that its composition and other properties were therefore naturally inhomogeneous.

The continued construction of motorways in 2008 has led to significantly stricter requirements for the application of slag (products) than before. This condition was the FPC Certificate, which by then was becoming more widely expected.

A further example of material innovation supporting environmental and performance goals can be found in the Hungarian experience with rubber modified bitumen (RMB 45/80-55). Almássy et al. (2021) evaluated this binder across more than 100 road sections over eight years, demonstrating that RMB not only meets but can exceed the performance of traditional and polymer-modified binders in terms of fatigue resistance and low-temperature durability. Additionally, it promotes circular economy practices by enabling the reuse of waste tires in asphalt production – an approach conceptually aligned with the reuse of metallurgical slags.

The results of the production control tests have shown that the quality of the slags produced under different conditions for each metallurgical technology and treated/processed separately for each technology is already homogeneous, with quality characteristics reaching and even exceeding the quality of crushed stones used in asphalt mixtures. These two conditions, together with the favorable international (asphalt industry) application experience, mean that slag products with high quality and homogeneous properties have a high potential for application in the asphalt industry. As a certified product, they can be expected on a market basis, especially in light of the recent difficulties in the supply of raw materials. A comprehensive program of research was developed in the early 2010s, the results of which provided an opportunity to assess the performance of asphalt mixtures made with metallurgical slag additives; as the results of this research have not been published more widely since then, and at the same time access to raw materials has become significantly more complicated, it may be appropriate to re-evaluate and publish the results of this research, which the authors attempt to do in this article.

2 Literature review

The demand for sustainable solutions in various industries, especially in construction and road paving, has driven interest in alternative materials. The asphalt industry, in particular, is actively exploring the use of metallurgical slags as a substitute for conventional raw materials in asphalt production. This literature review examines current research supporting the sustainability and feasibility of integrating metallurgical slags into asphalt applications.

Metallurgical slags, by-products of iron and steelmaking, primarily contain oxides such as calcium oxide (CaO), magnesium oxide (MgO), and silicon dioxide (SiO_2) (Guo et al., 2024). Their chemical composition makes them a viable alternative to traditional aggregates in asphalt mixtures. Repurposing these industrial byproducts not only conserves natural resources but also supports a circular economy by transforming waste materials into valuable components for infrastructure (Georgiou and Loizos, 2021a; 2021b; Moura et al., 2022). Using metallurgical slags in asphalt mixtures results in durable pavements while significantly reducing the environmental footprint of pavement production (Moura et al., 2022; Pasetto et al., 2023).

Research has demonstrated that incorporating steel slag aggregates (SSA) enhances the mechanical performance of asphalt mixtures. SSA exhibits superior angularity and rough texture, which improve the bond between aggregates and asphalt binders. This enhanced interaction increases resistance to deformation and cracking – critical factors in pavement durability (Georgiou and Loizos, 2021a; 2021b; Pasetto et al., 2023). Moura et al. (2022) highlighted that high SSA content enhances both sustainability and performance in asphalt mixtures, reinforcing its value as an industrial byproduct in road construction.

Additionally, the environmental benefits of using steel slag in warm mix asphalt (WMA) have been well-documented. WMA technology enables lower production temperatures, reducing energy consumption and greenhouse gas emissions compared to traditional hot mix asphalt (HMA) methods (Belc et al., 2021). Georgiou and Loizos (2021a; 2021b) found that combining steel slag with reclaimed asphalt optimizes resource efficiency while delivering substantial environmental benefits, such as reduced raw material extraction and lower bitumen consumption. These findings further validate the role of metallurgical slags in advancing sustainability within the asphalt industry.

Safety and performance concerns related to steel slag in asphalt mixtures have been addressed through improved processing and treatment methods that mitigate risks like leaching and volume expansion (Georgiou and Loizos, 2021a; 2021b). Studies confirm that when adequately treated, steel slag performs comparably to natural aggregates (Vaiana et al., 2019). Vaiana et al. (2019) emphasized that steelmaking waste provides an effective alternative to natural aggregates while contributing to sustainable industrial waste management.

Research has also explored the recycling and integration of electric arc furnace (EAF) slags, another byproduct of steel production. EAF slags possess a unique microstructure that serves as a high-quality mineral base for asphalt applications. Vaiana et al. (2019) noted that the microtextural properties of EAF slags surpass those of conventional natural stones, suggesting their potential to enhance asphalt pavement performance. These findings reinforce the value of metallurgical slags in delivering high-quality asphalt mixtures while providing an effective solution for industrial waste management.

Incorporating metallurgical slags into asphalt aligns with global initiatives aimed at reducing waste and promoting sustainability. Diverting industrial byproducts from landfills to infrastructure applications benefits both the environment and the asphalt industry. Additionally, utilizing metallurgical waste reduces reliance on virgin materials, potentially lowering costs and mitigating resource depletion (Movilla-Quesada et al., 2021; Pasetto et al., 2023). The integration of these practices represents a holistic approach to addressing environmental challenges while improving roadway infrastructure.

While the advantages of using metallurgical slags in asphalt are well-documented, ongoing research is necessary to address challenges such as variations in slag composition and their potential impact on performance. Future studies should focus on standardization, quality assessments, and lifecycle analyses to provide stakeholders with a comprehensive understanding of the risks and benefits associated with metallurgical slags in asphalt production (Belc et al., 2021; Mantalovas and Di Mino, 2020).

As the industry continues to prioritize sustainability, adopting metallurgical slags alongside other industrial byproducts presents a significant opportunity for innovation. Research has already identified additional materials, such as waste dust and polymers from various industries, as viable modifiers for asphalt mixtures (Ibrahimi et al., 2021; Ochoa Díaz et al., 2023). A diversified approach that incorporates metallurgical slags alongside other waste-based additives could propel the industry toward more durable, cost-effective, and environmentally responsible asphalt solutions.

Even though much research has explored the potential of metallurgical slags in asphalt production, there is still a noticeable gap when it comes to their large-scale use in the industry. Studies have shown that BFS and CS can meet or even exceed the performance of traditional aggregates, but their adoption remains slow. This is partly due to professional skepticism, outdated perceptions of secondary raw materials, and the absence of strong policies to encourage their use. While past projects in Hungary and other countries have demonstrated their feasibility, challenges such as concerns over consistency and a lack of standardized guidelines continue to hold back wider implementation. To bridge this gap, more work is needed to refine quality control measures, educate industry professionals, and push for regulatory support that recognizes the value of slag-based alternatives.

Another key missing piece is a deeper understanding of how these materials perform over time in real-world conditions. Most existing research focuses on controlled laboratory tests, but there is limited data on how slag-based asphalt mixture holds up on actual roads in different climates and traffic conditions. Questions around long-term durability, maintenance costs, and environmental impact still need thorough investigation. Additionally, fine-tuning slag processing techniques could help ensure more uniform quality, making these materials more appealing to asphalt producers. Filling these gaps is not just about advancing research – it is about providing the industry with the confidence and practical knowledge needed to make metallurgical slags a mainstream, sustainable solution for road construction.

3 Test program

The first step of the test program was to assess the properties of two types of slags (based on their quality) – crushed BFS and CS – which could be considered aggregates for asphalt concrete pavement layers. Physical tests have shown that both types of slag can be used in base and binding layers. For the application in wearing courses, the CS can be used (Table 1).

A fundamental objective in developing the test program was to compare the properties of asphalt mixtures made from slags with those of mixtures made from natural aggregates with similar rock physical properties. To this end, it was also required that the mixtures to be compared should have nearly the same particle size distribution, the same void content characteristics and the same bitumen quality (B 50/70). This was achieved by trial during the mix design phase by varying the additive composition and the amount of fillers and bitumen content. All mixtures were designed for increased loading circumstances. Basalt and lower-grade andesite were chosen as reference additives for the test series. The former was used as a reference aggregate for the CS mixture, and the latter for the BFS mixture. Using these materials, the mixtures, according to Table 2, were created. During the tests, it was a basic requirement that all the mixtures comply with the requirements of the technical specification ÚT 2-3.301:2002 (Ministry of Transport and Water Management, 2002), i.e., the suitability criteria for the field of application. In addition to the suitability tests (CEN, 2003b), the properties of the mixtures (CEN, 2003a; 2003c; 2006a; 2006b; 2007; 2008a; 2008b; 2008c; 2009) were also compared using the results of (additional) tests carried out in parallel. Due to the high volume of material requirements for the tests, comparative tests were performed on Marshall specimens. A subset of the samples was placed in a climatic chamber and subjected to 10 cycles of "thermal stress" between –20 °C and +40 °C. This frost-thaw procedure was also performed with underwater storage and air storage. The effect of the treatment was expected to determine the sensitivity of each mixture to a property through the results of the target tests due to the possible specific (combined) behavior of bitumen and different aggregates, which age differently in the mixtures. The study also provided the opportunity to determine the property changes of a single mixture under the effect of 'thermal stress'. The basis for comparison was provided by the tensile tear strength (ITS), dynamic creep, and stiffness (IT-CY) tests.

4 Results and discussion

The mix design process was carried out according to the road technical specification e-UT 05.02.11 (ÚT 2-3.301:2002) (Ministry of Transport and Water Management, 2002). Two types of mixes were produced in the laboratory to test the suitability of the slag asphalt. AC-11 wearing course (F) and AC-32 base course (F) slag asphalt mixtures were produced with B 50/70 grade bitumen. To ensure basic comparability, additional asphalt mixtures were also prepared with basalt for both types and andesite for the AC-32 base (F) type. The aggregate mixes designed with the same grain size distribution had to be slightly modified to ensure almost identical void characteristics of the mixtures due to the different flakiness indexes of particles per material type. However, in all cases, the grain size distribution characteristics met the requirements of the mix design (Table 2).

Additional suitability characteristics for mixtures meeting the requirements for grain structure and void properties were also determined. The water sensitivity test results are shown in Fig. 1.

Table 1 Rock physical properties and requirements of the tested BFS and CS based on ÚT 2-3.301:2002 (Ministry of Transport and Water Management, 2002)*

Type of layer	Normal load (N)				Increased load (F)			
	LA (%)	MDE (%)	MS (%)	PSV	LA (%)	MDE (%)	MS (%)	PSV
Wearing course	≤ 25	≤ 20	≤ 18	≥ 50	≤ 20	≤ 15	≤ 18	≥ 50
Bonding layer	≤ 30	≤ 20	≤ 25	–	≤ 25	≤ 20	≤ 25	–
Base layer	≤ 40	≤ 25	≤ 25	–	≤ 25	≤ 20	≤ 25	–
Characteristic values of CS	10–12	6–8	1–2	50	10–12	6–8	1–2	50
Characteristic values of BFS	33–35	22–25	2	60	33–35	22–25	2	60

* In Table 1 LA is the Los Angeles abrasion, i.e., resistance to fragmentation; MDE is the Micro-Deval abrasion, i.e., resistance to wear; MS is the magnesium sulfate soundness; PSV is the Polished Stone Value (PSV is a unitless parameter (i.e., [–]))

Table 2 Characteristics of the compared mixtures

Number/type of mixture	I-AC-32 (BFS)	II-AC-32 andesite	IV-AC-32-CS	VI-AC-32 basalt	III-AC-11-CS	V-AC-11-basalt
Type of aggregates	BFS	Andesite	CS	Basalt	CS	Basalt
Bitumen content (%)	5.92	5.40	5.92	5.45	5.65	5.66
Marshall test density (mg/m³)	2.39	2.349	2.697	2.382	2.478	2.361
Density without void (mg/m³)	2.509	2.459	2.828	2.519	2.585	2,.443
Void (v%) (3–6%; 2.5–4.5%)	4.74	4.47	4.63	5.43	4.14	3.36
1 m³ composition of compacted asphalt mix						
Bitumen content (kg/m³)	141	127	160	130	140	134
Filler (limestone) (kg/m³)	90	89	101	113	187	178
Mass of aggregates (kg/m³)	2,159	2,133	2,436	2,140	2,151	2,049

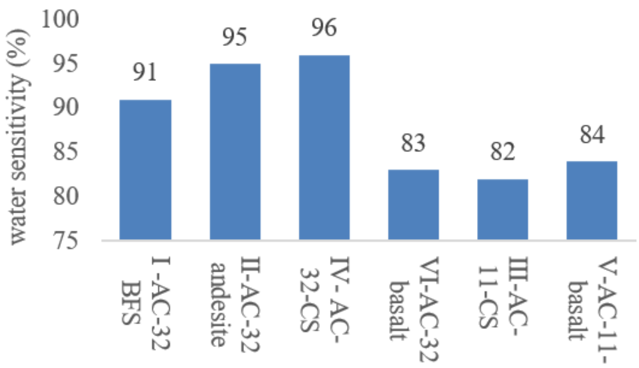

Fig. 1 Water sensitivity (ITSR) values of reference and slag asphalts

The results show that all mixtures met the conditions of use. The residual deformation characteristics were tested according to method B of the EN 12697-22:2003+A1:2007 standard (CEN, 2007), small wheel at +60 °C. In the technical specification for roads, the maximum allowable permanent deformation rate for both AC-11 wearing (F) and AC-32 base (F) asphalts was *P* = 7.0% using normal bitumen. The results of the tests are presented in Fig. 2. The results show the suitability of all mixtures in this respect.

Road Technical Specification e-UT 05.02.11 (ÚT 2-3.301:2002) (Ministry of Transport and Water Management, 2002) does not impose any requirements on the stiffness and fatigue properties of asphalt mixtures for

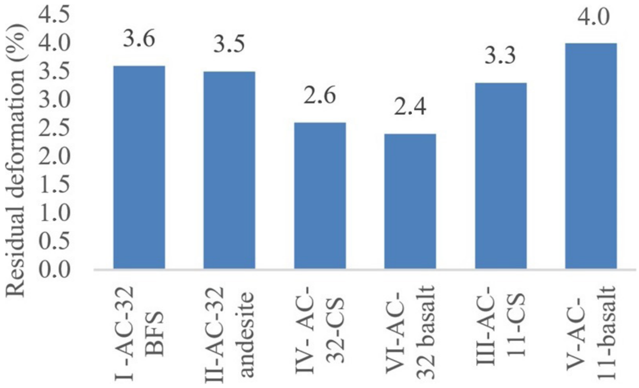

Fig. 2 Residual deformation of reference and slag asphalts

these types of mixes, but it does make it mandatory to specify their values. The stiffnesses are measured according to the IT-CY method of the EN 12697-26:2018+A1:2022 standard (CEN, 2022). The results are summarized in Fig. 3.

The results show that of the AC-11 wearing (F) type asphalt mixes, the mix with the CS showed roughly 11% higher stiffness. For the AC-32 base (F) asphalt mixes, both slag-asphalts, especially the CS mix, had higher stiffness modulus than the andesite and basalt mixes. The fatigue properties of the mixtures were not determined in this series of tests.

Examining the characteristics of the asphalt mixtures prepared according to e-UT 05.02.11 (ÚT 2-3.301:2002) (Ministry of Transport and Water Management, 2002), it can be stated that the asphalt mixtures prepared with the CS and the BFS mineral skeleton met the application conditions in all cases. They showed similar but generally better (IT-CY stiffness, residual deformation) performance in the parameters tested. The use of CS and BFS is recommended in AC-11 wearing (F) and AC-32 base (F) asphalt mixes with the appropriate mix design and the use of additional additives/limestone filler.

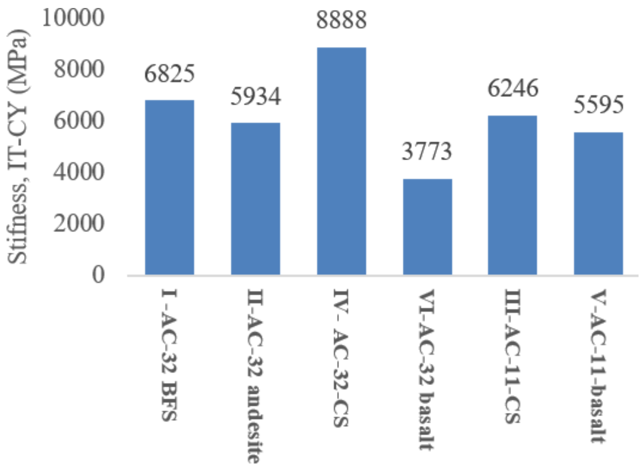

Fig. 3 Asphalt stiffness according to the IT-CY method based on CEN (2022)

For a detailed performance study, all Marshall test specimens of the mixtures were subjected to a comprehensive – parallel – test. The properties tested were also carried out after the specimens had been prepared and on specimens that had been subjected to 'heat loading'. The "wet" and "air" thermal shocks were expected to affect the mechanical properties of the specimens differently, in a negative direction. The comparison of the specific effect of this negative variation on the mixtures provided an opportunity to determine the performance of the slag mixture (compared to conventional mixtures from crushed stone).

In the first step, the specimens were compared in terms of their tensile and splitting strength, i.e., ITS. Fig. 4 shows the treatment-dependent values of the ITS values in MPa per mix. Fig. 4 also shows that both AC-32 (F) and AC-11 (F) mixtures have the highest ITS values per treatment group for the mixtures made from CS. The negative effect of "heat loading" on strength also shows a trend, with the worst results being observed for specimens frozen in water. The proportion of strength differences per treatment group compared to the basaltic mixture treated as a reference. Both the "air" and "water" heat loads were investigated, and a further increase in the difference between the slag and basalt mixes was observed in favor of the slag mixes. This suggests that the effect of "heat loading" on slags is less pronounced in terms of ITS value, i.e., they are less susceptible to a reduction in splitting strength.

Residual deformation is significant due to the traffic loads experienced today, and the sensitivity of the mixtures to this property was investigated by further measurements. Since the wheel track test requires a significant amount of asphalt mix, which is quite labor-intensive to produce in the laboratory for such a large number of samples, the residual deformation susceptibility was analyzed by performing the dynamic creep test according to the withdrawn Road Regulation No. ÚT 2-3.301:2002 (Ministry of Transport and Water Management, 2002). The advantage of this method is that the test can be performed on Marshall specimens, thus requiring orders of magnitude less material compared to the wheel track test, and the measurement reliability is outstanding. Given that the analysis concentrated on the values of each property relative to a reference mix, the test was considered suitable for comparing the performance of mixes. In addition to the standard 40,000 pulse load, the specific strain values of the mixtures were determined at two (80,000) and three times (120,000) higher pulse loads. The results have provided the opportunity for a more comprehensive analysis of the deformation susceptibility of mixtures. The aggregated results are presented in Fig. 5. Test results for specimens subjected to "thermal loading" are also shown in Fig. 5 so that the sensitivity of the mixtures to this loading can be determined.

The results of the 40,000 pulse test, i.e., the test carried out according to the withdrawn standard, No. ÚT 2-3.301:2002 (Ministry of Transport and Water Management, 2002) show that there is no significant difference in specific deformation between the mixtures. Unfortunately, the test specimen(s) made from the basaltic AC-32 mixture used as a reference could not be tested due to a sample preparation error, and thus, its duplicate and triplicate test results are also missing. However, the test results for the 'heat-loaded' specimens were available for all mixtures, so a comparison of the results was possible. It can be seen that the specific deformations increase proportionally as expected under the double and triple loading. The plot of the 'heat-loaded' specimens shows that the CS mixture had the lowest deformation.

The stiffness of asphalt mixes is a key determinant of the performance of the mixes. All mixtures were tested in

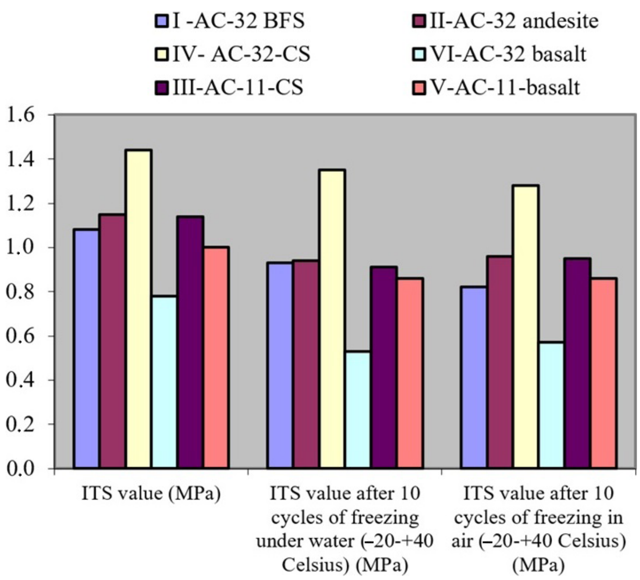

Fig. 4 Treatment-dependent values of ITS per mixture (tested at 20 °C)

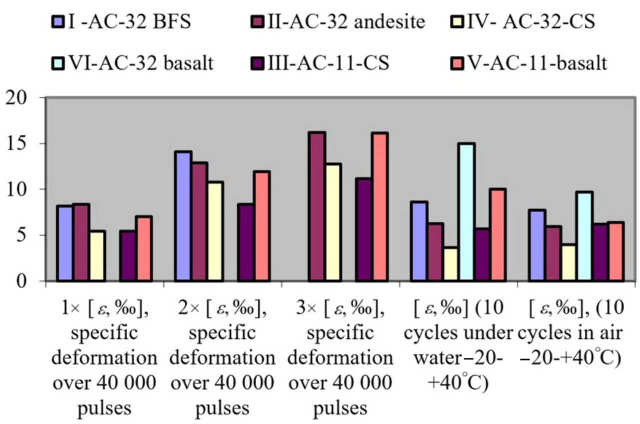

Fig. 5 Results of the dynamic creep test

all conditions ("no heat load", "heat load in air", "heat load in water"). The aim was to assess the changes in stiffness of the mixtures in relation to each other and to the "treatment". It is important to mention that the specification of ÚT 2-3.301:2002 (Ministry of Transport and Water Management, 2002) contains a requirement for stiffness only for polymer-modified binder mixtures, which is set at a minimum of 7,000 MPa. In the current case, no bonding layer mix was tested, and the bitumen used was normal bitumen without modification. The stiffness results are shown in Fig. 6.

The results show that the AC-11 (F) mixes have almost the same stiffness regardless of the "treatment", but the slag mix has a slightly higher stiffness. Among the base course mixes, the stiffness of the BFS and andesite mixes are close, with the basalt mix having the lowest value and the CS mix having the highest. It is important to note that the stiffness limit of 7,000 MPa for bonding layers is met only by the AC-32 mix with CS, so its use in bonding layers subject to high stresses is also an option. From Fig. 6, it can be observed that the "heat loading" of AC-32 (F) mixtures led to a decrease in stiffness for BFS and an increase in stiffness for CS. For andesitic and basaltic mixtures, the trend was different from the others, with the highest stiffness values for specimens subjected to "air heat loading" and the lowest values for "water heat loading". For the AC-11 (F) wear layer mixtures, both the magnitude of the stiffness values and the trend in stiffness change due to "thermal loading" were almost identical.

The reason for the increase in stiffness of the AC-32 CS mix due to "thermal loading", which differs from other mixes, was first assumed to be due to the increased aging of the bitumen due to thermal aging. In order to find out the cause of this phenomenon, bitumens were reclaimed from the specimens subjected to the ‚heat load' and tested, and their softening point, penetration and fracture point were determined. The characteristics of the bitumens reclaimed from each mixture were compared with those of the initial bitumen and those of the bitumen aged by the RTFOT method (Fig. 7).

Fig. 7 clearly shows that the bitumen properties reclaimed from basaltic and andesitic mixtures (subjected to thermal aging) are almost identical to those of bitumen aged by RTFOT. It can, therefore, be concluded that the aging effect of the thermal aging (on Marshall specimens) used is almost equivalent to that of the RTFOT method. However, it can also be observed that the bitumen properties reclaimed from the slag mixtures did not change significantly in practice as a result of the thermal aging compared to the bitumen properties without aging, i.e., the initial bitumen properties. This implies that the mineral composition of the aggregates used in the mixtures is related to the aging rate of the bitumen used in the mixture, which is significantly slowed down in the slag mixtures, as explained in the literature by the basic (pH = 8…10) characteristics of the slags. The use of slags from Dunaújváros in asphalt mixtures, therefore, has a positive effect on both the bitumen properties of the mixtures and their change over time.

5 Conclusions

During previous research at the Institute for Transport Sciences, the authors reviewed the national and international literature on the use of metallurgical slags in the asphalt industry. They found that the experience of the types of slags studied in Dunaújváros is very positive.

Thanks to the emergence of EN product standards and the production control system (certified) introduced and operated by ISD Dunaferr Zrt. in the 2010s, both the

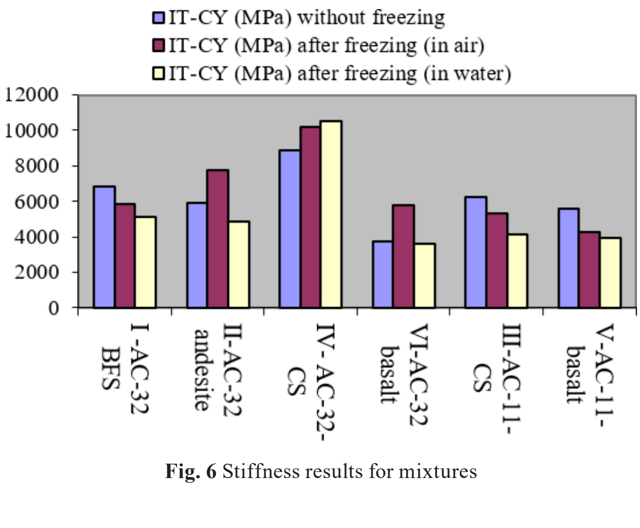

Fig. 6 Stiffness results for mixtures

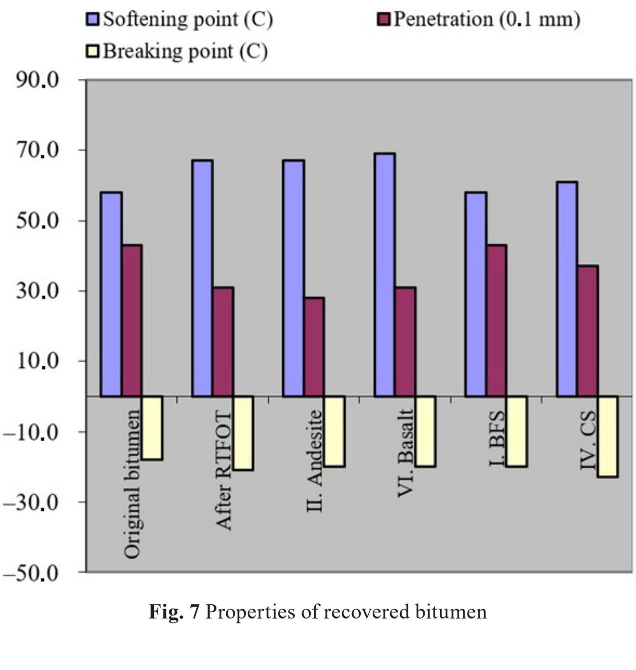

Fig. 7 Properties of recovered bitumen

necessary regulatory background and homogeneous quality have been ensured.

The SNAP-SEE project (SNAP-SEE, online) showed that even in the optimal case, 10–20% of the mineral raw material demand in the construction industry could be met by secondary raw materials, which means that the supply of mineral raw materials for construction will continue to rely on primary raw materials for a significant part of its supply, 80–90%, which could increase from the current 6 t/person/year to 9–12 t/person/year in the medium term, thus showing an increasing trend. Meeting the raw material needs of the asphalt industry has become increasingly difficult in recent years, with typically 3 to 5 mines per mixing plant available to meet the needs of asphalt producers and difficulties in sourcing raw materials for many years. This supply difficulty could also be alleviated by, among other things, the use of these metallurgical slag products.

In the experiments, all properties of the asphalt mixtures made from the slags were compared with those of the andesite and basalt asphalt mixtures treated as reference mixtures. This allowed the performance of the slag asphalts to be compared with that of conventional aggregate mixes. All mixtures met the design requirements according to the road specification ÚT 2-3.301:2002 (Ministry of Transport and Water Management, 2002). A special series of tests were then carried out to assess the changes in properties of the asphalt mixtures under significant "thermal stress", with reference to the expected development of durability. The same change values for the slag mixtures AC-11 (F) and AC-32 (F) were determined in relation to the change in some properties of the basaltic and andesitic asphalt mixtures treated as reference mixtures. Based on these results and the results of the type test, it was concluded that both BFS and CS are particularly suitable as additives for asphalt layers. Equivalent or better performance compared to the reference mixes was demonstrated.

Overall, it can be concluded that mixtures made from slag have almost the same performance as mixtures made from natural crushed stones. Asphalt mixtures made from slags have a number of advantageous properties:

- Environmental aspects (possibility to reduce CO_2 emissions, less use of the natural environment, saving primary raw material resources).
- Favorable friction and skid resistance (traffic safety) characteristics.
- Better rolling noise (based on international application experience).
- Favorable logistical conditions – within ~30–50 km of Dunaújváros.
- The basicity of slags has a positive effect on the aging of bitumens and, thus, on the life of the mixtures/layers, as well as on the expected maintenance costs over the whole life cycle.
- Slag mixes offer better stiffness properties than crushed stones, which can be exploited both in terms of lifetime and cost.
- Raw material shortages in asphalt production can be reduced.

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