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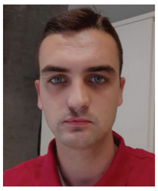
Prevention and remediation measures for reflective cracks in flexible pavements

Authors:



Matija Zvonarić, MCE
University of Josip Jurj Strossmayer in Osijek
Faculty od Civil Engineering and Architecture Osijek
mzvonaric@gfos.hr
Corresponding author

Prof.. **Sanja Dimter**, PhD. CE
University of Josip Jurj Strossmayer in Osijek
Faculty od Civil Engineering and Architecture Osijek
sdimter@gfos.hr

Subject review

Matija Zvonarić, Sanja Dimter

Prevention and remediation measures for reflective cracks in flexible pavements

Considering the high price and the number of natural resources used in transport infrastructure, extending pavement lifetime is a priority for engineers. One of the most common issues in flexible pavement maintenance are reflective cracks, which reduce driving comfort and passenger safety. These cracks have two main origins, those initiated by shrinkage of the cement stabilized layer and the cracks reflected from the old pavement to a new overlay. During road maintenance, the usual remediation measure is to overlay and place a new asphalt wearing course over the old, deteriorated pavement surface. After an asphalt overlay is placed on the deteriorated pavement, the overlay can exhibit an identical crack pattern as the layer below. The main cause of reflective cracks is in the cement bound base course (CBC). Due to cement hydration, traffic load, and temperature oscillations, cracks may occur and propagate through upper layers. Much research has been conducted to prevent this problem. Some research, with an emphasis on recycled materials, is presented in this paper. The remediation measures include thin and thick interlayers and modification of the asphalt overlay characteristics.

Key words:
cement bound base course, recycled materials, reflective cracks, thick interlayer, thin interlayer

Pregledni rad

Matija Zvonarić, Sanja Dimter

Mjere prevencije i sanacije reflektirajućih pukotina u savitljivim kolnicima

S obzirom na visoku cijenu i količinu prirodnih resursa koji se koriste u prometnoj infrastrukturi, produljenje uporabljivosti kolničkih konstrukcija prioritet je za inženjere. Jedan od najvećih izazova u održavanju savitljivih kolničkih konstrukcija je sprječavanje pojave reflektirajućih pukotina koje smanjuju udobnost i sigurnost vožnje. Reflektirajuće pukotine se prema načinu nastanka dijele na pukotine nastale kao posljedica skupljanja cementom stabiliziranog nosivog sloja i pukotine "reflektirajuće" sa starog kolnika na novu asfaltnu prevlaku. Tijekom održavanja kolnika, najčešće mjere sanacije su izvođenje asfaltne prevlake preko starog, istrošenog habajućeg sloja kolnika. Nakon postavljanja novog asfaltnog sloja preko starog kolnika, asfaltna prevlaka može razviti pukotine identičnog uzorka kao na sloju ispod. Osnovni uzrok nastanka reflektirajućih pukotina je u cementom stabiliziranom nosivom sloju, u kojem tijekom hidratacije cementa, a uslijed prometnog opterećenja i temperaturnih oscilacija, mogu nastati pukotine i proširiti se na gornje slojeve. Brojna su istraživanja provedena u svrhu sprječavanja pojave i širenja reflektirajućih pukotina, a neka od njih provedena na recikliranim materijalima, opisana su u ovom radu. Osim toga, opisana je sanacija reflektirajućih pukotina koja uključuje izvođenje tanjih i debljih asfaltnih međuslojeva te neki od načina kojima je moguće modificirati svojstva asfaltnih mješavina za prevlake u svrhu poboljšanja njihove otpornosti na pojavu reflektirajućih pukotina.

Ključne riječi:
cementom stabilizirani nosivi sloj, reflektirajuće pukotine, reciklirani materijali, međuslojevi

1. Introduction

It is well known that asphalt pavements are usually designed for a 20-year life span. The design life span is the time in which a road can be fully exploited with optimum maintenance. After this period, pavement structure can be repaired relatively easily [1]. Good maintenance is a very important factor that increases the life expectancy of the road and enables smooth and safe operation of traffic. Significant funds are allocated for road maintenance. However, with an increase in traffic load, impact of weather conditions, and untimely or unprofessional maintenance, the pavement structure is bound to deteriorate prematurely. Consequently, surface deformation reduces driving comfort and safety. When reconstruction is not an option, engineers resort to pavement remediation measures. The most commonly used rehabilitation measure for deteriorated pavements is the placement of asphalt (bituminous) overlays [2, 3]. The experience has shown that, due to varying weather conditions, the existing cracks on the old pavement [4] quickly propagate through the overlay. This can best be observed in the spring when, due to elevated temperatures, ice lenses in previously deteriorated pavement melt. As a consequence of this phenomenon, the bearing capacity reduces significantly. This phenomenon is called "reflective cracking". It can be observed when an overlay assumes an identical crack pattern as the layer below [5]. The reflective cracks can be observed after overlaying the existing deteriorated pavement. However, cracks in the original asphalt course that are reflected from below the positioned cement bound base course (CBC) are also called reflective cracks.

Natural materials such as the quality stone material and a certain quantity of bituminous binders, necessitating consumption of large amounts of energy, are used for overlay construction. From an environmental point of view, the use of natural materials and energy consumption should be reduced.

Reflective cracks have been the subject of many research endeavours. The cracks originate from cement treated layers. After installation, the CBC goes through an initial setting time. During this period, the cement hydrates with water molecules and forms bonds between the cement paste and aggregate particles. During the hardening process, the cement paste tends to shrink, thus producing tensile stresses. Cracks begin to appear when these tensile stresses exceed the tensile strength of the mixture. Furthermore, due to dynamic traffic load, the stress concentration occurs in the cracking zone as there is no material to assume these stresses. Such concentrated stresses are transferred to the upper layer where they also initiate formation of cracks. In the described manner, the cracks spread through the layers all the way to the road surface. When a vehicle wheel passes over a crack, it depresses one side of the crack with its weight, which causes shear stress on the contact surface of the crack. The traffic load has the greatest impact on crack formation and propagation [1]. These cracks are also affected by temperature oscillations, which produce thermal expansion and contraction in the CBC. Cracks that occur as a result of cement hydration also tend to expand under cyclic traffic load and temperature oscillations. In addition, subgrade behaviour can significantly contribute to crack occurrence due to swelling and shrinkage induced by temperature and moisture changes in the foundation soil, which is especially evident in the case of a low bearing capacity soil [6]. Wang et al. [7] claim that the initial crack length has a major influence on crack propagation under temperature oscillations. They also conclude that a greater inclination of the initial crack reduces propagation velocity because of the force projection on the existing crack. The largest tensile strains concentrate around a vertical crack. With the combination of traffic load and thermal stresses, the mechanism of crack propagation becomes highly unpredictable. These cracks reflect to the asphalt pavement and allow water to infiltrate into all pavement layers. Under freezing weather conditions, the infiltrated water forms ice lenses that further disrupt the structure of the mixture. These cracks can also propagate downward, which causes another negative effect: pumping material from below. The effect of pumping can disrupt the bearing capacity of the soil. In 1993, the RILEM Conference [3] adopted remediation proposals that were divided into four groups:

- anti-reflective cracking measures
- interlayer between the old and new overlay
- modification of overlay characteristics
- temperature limitations to the use of fibres in asphalt overlaying.

Noori et al. [8] also summarized and ranked the most practical reflective cracking mitigation methods. The first method is the modification of the existing pavement surface. The second one is the treatment of the existing pavement. The third is the installation of interlayer systems, and the fourth method involves reinforcement of the asphalt overlay. When speaking of reflective crack prevention, we mean preventing cracks in bottom layers and adopting measures to prevent reflection of the existing cracks from the old pavement to a new asphalt overlay. This paper describes the latest research on all remediation measures with an emphasis on measures for preventing crack formation in the cement stabilized layer. This is in accordance with the assertion that cracks can be avoided or delayed with a thorough understanding of their underlying mechanisms [9]. The authors [9] point out this measure as a more responsible approach, compared to the approach that allows occurrence of cracks and their subsequent remediation.

2. Anti – reflective cracking measures

Despite benefits of the cement bound base course such as its roughness and high strength support for the upper pavement layers, it also has some disadvantages, one of them being shrinkage due to cement hydration and temperature differences [10]. Drying shrinkage is closely related to the curing regime, pore size distribution, thermodynamic behaviour of water, and morphology of hydrate solids. There are four mechanisms for the formation of internal stresses in mixtures: changes in the surface free energy (the Gibbs - Bangham effect), capillary tension, disjoining pressure, and interlayer water movement from C-S-H gel [11]. Many research activities have so far been conducted to maximise benefits of the cement bound base course and to reduce to minimum its disadvantages. These activities are based on examining the applicability of waste and recycled materials in pavement construction, which is beneficial from both financial and environmental points of view. The position of the cement bound base course in pavement structure is shown in Figure 1.

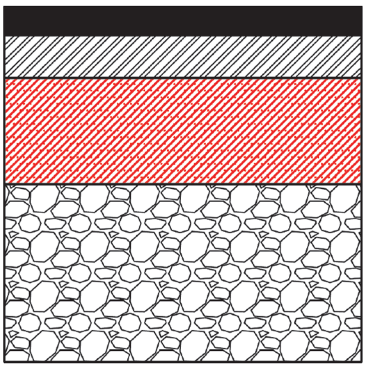


Figure 1. Position of cement bound base course in pavement structure

2.1. Steel slag

Steel slag is a by-product of steel production, and its use in construction is justified from both environmental and financial standpoints, especially in regions with a developed steel industry. Liu et al. [12] investigated the use of steel slag in the cement bound base course with limestone in terms of its mechanical properties, strength, stiffness, durability, and shrinkage, and its anti-freezing and anti-scouring characteristics. They concluded that steel slag has an inhibitive effect on drying shrinkage. In addition, it is economical and environmentally safe. High water absorption capability of steel slag induces an increase in optimum moisture content (OMC) and maximum dry density (MDD), while negatively affecting strength and rigidity. Fifty percent has been determined as the maximum replacement value for steel slag. Li et al. [13] examined the possibility of replacing macadam with waste steel slag of fine, intermediate, and coarse gradations based on the drying and temperature shrinkage and water loss results. Authors concluded that, by using the coarse steel slag, the new material achieves smaller dry shrinkage strain compared to the cement stabilized macadam. Barišić et al. [14, 15] discovered that steel slag contributes to an increase in compressive strength and dynamic modulus of elasticity in mixtures where gravel is partly replaced with steel slag. Furthermore, a steel slag mixture has a higher compressive strength and a higher dynamic modulus of elasticity under freezing or thawing conditions than stabilized gravel, which is the result of the rough surface of steel slag, contributing to stronger bonding in the interfacial transition zone (ITZ). Pasetto and Baldo [16] combined steel slag with four different recycled aggregates (ladle slag, foundry sand, glass waste, and coal ash) and designed an appropriate recipe for the cement bound base course (CBC) mixture. They examined toxicological, physical, and mechanical characteristics and emphasized the importance of examining toxicological properties of industrial by-products when incorporated in a pavement structure.

2.2. Fly ash

Fly ash is one of the first waste materials to be used in pavement structures, that is, in hydraulically bound base courses. The coal fly ash (CFA) is produced by the combustion of coal in thermal power plants. Contrary to the previously described steel slag, CFA has been investigated as binder due to its pozzolanic characteristics. Large amounts of fly ash are produced in power plants (CFA) or by incineration of municipal solid waste (MFA). When using CFA as binder in a stabilizing mixture, one must be cognizant of three types of ash: fly ash, bottom ash, and their mixture called pond ash. All three types of ash differ in pozzolanic characteristics, which are dependent on their origin. Based on previously conducted research, Jose et al. [17] investigated the possibility of applying pond ash in combination with cement. They determined the dependence of hydration reactions on the coal pond ash to cement ratio, temperature, and curing period. Fly ash from the municipal solid waste (MFA) has been used as an additive to cement in the amounts of 5 % and 10 %, as described in paper [18]. This research showed that the unconfined compressive strength (UCS), cohesion, and the internal friction angle of cement stabilized mixture with the addition of fly ash, actually increase with an increase in the cement and fly ash content, and with an increase in the curing period. 10 % of pond fly ash as a replacement for 5 % of Portland cement was pointed out as an improving boundary for UCS. Pond fly ash also promotes hydration reaction quite effectively. The final report of the Action [19] states that fly ash can retard hydration, but also that it can ultimately develop compressive strength as high as that of cement. The evolution of tensile strength as a function of time is shown in Figure 2 for various types of binder agents. Dimter et al. [20] investigated how the compressive and indirect tensile strength of stabilized sand mixtures is affected by various gradations of CFA and cement in binders, by different temperatures, and by different curing periods. The authors concluded that up to 25 % of cement in binder can be replaced by CFA. They also emphasized that slow hydration of CFA in combination with cement reduces the tendency of the layers to crack. In further research on the same mixture, the authors [21] used two nondestructive methods for the determination of the dynamic modulus of elasticity: the resonant frequency method and the ultrasonic pulse velocity method. A strong relationship between these two methods was observed. They concluded that higher modulus-of-elasticity values are achieved at lower curing temperatures and that fly ash has direct impact on modulus.

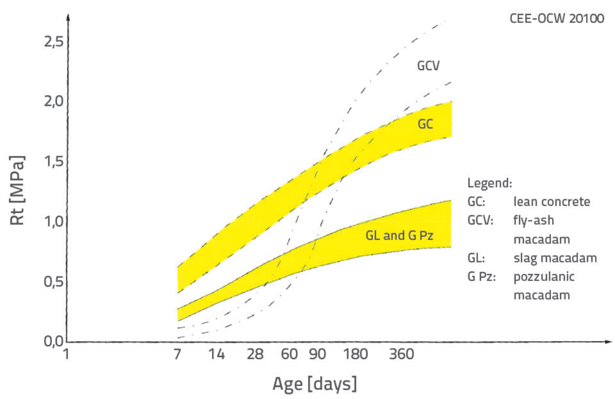


Figure 2. Evolution of the tensile strength Rt in function of time [19]

Zhang et al. [22] investigated the contribution of fly ash to the freeze - thaw resistance of loess soil. Loess soil was stabilized with the cement containing 10 %, 15 % and 20 % of fly ash. Their conclusion was that fly ash in the amounts of >15 % improves the freeze - thaw resistance of loess soil compared to pure loess soil. However, lower amounts of fly ash do not bring significant improvement. Tran et al. [11] approved the use of pozzolanic materials as a partial replacement for cement. They pointed out that unreacted pozzolan particles can serve as filler in a microstructure.

2.3. Recycled rubber

Thanks to its elasticity, recycled rubber is another material that can contribute to the prevention of cracks by inclusion in the CBC mixture. Farhan et al. [23] explored mechanical characteristics of rubberized limestone stabilized with Portland cement. The MDD is negatively affected by the incorporation of rubber. Based on compacity calculation, they concluded that MDD is not affected by the low specific gravity of rubber only, but also by the reduction of compaction efficiency as a result of damping action of rubber particles. The indirect tensile strength (ITS) testing showed that the ITS decreases by 3 % with an increase in rubber content by 1 %. Based on crack observation, they assumed that cracks propagate through rubber particles that absorb energy and may lengthen the path of a crack. In further research, the same authors [24] showed the difference between the reduction of compressive strength and tensile strength of rubberized mixtures. Specifically, the compressive strength showed higher reduction compared to the tensile strength of rubberized mixtures. By studying distribution of rubber, uniform vertical and radial distributions were observed in the mixtures with a lower rubber content. On the other hand, the mixtures with higher rubber content were characterized by greater variability, which caused a decrease in the UCS and ITS values. Liu et al. [25] proved that shrinkage strain decreases when a certain volume of fine aggregate particles is replaced with rubber particles. The addition of rubber generally contributes to the deterioration of mechanical characteristics, namely the compressive strength, flexural strength, and modulus of elasticity, which is a result of bond defects between the cement matrix and rubber particles. Pham et al. [26] examined the effect of a binder additive (copolymer) on rubber particles in an aggressive environment. They concluded that the additive enhanced the bonding effect and had a positive influence on pavement durability. The same authors [27] also stated that the addition of rubber improves the freeze-thaw resistance of the mixture when compared to the control mixture. Another conclusion was also highlighted: the coating additive leads to a slight increase in specimen length.

2.4. Recycled asphalt pavement (RAP)

The addition of recycled asphalt layers, which are formed during reconstruction of asphalt pavements, was also investigated with regard to the production of mixtures for stabilized layers. Such materials could be combined in the pavement as a base layer. Kasu et al. [28] investigated the content of recycled asphalt, virgin aggregate, and cement in cement bound mixtures. The authors stated that an optimum ratio of recycled asphalt to virgin aggregate is 30 to 70 percent. They also stated that the recycled asphalt modified mixtures achieve higher ductility despite lower dynamic modulus values. The durability and UCS values decrease with an increase in RAP content, which can be attributed to the hydrophobic nature of bitumen because weaker bonds are formed in ITZ. Likewise, Isola et al. [29] concluded that mixtures with 70 % of the reclaimed asphalt pavement (RAP) satisfy the requirements for use in pavement structures. They first conducted laboratory tests to determine an appropriate recycled asphalt mixture. The mixtures contained 30 and 70 percent of RAP. Afterwards, a trial section was built using a traditional mixture and RAP mixture with different subbase conditions. The trial section was then opened to traffic and the situation was continuously monitored for 15 months. At the end of this period, the mixture with 70 % of RAP exhibited better stiffness when compared to other mixtures. The results obtained were based on well-known test methods: Lightweight Deflectometer, Falling Weight Deflectometer, and Ground Penetrating Radar. Furthermore, Tataranni et al. [30] carried out laboratory and in situ tests under traffic load to study applicability of the recycled asphalt pavement with the addition of waste tiles and crushed concrete. The results obtained by testing mechanical properties of modified mixtures were lower compared to those of the virgin mixture.

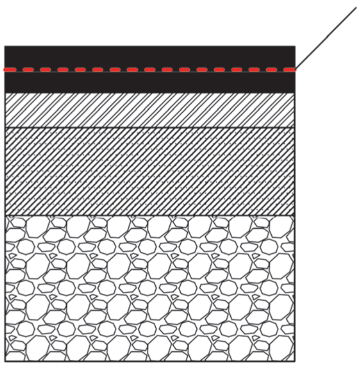
Table 1. The effect of various waste materials on CBC mixture properties

Material	Authors	Effect
Steel slag	Liu et al [12] Li et al [13] Barišić et al [14, 15] Passeto i Baldo [16]	Inhibitive effect on drying shrinkage Higher compressive strength and dynamic moduli of elasticity Better resistance to freeze – thaw cycles Stronger bonds in ITZ Up to 50 % replacement of natural aggregates Detrimental effect on rigidity Toxicological by-products
Fly ash	Liang et al [18] Development of New Bituminous Pavement Design Method [19] Dimter et al [20, 21] Zhang et al [22]	Higher unconfined compressive strength, tensile strength, modulus of elasticity Slower hydration Up to 25 % binder replacement Better performance at lower curing temperatures Improved freeze – thaw resistance Heavy metal release
Recycled rubber	Farhan et al [23, 24] Liu et al [25] Pham et al [26, 27]	Deterioration of mechanical characteristics Lengthened crack path Decrease of shrinkage strain Improved durability in combination with copolymer Improved freeze – thaw resistance
Recycled asphalt pavement	Kasu et al [28] Isola et al [29] Tataranni et al [30]	Up to 70 % replacement Ability to combine with other recycled materials

The mixture with crushed concrete exhibited higher stiffness, while the stiffness exhibited by the other mixture was lower. The main intent of this approach is to prevent the occurrence of the cracks induced by shrinkage due to hydraulic reaction in the CBC, which spread due to cyclic traffic load, temperature oscillations, and lens formation under freezing and thawing conditions. The effects of all these materials on CBC mixtures are summarized in Table 1.

3. Interlayer between old and new overlay and overlay reinforcement

An overlay is often applied as a measure for the remediation of deteriorated pavements. Asphalt overlays provide a roughness surface ensuring comfortable and safe ride. But a problem arises when an old pavement damage starts to reflect on the newly placed overlay. Figure 3.a) shows the position of an interlayer whose main purpose is to strengthen the bond between the lower and upper layers and to reduce propagation of cracks to the upper layer. To prevent an upward propagation of cracks, some anti-reflective crack measures have been investigated. According to Francken [31], interlayers can be divided into thin and thick interlayers. Thin interlayers differ by their stiffness. Low-stiffness interlayers do not strengthen the pavement but assume a significant role in reducing stress concentration (Stress Absorbing Membrane Interlayer or SAMI). Such interlayers are made of non-woven geosynthetics. Unlike low stiffness interlayers, very stiff interlayers are best suited for strengthening. Suitable materials for these interlayers are grids and woven fabrics. Thin interlayers can be regarded as a two-dimensional material. In contrast, thick interlayers are three-dimensional. Wang et al. [32] evaluated three different types of tack coats: hot bitumen cement, cutback bitumen, and bitumen emulsion (the most common tack coat). The emulsified bitumen is easy to handle, and it is energy efficient, environmentally friendly, and safe for personnel. The shear strength testing is a common tack coat evaluation procedure. This strength is influenced by temperature, e.g., an increase in temperature causes a decrease in shear strength. Proper flowability is also an important factor which, in combination with proper viscosity, contributes to an increase in shear strength between the tack coat and asphalt layers [33]. These conclusions were made by examining, via shear testing, the coefficient of interface bond on two types of emulsified asphalt tack coats. Wang and Zhong [34] proved that a decrease in the tack coat modulus contributes to the resistance of asphalt pavements to reflective cracking. They also pointed to the temperature sensitivity of the tack coat. Geotextiles and geogrids used in interlayers are placed in combination with bituminous materials to ensure proper bonding between layers. Geofabrics tend to reduce the peak stress value at the contact between the two materials. In addition, when combined with a sealing material with waterproofing characteristics, geotextiles protect cement bound layers from water leakage and detrimental effects of freezing and thawing [35]. Zamora Barraza et al. [36]



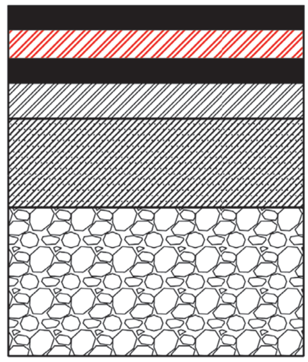


Figure 3. Position of interlayer in pavement structure a) Thin interlayer; b) Thick interlayer

examined the influence of geotextiles, geogrids, and SAMI on the development of reflective cracks. Six anti-reflective cracking systems were analysed in a dynamic test, which simulated fissure movements due to traffic load. The results showed a delayed appearance of reflective cracking in all specimens subjected to this testing. Geogrids have also proven to be the best modification and it is dependent on the geogrid modulus, stiffness, and cross-section. Walubita et al. [37] demonstrated by in situ testing that the use of geogrids for overlay reinforcement is quite beneficial. The testing was conducted on the US Route 59 in Atlanta, Texas. These authors first evaluated the condition of an old, deteriorated pavement with the ground penetrating radar, falling weight deflectometer, and via the dynamic cone penetration testing. Three sections were observed: a reinforced control section, a fibreglass/polyester-based reinforced section, and a polypropylene-based reinforced section. The road was monitored twice a year. The use of geosynthetics in the interlayer can be adopted as reinforcement of the asphalt overlay. Thick interlayers, (Figure 3.b) were used for stress-relief and thermal insulation in cold regions in order to reduce shrinkage of the CBC layer [38]. Shafabakhsh and Ahmadi [39] investigated the influence of a modified interlayer and overlay on the propagation of reflective cracks. The interlayer was sand asphalt, and the overlay was an asphalt mixture. The materials were modified with crumb rubber and hydrated lime, and crumb rubber and natural zeolite. The experiment involved a modified interlayer, a modified overlay, a modified combined interlayer, and overlay specimens. The main conclusion was that the sand asphalt interlayer is capable of absorbing the crack propagation energy, thereby delaying such propagation.

4. Modification of asphalt overlay characteristics

An asphalt overlay takes on the role of a new wearing course. The overlay is placed on top of the deteriorated, milled and bitumen-treated surface of an old pavement. Ordinary asphalt mixtures for pavement construction are usually also used as overlay mixtures. As stated in [38], the most influential factors affecting overlay behaviour are its thickness, mix properties, and the condition of the underlying pavement structure. The aim of this measure is to modify the asphalt mixture in order to improve its resistance to cracking. The modification can be made by replacing the natural aggregate with alternative materials, using new binders or coating agents. Almaali and Al-Busaltan [40] modified an ultra-thin asphalt overlay by varying the quantity of crumb rubber modifier and low-density polyethylene. They concluded that these materials improve resistance to permanent deformations. Radeef et al. [41] indicated that a rubberized asphalt mixture exhibits a lower tensile strength after moisture conditioning, but a higher fracture energy compared to the control mixture. Picado-Santos et al. [42] investigated the use of crumb rubber in asphalt mixtures produced by the wet process, the dry process, and the terminal blend process. For the wet process, crumb rubber was mixed with bitumen at high temperatures and acted as a binder. The paper points to the improvement of mechanical characteristics and durability of this kind of mixtures. On the other hand, in asphalt mixtures produced by the dry process, crumb rubber was used in a coarser gradation and acted as an aggregate. These mixtures exhibit better resistance to fatigue, permanent deformation, and reflection cracking at summer temperatures. In the crumb asphalt rubber mixtures produced by the terminal blend process, the crumb rubber is added to the asphalt binder, heated, and transported as a finished binder. Terminal blend mixtures with crumb rubber exhibit an improved resistance to rutting and fatigue. The authors concluded that the asphalt mixture with rubber is slightly more expensive than a conventional mixture, but that it is more durable and has advantages from an ecological point of view. An emphasis is also placed on the possibility of recycling the crumb rubber modified asphalt.
Xianyang et al. [43] examined the influence of four different fibres in asphalt mixtures: lignin, sepiolite, basalt, and aramid fibres. The mixtures were subjected to the following tests: indirect tensile stiffness modulus test, indirect tensile

fatigue test, indirect tensile strength test, moisture damage test, repeated load axial test, semi-circular bending test, and image analysis. The authors concluded that the fibres positively affect the fracture toughness of the mixture compared to the reference mixture. Their main conclusion was that fibres enhance properties of asphalt mixtures, prolong their fatigue life, and have no detrimental effect on asphalt mixtures. No improvement was observed in the moisture damage test for mixtures with fibres. The positive effect of basalt fibres was also emphasized by Guo et al. in [44] where the critical stress intensity factor and the critical fracture energy were investigated. Bagasse fibres have also been examined and the results reveal that they contribute to the low temperature cracking resistance, as reported in [45]. Bagasse fibres have a corrugated surface that improves the anchoring effect with binder. This was observed by electron microscopy. Poly-propylene fibres also enhance cracking resistance of low-temperature mixtures [46]. It is stated that longer fibres, and a higher quantity of fibres, result in higher tensile strength due to the bridging effect of fibres. The optimal fibre content was determined to be 1 % by the weight of mastic. Wang et al. [46] investigated asphalt mixtures with 0.3 % of bagasse fibres under various load and temperature conditions.

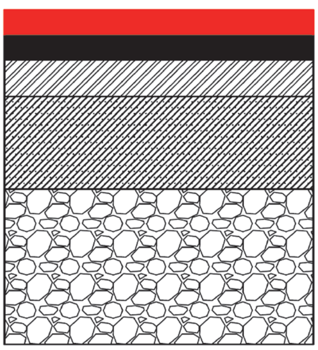


Figure 4. Pavement structure with modified asphalt overlay

The dynamic modulus, stress sweep rutting, and fatigue cyclic tests were conducted. The conclusion can be drawn that bamboo fibres improve the cracking performance of asphalt mixtures at intermediate temperatures, while improvement of asphalt mixtures at higher temperatures is not significant. It should be noted that a new type of geocells, high temperature resistant, can also be used for improvement of asphalt mixture properties [47]. Additional materials for asphalt mixtures, and the suitability of many modifiers, were also investigated, such as the engine oil, cooking oil, and graphene [48-50].

5. Conclusion

The main purpose of this paper is to review reflective cracks prevention and remediation measures with special references to the use of waste materials. The direct consequence of this phenomenon is an unsatisfactory pavement surface that requires reconstruction. The paper presents an overview of three remediation measures, and one measure for preventing occurrence of reflective cracks. The anti-reflective crack measure is assumed to be the most economical measure because it prevents the occurrence and propagation of cracks, which causes deterioration of the pavement surface. The modification of the cement bound bearing courses involves the use of waste materials, such as steel slag, fly ash, crumb rubber, and other crushed solid materials, as a partial replacement of natural materials, thus preserving natural resources and reducing the need to dispose of waste materials. The aim of other mentioned measures, an interlayer between an old and new overlay, overlay reinforcement and modification of overlay characteristics, is to prevent propagation of existing cracks to the surface layers. These measures, besides the waste materials, also involve the use of geosynthetics and bituminous materials. The thin interlayer between the old and the new layer should mimic the protection from crack propagation to the upper layers, which can be obtained by using bitumen or bitumen in combination with geosynthetics, such as geotextiles and geogrids. Given the high cost of bitumen and detrimental environmental effects of its production, as well as the artificial nature of the geosynthetics, this measure is not in accordance with current approaches encouraging preservation of nature and the use of waste materials in construction. Thick interlayers also involve the use of natural resources. It is well known that thick asphalt layers increase bearing capacity of pavements, but our task is to find the way of ensuring sufficient bearing capacity that is compliant with principles for the responsible use of natural resources. Many fibres, natural or synthetic origin, have been investigated to determine their potential for use in asphalt mixtures. Fibres have high tensile strength due to their elongated shape. Based on the research results, fibres show higher improvement for the low and intermediate temperature asphalt mixtures, than for high temperature asphalt mixtures (HMA).

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REFERENCES

[1] Babić, B.: Projektiranje kolničkih konstrukcija. Zagreb: Hrvatsko društvo građevinskih inženjera, 1997.

[2] Haas, R., Joseph, Ponniah, E.: Design oriented evaluation af alternatives for reflection cracking through pavement overlays, In: First International Conferenec on Reflective Cracking in Pavements, 1989.

[3] Rigo, J.M., Degeimbre, R., Francken L. (eds): Reflective Cracking in Pavements. In: State of the Art and Design Recommendations, Liege, Belgium, 1993, pp. 672.

[4] Adaska, W.S., Luhr, D.R.: Control of reflective cracking in cement-stabilized pavements, In: Control of Reflective Cracking in Cement Stabilized Pavements, Limoges, France, 2004.

[5] Pais, J.: The reflective cracking in flexible pavements, Romanian Journal of Transporat Infrastructure, 2 (2013), pp. 63-87.

[6] Mavar, R., Vrkljan, I., Štefanel, M.: Geotechnical Engineering in Transportation Projects, First edit. Novigrad, Croatia: Institut građevinarstva Hrvatske, Zagreb, 1994.

[7] Wang, X., Li K., Zhong, Y., Xu, Q., Li, C.: XFEM simulation of reflective crack in asphalt pavement structure under cyclic temperature, Construction and Building Materials, 189 (2018), pp. 1035-1044.

[8] Noori, M., Tatari, O., Nam, B., Golestani, B., Greene, J.: A stochastic optimization approach for the selection of reflective cracking mitigation techniques, Transportation Research Part A, 69 (2014), pp. 367-378.

[9] Buttlar, W.G., Chabot, A., Dave, E.V., Petit, C., Tebaldi, G. (eds): Mechanisms of Cracking and Debonding in Asphalt and Composite Pavements, 2018, https://doi.org/10.1007/978-3-319-76849-6.

[10] Wang, X., Zhong, Y.: Reflective crack in semi-rigid base asphalt pavement under temperature-traffic coupled dynamics using XFEM, Construction and Building Materials, 214 (2019), pp. 280-289.

[11] Tran, N.P., Gunasekara, C., Law, D.W., Houshyar, S., Setunge, S., Cwirzen, A.: A critical review on drying shrinkage mitigation strategies in cement-based materials, Journal of Building Engineering, 38 (2021), pp. 17.

[12] Liu, J, Yu, B, Wang, Q.: Application of steel slag in cement treated aggregate base course, Journal of Cleaner Production, 269 (2020), https://doi.org/10.1016/j.jclepro.2020.121733.

[13] Li, W., Lang, L., Lin, Z., Wang, Z., Zhang, F.: Characteristics of dry shrinkage and temperature shrinkage of cementstabilized steel slag, Construction and Building Materials, 134 (2017), pp. 540-548.

[14] Barišić, I., Marković, B., Zagvozda, M.: Freeze-thaw resistance assessment of cementbound steel slag aggregate for pavement structures, International Journal of Pavement Engineering, 20 (2017), pp. 448-457.

[15] Barišić, I., Dimter, S., Rukavina, T.: Elastic properties of cement-stabilised mixes with steel slag, International Journal of Pavement Engineering, 17 (2015), pp. 753-762.

[16] Pasetto, M., Baldo, N.: Recycling of waste aggregate in cement bound mixtures for road pavement bases and sub-bases, Construction and Building Materials, 108 (2016), pp. 112-118.

[17] Jose, A., Nivitha, M.R., Krishnan, J.M., Robinson, R.G.: Characterization of cement stabilized pond ash using FTIR spectroscopy, Construction and Building Materials, 263 (2020), pp. 13.

[18] Liang, S., Chen, J., Guo, M., Feng, D., Liu, L., Qi, T.: Utilization of pretreated municipal solid waste incineration fly ash for cement-stabilized soil, Waste management, 105 (2020), pp. 425-432.

[19] Development of New Bituminous Pavement Design Method, Brussels, 1999.

[20] Dimter, S., Rukavina, T., Dragčević, V.: Strength Properties of Fly Ash Stabilized Mixes, Road Materials and Pavement Design, 12 (2011), pp. 687-697.

[21] Dimter, S., Rukavina, T., Minažek, K.: Estimation of elastic properties of fly-ash stabilized mixes using nondestructive evaluation methods, Construction and Building Materials, 102 (2016), pp. 505-514.

[22] Zhang, Y., Johnson, A.E., White, D.J.: Freeze-thaw performance of cement and fly ash stabilized loess, Transportation Geotechnics, 21 (2019), pp. 10.

[23] Farhan, A.H., Dawson, A.R., Thom, N.H.: Characterization of rubberized cement bound aggregate mixtures using indirect tensile testing and fractal analysis, Construction and Building Materials, 105 (2016), pp. 94-102.

[24] Farhan, A.H., Dawson, A.R., Thom, N.H.: Compressive behaviour of rubberized cement-stabilized aggregate mixtures, Construction and Building Materials, 262 (2020), https://doi.org/10.1016/j.conbuildmat.2020.120038.

[25] Liu, Q., He, M., Wang, J.: Research on improving shrinkage performance of cement stabilized gravel with waste rubber particles, Advanced Materials Research, 963 (2014), pp. 1446-1450.

[26] Pham, N.P., Toumi, A., Turatsinze, A.: Evaluating damage of rubberized cement-based composites under aggresive environments, Construction and Building Materials, 217 (2019), pp. 234-241.

[27] Pham, N.P., Toumi, A., Turatsinze, A.: Effect of an enhanced rubber-cement matrix interface on freeze-thaw resistance of the cement-based composite, Construction and Building Materials, 207 (2019), pp. 528-534.

[28] Kasu, S.R., Manupati, K., Muppireddy, A.R.: Investigations on design and durability characteristics of cement treated reclaimed asphalt for base and subbase layers, Construction and Building Materials, 252 (2020), pp. 11.

[29] Isola, M., Betti, G., Marradi, A., Tebaldi, G.: Evaluation of cement treated mixtures with high percentage of reclaimed asphalt pavement, Construction and Building Materials, 48(2013), pp. 238-247.

[30] Tataranni, P., Sangiorgi, C., Simone, A, Vignali, V., Lantieri, C., Dondi, G.: A laboratory and field study on 100% Recycled Cement Bound Mixture for base layers. International Journal of Pavement and Technology, 11(2018), pp. 427-434.

[31] Francken, L.: Laboratory simulation and modeling of overlay systems, In: Rigo JM, Degeimbre R, Francken L (eds) Reflective cracking in pavements. Liege, Belgium: W&FN Spon, 1993, p. 496.

[32] Wang, J., Xiao, F., Chen, Z., li X, Amirkhanian, S.: Application of tack coat in pavement engineering, Construction and Building Materials, 152 (2017), pp. 856-871.

[33] Hu, X., Lei, Y., Wang, H., Jiang, P., You, Z.: Effect of tack coat dosage and temperature on the interface shear properties of asphalt layers bonded with emulsified asphalt binders, Construction and Building Materials, 141 (2017), pp. 86-93.

[34] Wang, X., Zhong, Y.: Influence of tack coat on reflective cracking propagation in semi-rigid base asphalt pavement, Engineering Fracture Mechanics, 213 (2019), pp. 172-181.

[35] Jaecklin, F.P.: Geotextile Use in Asphalt overlays - Design and Installation Techniques for Successful Applications, In: Rigo J.M., Degeimbre R., Francken L. (eds) Reflective cracking in pavements, Liege, Belgium, 1993, p. 496.

[36] Zamora-Barraza, D., Calzada-Perez, M.A., Castro-Fresno, D., Vega-Zamanillo, A.: Evaluation of anti-reflective cracking systems using geosynthetics in the interlayer zone, Geotextiles and Geomembranes, 29 (2011), pp. 130-136.

[37] Walubita, L.F., Mahmoud, E., Lee, S.I., Carrasco, G., Komba, J., Fuentes, L., Nyamuhokya, T.P.: Use of grid reinforcement in HMA overlays - A Texas field case study of highwayUS 59 in Atlanta District, Construction and Building Materials, 213 (2019), pp. 325-336.

[38] Sun, Z., Xu, Y., Tan, Y., Zhang, L., Xu, H., Meng, A.: Investigation of sand mixture interlayer reducing the thermal constraint strain in asphalt concret overlay, Construction and Building Materials, 171 (2018), pp. 357-366.

[39] Shafabakhsh, G., Ahmadi, S.: Reflective cracking reduction by a comparison between modifying asphalt overlay and sand asphalt interlayer: an experimanetal evaluation, International Journal of Pavement Engineering, 22 (2019), pp. 192-200.

[40] Almaali, Y.A., Al-Busaltan, S.: Permanent deformation characteristics of modified thin overlay bitumen mixtures comprising waste polymers, Materials Today: Proceedings, 42 (2021), pp. 2717-2724.

[41] Radeef, H.R., Hassan, N.A., Abidin, A.Z.R., Mahmud, A.M.H., Yaacob, H., Mashros, N., Mohamed, A.: Effect of aging and moisture damage on the cracking resistance of rubberized asphalt mixture, Materials Today: Proceedings, 42 (2021), pp. 2853-2858.

[42] Picado-Santos, L.G., Capitao, S.D., Neves, J.M.C.: Crumb rubber asphalt mixtures: A literature review, Construction and Building Materials, 247 (2020), https://doi.org/10.1016/j.conbuildmat.2020.118577.

[43] Xianyang, X., Chen, S., Li, Y., Pei, J., Zhang, J., Wen, Y., Li, R., Cui, S.: Effect of different fibers on the properties of asphalt mastics, Construction and Building materials, 262 (2016) 8, https://doi.org/10.1016/j.conbuildmat.2020.120005.

[44] Guo, Q., Chen, Z., Liu, P., Li, Y., Hu, J., Gao, Y., Li X.: Influence of basalt fiber on mode I and II fracture properties of asphalt mixtures at medium and low temperatures, Theoretical and Applied Fracture Mechanics, 112 (2021), https://doi.org/10.1016/j.tafmec.2020.102884.

[45] Li, Z., Zhang, X., Fa C., Zhang, Y., Xiaong, J., Chen, H.: Investigation on characteristics and properties of bagasse fibers: Performances of asphalt mixtures with bagasse fibers, Construction and Building Materials, 248 (2020), https://doi.org/10.1016/j.conbuildmat.2020.118648.

[46] Wang, S., Mallick, R.B., Rahbar, N.: Toughening mechanisms in polypropylene fiber-reinforced asphalt mastic at low temperature, Construction and Building Materials, 248 (2020), https://doi.org/10.1016/j.conbuildmat.2020.118690.

[47] Li, X., Zhu, Y., Su, T., Wang, X., Zhang, X.: Study on performance improvement of new geocell reinforced asphalt mixtures, Construction and Building Materials, 273 (2021), https://doi.org/10.1016/j.conbuildmat.2020.121693.

[48] Li, H., Zhang, F., Feng, Z., Li, W., Zou, X.: Study on waste engine oil and waste cooking oil on performance improvement of aged asphalt and application in reclaimed asphalt mixture, Construction and Building Materials, 276 (2021), https://doi.org/10.1016/j.conbuildmat.2020.122138.

[49] Li, X., Wang, Y.M., Wu, Y.L., Wang, H-R., Chen, M., Sun, H.D., Fan, L.: Properties and modification mechanism of asphalt graphene as modifier, Construction and Building Materials, 272 (2021), https://doi.org/10.1016/j.conbuildmat.2020.121919.

[50] Phan, T.M., Nguyen, S.N., Seo, C.B., Park, D.W.: Effect of treated fibers on performace of asphalt mixture, Construction and Building Materials, 274 (2021), https://doi.org/10.1016/j.conbuildmat.2020.122051.