Qazaq Highway Science and Innovation, 2026, №3, DOI: https://doi.org/10.71031/

Qazaq Highway
Science and Innovation
https://science-jolshy.qazjolgzi.kz/ru/index

ISSN
3008-1491

FINITE ELEMENT PERFORMANCE EVALUATION OF ASPHALT CONCRETE PAVEMENTS WITH BASIC OXYGEN FURNACE SLAG AS A COARSE AGGREGATE REPLACEMENT

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Abstract. The use of steelmaking by-products in road construction reduces the demand for virgin aggregate and supports circular economy practices in the road sector. This paper evaluates the structural performance of an asphalt concrete pavement in which the coarse aggregate of the wearing course is replaced with Basic Oxygen Furnace (BOF) slag. A four-layer flexible pavement was modelled in ABAQUS 2021 under both linear elastic and linear viscoelastic constitutive laws, the latter through a four-term Prony series with a Williams-Landel-Ferry shift function fitted to laboratory data, and was validated against published benchmark results with a deviation of 1.32 % in maximum rutting depth. A conventional pavement with a fine-grained gravel wearing course (E = 3340 MPa at 20 °C) was compared with a BOF slag-modified pavement (E = 2135 MPa at 20 °C). The rutting depths were 2.49 mm and 2.58 mm under the elastic assumption (3.6 %) and 2.42 mm and 2.53 mm under the viscoelastic assumption (4.5 %), while the peak von Mises stress was lower in the BOF slag pavement in both cases (1.31 MPa against 1.48 MPa and 1.41 MPa against 1.59 MPa). The sensitivity of the structure to the surface layer is expressed as a power law: the rutting depth scales with the wearing course modulus to the power of -0.08 under the elastic and -0.10 under the viscoelastic assumption and the peak stress to the power of +0.27, so that a reduction of the surface stiffness by 36 % changes the structural response by less than 5 %. At the scale of a two-lane carriageway the substitution replaces about 800 t of natural crushed stone per kilometre of wearing course. BOF slag can therefore be regarded as a technically viable and sustainable aggregate substitute for wearing course mixtures, provided that the volumetric stability of the slag is verified before placement.

Keywords: Basic Oxygen Furnace slag, asphalt concrete pavement, finite element analysis, viscoelastic behaviour, rutting, sustainable road materials

Introduction

Asphalt concrete accounts for about 94 % of the paved road surfaces in the world [1] and consumes roughly 2.5 billion tonnes of mineral aggregate every year, a demand projected to grow by nearly 50 % by 2050 [2]. Rising material costs, the depletion of natural aggregate deposits and tighter environmental regulation make alternative aggregate sources an urgent task for the road sector, including in Kazakhstan.

Basic Oxygen Furnace (BOF) slag, a by-product of converter steelmaking, is one of the most promising candidates. World crude steel output exceeded 1.95 billion tonnes in 2023 [3], and 150-200 kg of BOF slag is generated per tonne of steel, which corresponds to more than 300 million tonnes of potential aggregate per year. BOF slag is highly angular (more than 70 % crushed faces), resistant to abrasion (Los Angeles loss of 15-25 %), has a high polished stone value (above 55) and a high internal friction angle (42-48°), all of which are favourable for pavement mixtures [4, 5]. Two factors restrict its direct use in a surface layer. The first is the content of free lime and periclase, which can hydrate with a delay and cause volumetric expansion, so that weathering and an expansion check are required before the slag is accepted as an aggregate [6]. The second is the lower stiffness of the resulting asphalt concrete compared with mixtures based on natural gravel, which makes a structural verification of the pavement necessary before the material can be recommended for the wearing course.

Finite element analysis (FEA) has become the standard computational tool for such a verification, since it provides the full stress-strain field in a layered system under an arbitrary load [7]. Published studies have addressed tyre-pavement contact stresses [8], the rutting of geosynthetically reinforced pavements [9] and the optimisation of tack coat layers [10], while slag materials have been examined mainly as subbase constituents [11]. No published work, however, has systematically assessed BOF slag in the wearing course using both elastic and viscoelastic material models, and none has done so for Kazakhstani materials and the local climatic range from -40 °C in winter to +40 °C in summer.

The aim of this study is therefore to develop and validate a finite element model of a flexible pavement and to compare the structural response of a conventional gravel pavement with that of a BOF slag-modified pavement under both linear elastic and linear viscoelastic material assumptions. The contribution is threefold: the model is verified against published benchmark data before use; both constitutive assumptions are applied to the same structure, which separates the instantaneous from the time-dependent response; and the sensitivity to the wearing course stiffness is expressed as a dimensionless power law transferable to other mixtures and moduli.

Methodology

A four-layer pavement structure was built in ABAQUS 2021: an asphalt concrete wearing course 120 mm thick, a stabilised gravel-sand base course 180 mm thick, an unstabilised granular foundation layer 300 mm thick and a subgrade 2000 mm thick. The model extends 3000 mm in the direction of traffic and 2000 mm transversely; these dimensions were established by a preliminary convergence study so that the boundaries do not affect the response in the wheel path. Layer thicknesses follow the design recommendations R RK 218-130-2016 [12] and reproduce a typical flexible pavement cross-section used in Kazakhstani highway practice (Figure 1).

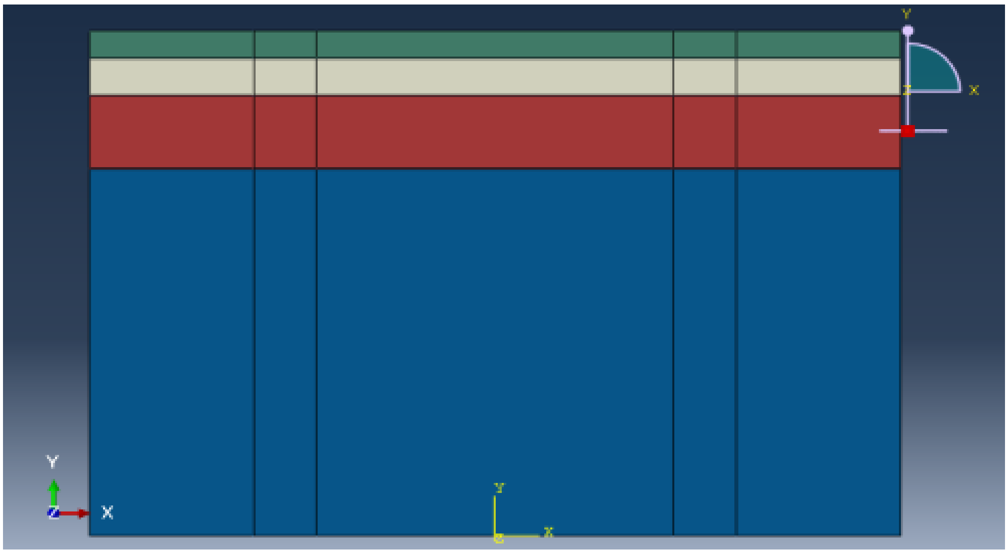


Figure 1 – Assembled four-layer pavement model: wearing course, base course, foundation layer and subgrade

The layers were discretised with S4R shell elements (four-node elements with reduced integration and hourglass control) using five Simpson integration points through the thickness, which captures the flexural stress gradient of a layered pavement at a modest computational cost [13]. Mesh sensitivity was examined by refining the element size from 100 mm to 10 mm in the wheel path region until the maximum displacement and the von Mises stress changed by less than 2 % between successive refinements; the final mesh contains 1120 quadrilateral elements and 1312 nodes, with an aspect ratio below 3:1 and a Jacobian determinant above 0.7. Perfect bonding was reproduced by three tie constraints that keep displacements and rotations continuous at the interfaces, including the foundation-subgrade interface where the stiffness contrast exceeds 40:1; this formulation transfers both normal and shear forces and is appropriate for pavements in which interlayer slip and debonding are negligible under normal traffic.

The tyre load was applied as a uniform pressure of 0.66 MPa over rectangular contact patches of 260 × 180 mm representing a dual tyre configuration; this is the design contact stress of a 13-tonne single axle adopted in Kazakhstani practice and is consistent with the AASHTO standard axle of 80 kN. In the time-dependent analysis the load amplitude followed a period equal to the passage time of a wheel at the design speed, and traffic accumulation was simulated by a stabilised static procedure. The bottom of the subgrade was restrained against vertical displacement and the lateral boundaries against horizontal translation normal to them, which represents a rigid base at depth and symmetry at the sides. Two response quantities were extracted at the reference temperature of 20 °C: the maximum vertical displacement in the wheel path, reported as the rutting depth, and the peak von Mises stress, a scalar measure of the multiaxial stress state that governs shear-related distress in a layered system.

Elastic properties were taken from R RK 218-130-2016 [12] and supplementary laboratory testing (Table 1): the wearing course modulus of 3340 MPa at 20 °C from a dynamic modulus master curve at 10 Hz according to AASHTO T 342, the base and foundation moduli from resilient modulus tests according to AASHTO T 307, and the subgrade modulus from a correlation with the California Bearing Ratio. For validation the properties were set equal to those of the benchmark study [14]. In the comparative analysis only the wearing course modulus was changed, from 3340 MPa to 2135 MPa, so that the effect of the replacement is isolated from any other factor.

Table 1 – Material properties of the pavement layers

Layer	Material	h, mm	E, MPa	ν	ρ, kg/m³
Wearing course	AC, fine-grained gravel	120	3340	0.35	2350
Wearing course	AC, BOF slag aggregate	120	2135	0.35	2350
Base course	Stabilised gravel-sand mix	180	650	0.35	2200
Foundation	Unstabilised gravel-sand	300	180	0.35	2100
Subgrade	Clayey soil	2000	46	0.35	1900

The viscoelastic behaviour of the asphalt concrete was described by a generalised Maxwell model in the form of a four-term Prony series fitted by nonlinear least squares to stress-relaxation data measured at 20 °C:

$$E(t) = E_\infty + \Sigma\, g_i \exp(-t / \tau_i), \quad (1)$$

where E_∞ is the long-term equilibrium modulus, g_i the relaxation strength and τ_i the relaxation time of the i-th element. Temperature dependence was introduced through the Williams-

Landel-Ferry shift function with the constants $C_1 = 8.9$ and $C_2 = 102$ for a reference temperature of 20 °C over the range -10 °C to 50 °C; the fitted set reproduces the measured relaxation data within ±5 % for times from 10^{-5} to 10^3 s.

Dynamic modulus testing followed AASHTO T 342 at 0, 10, 20, 30 and 40 °C and at 0.1-25 Hz, and master curves were built at a reference temperature of 20 °C. The instantaneous modulus for a loading time of 0.1 s follows an exponential temperature law:

$$\text{traditional wearing course: } E_{0.1}(T) = 12961 \exp(-0.085T) \text{ MPa}, \; R^2 = 0.998; \tag{2}$$

$$\text{BOF slag wearing course: } E_{0.1}(T) = 6852.7 \exp(-0.082T) \text{ MPa}, \; R^2 = 0.999. \tag{3}$$

Results and Discussion

The model was first validated against the benchmark results of Bouacha et al. [14], who analysed flexible, geosynthetically reinforced and rigid pavements under the same 13-tonne axle load. The maximum rutting depth computed here, 2.324 mm, differs from the published value of 2.294 mm by 1.32 %, well inside the tolerance of 5 % normally accepted in pavement finite element verification [15]. The agreement confirms the geometry, the materials, the load, the mesh and the boundary conditions, and justifies extending the model to the BOF slag configuration.

The von Mises stress field decays through the depth of the structure in the manner predicted by layered elastic theory (Figure 2). Averaged over 75 % of the evaluated elements, the stress falls from about 2.37 MPa in the surface layers to 1.97-0.79 MPa in the intermediate layers and to less than 0.2 MPa in the lower strata, with a peak of 3.17 MPa in the critical load transfer zones, which confirms that the subgrade is adequately protected.

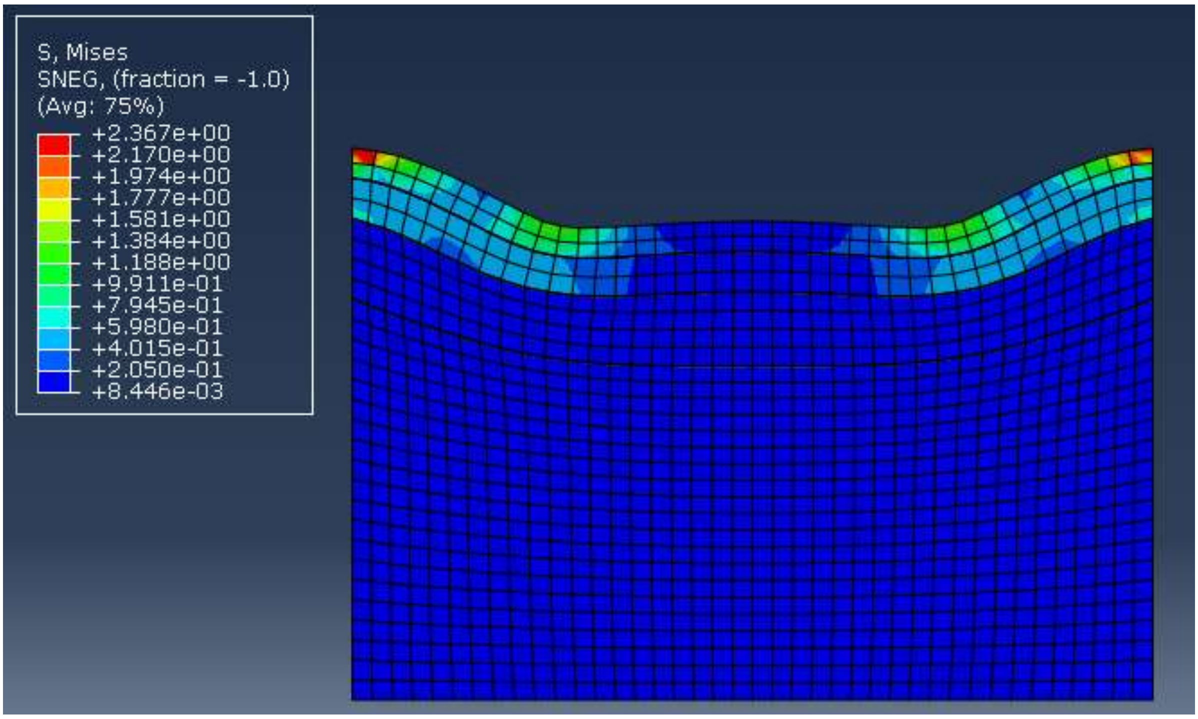
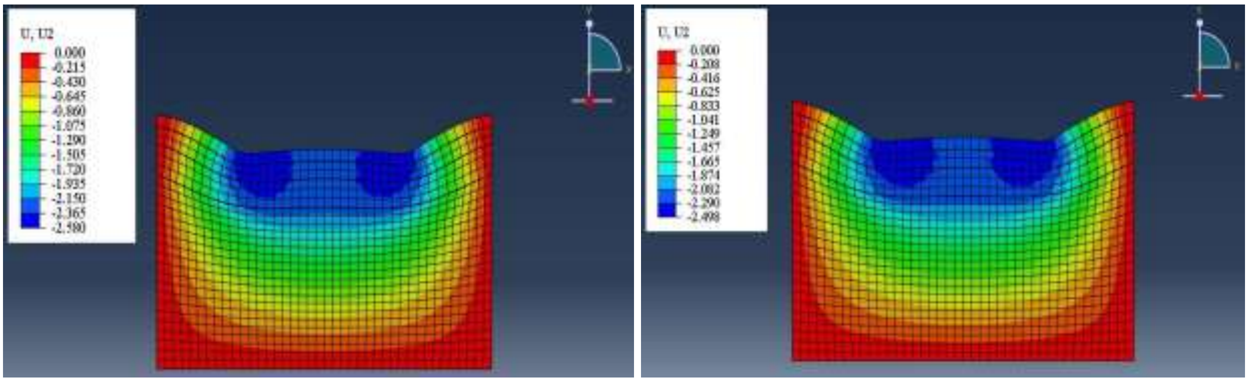


Figure 2 – Von Mises stress contour showing the progressive attenuation of stress through the pavement structure

Under the linear elastic assumption the two pavements behave almost identically (Table 2). The BOF slag pavement shows a slightly larger maximum rutting depth, 2.58 mm against 2.49

mm, an increase of 3.6 %, which follows directly from the lower effective stiffness of the near-surface system and the correspondingly higher vertical compliance under the same load. At the same time the peak von Mises stress is 11.5 % lower, 1.31 MPa against 1.48 MPa, because the reduced stiffness contrast between the wearing course and the base course changes the load-spreading trajectory and smooths the stress field in the critical load transfer zones.



A) *B)*

Figure 3 – Rutting depth contours under the linear elastic assumption: A) BOF slag pavement; B) traditional pavement

The viscoelastic analysis leads to the same conclusion (Table 2). The rutting depth of the BOF slag pavement exceeds that of the traditional pavement by 4.5 %, 2.53 mm against 2.42 mm, which is explained by the slightly higher time-dependent compliance of the BOF slag mixture and the resulting accumulation of viscoelastic strain under repeated loading. The peak von Mises stress is again lower by 11.3 %, 1.41 MPa against 1.59 MPa. Accumulated plastic strain in the BOF slag pavement is 11.0 % higher, which indicates that viscoelastic relaxation redistributes the load and limits local stress concentrations at the cost of a gradual concentration of strain.

Table 2 – Response of the two pavements under the elastic and the viscoelastic assumption

Assumption	Response parameter	Traditional pavement	BOF slag pavement	Change, %
Elastic	Maximum rutting depth, mm	2.49	2.58	+3.6
Elastic	Peak von Mises stress, MPa	1.48	1.31	-11.5
Viscoelastic	Maximum rutting depth, mm	2.42	2.53	+4.5
Viscoelastic	Peak von Mises stress, MPa	1.59	1.41	-11.3

The viscoelastic model predicts slightly smaller deformations than the elastic one for both structures, which shows that an elastic analysis remains conservative for this type of pavement. The rutting profiles of the two structures are practically parallel over the whole wheel path and differ only near the wheel centreline (Figure 4).

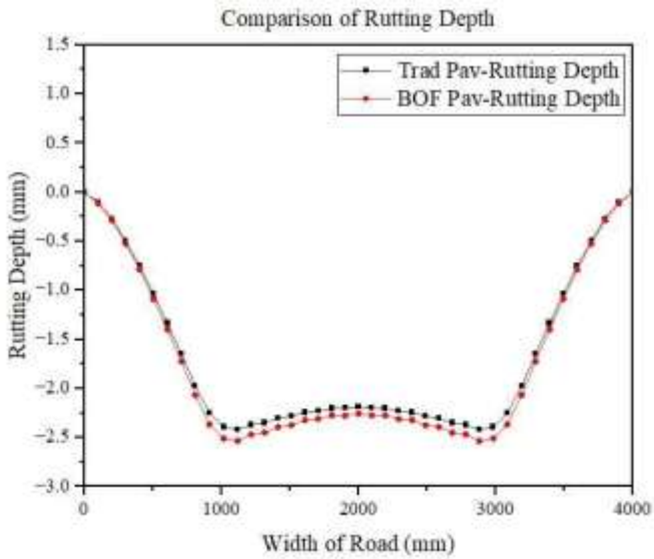


Figure 4 – Rutting depth profiles of the traditional and BOF slag pavements

Since only the wearing course modulus was changed between the two configurations, the results can be generalised by expressing the response R as a power function of the surface stiffness E, $R = R_0 (E / E_0)^n$, in which the dimensionless exponent follows from the two computed states:

$$n = \ln (R_2 / R_1) / \ln (E_2 / E_1), \quad (4)$$

The reduction of the wearing course modulus by 36 %, from 3340 MPa to 2135 MPa, gives $n = -0.08$ for the rutting depth under the elastic assumption and $n = -0.10$ under the viscoelastic assumption, and $n = +0.27$ for the peak von Mises stress in both cases. All three exponents are an order of magnitude smaller than unity, that is the global response is close to insensitive to the stiffness of the surface layer: extrapolating the power law, a tenfold reduction of the surface modulus would increase the rutting depth by only about 20 %. This quantifies why the loss of stiffness caused by the BOF slag has so little structural consequence and gives a design rule independent of the moduli measured here.

The stiffness reduction adopted here is conservative with respect to the published data: steel slag has repeatedly been reported to increase the Marshall stability and the mechanical strength of hot mix asphalt when it replaces natural coarse aggregate [4, 5], whereas the local mixture gave a dynamic modulus at the lower end of the reported range. The computed response is therefore an upper bound of the deformation and a lower bound of the performance to be expected in the field.

The practical scale follows from the geometry of the layer: a wearing course 120 mm thick on a carriageway 7 m wide contains about 840 m^3 per kilometre, close to 2000 t of mixture, so that with a coarse fraction of about 40 % some 800 t of natural crushed stone are replaced per kilometre of road. The annual BOF slag output of the domestic converter production, of the order of hundreds of thousands of tonnes, is sufficient for several hundred kilometres of wearing course per year.

In engineering terms the differences of 3.6-4.5 % in rutting and of about 11 % in peak stress are small against the normal scatter of material properties and construction quality: the wearing course governs contact stresses, surface durability and skid resistance rather than the load-bearing capacity of the structure, so the loss of stiffness is not a structural disadvantage.

Three limitations should be kept in mind. The shell element idealisation and the linear constitutive laws reproduce the stress and displacement fields but describe neither damage accumulation nor viscoplastic flow, so the values reported are structural responses and not service life predictions. The comparison was made at 20 °C, whereas the difference between the mixtures is largest at the extremes of the local climatic range. Finally, the volumetric stability of the slag has to be confirmed by a potential expansion test and its higher specific gravity requires the mixture to be redesigned on a volumetric basis.

Conclusions

1. The finite element model of a four-layer flexible pavement built in ABAQUS 2021 reproduces published benchmark results with a deviation of 1.32 % in the predicted rutting depth, which confirms its reliability for both elastic and viscoelastic analysis with a Prony series representation of the relaxation modulus.

2. Replacing the coarse aggregate of the wearing course with BOF slag increases the maximum rutting depth by 3.6 % under the elastic and by 4.5 % under the viscoelastic assumption, both small relative to the scatter normally accepted in pavement design.

3. The peak von Mises stress in the BOF slag pavement is lower by 11.5 % in the elastic analysis and by 11.3 % in the viscoelastic analysis, which indicates a more uniform load transfer and a reduced stress concentration at the critical interfaces.

4. The sensitivity of the structure to the surface layer is described by a power law with the exponents -0.08 and -0.10 for the rutting depth and +0.27 for the peak stress. The global response is therefore close to insensitive to the stiffness of the wearing course, which is the mechanical reason why a mixture of lower modulus remains acceptable in this position and why the result can be transferred to other slag mixtures.

5. BOF slag can therefore be regarded as a technically viable and sustainable substitute for natural coarse aggregate in asphalt concrete wearing courses, replacing about 800 t of crushed stone per kilometre of a two-lane carriageway and supporting circular economy principles in Kazakhstani road construction. Two conditions apply: the volumetric stability of the slag must be confirmed by an expansion test, and the mixture must be redesigned volumetrically because of the higher specific gravity of the slag. Observation of instrumented test sections is needed before the material enters normative documents.

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Cao Rongji: methodology, resources, experimental testing, analysis, interpretation, manuscript review and editing, and supervision.

Conflict of Interest: The authors declare no conflict of interest.

НЕГІЗГІ ОТТЫҚ ПЕШ ҚОЖЫН ІРІ ТОЛТЫРҒЫШ РЕТІНДЕ ПАЙДАЛАНУ АРҚЫЛЫ АСФАЛЬТБЕТОН ЖАБЫНДАРЫНЫҢ ШЕКТІК ЭЛЕМЕНТТЕР ӘДІСІМЕН ПАЙДАЛАНУ ТИІМДІЛІГІН БАҒАЛАУ

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Аңдатпа. Болат өндірудің жанама өнімдерін жол құрылысында пайдалану бастапқы табиғи толтырғыштарға деген сұранысты азайтып, жол саласында айналмалы экономика қағидаттарын дамытуға ықпал етеді. Бұл жұмыста асфальтбетон жабынының конструкциялық тиімділігі бағаланды, мұнда жоғарғы қабаттың ірі толтырғышы негізгі отттық пеш (Basic Oxygen Furnace, BOF) қожымен алмастырылды. ABAQUS 2021 бағдарламасында төрт қабатты иілгіш жол жабыны сызықтық серпімді және сызықтық тұтқыр-серпімді конститутивтік модельдер негізінде модельденді. Тұтқыр-серпімді модельдеу кезінде зертханалық деректерге сәйкестендірілген Williams–Landel–Ferry ығысу функциясы бар төрт мүшелі Prony қатары қолданылды. Модель жарияланған эталондық нәтижелермен салыстырылып, максималды колея тереңдігі бойынша ауытқу 1,32 % құрады. Дәстүрлі ұсақ түйіршікті қиыршықтас беткі қабаты бар жабын (20 °C температурада E = 3340 МПа) BOF қожымен түрлендірілген жабынмен (20 °C температурада E = 2135 МПа) салыстырылды. Серпімді модель жағдайында колея тереңдігі тиісінше 2,49 мм және 2,58 мм (3,6 %), ал тұтқыр-серпімді модель жағдайында 2,42 мм және 2,53 мм (4,5 %) болды. Бұл ретте ең жоғары von Mises кернеуі екі жағдайда да BOF қожы қолданылған жабында төмен болды: сәйкесінше 1,31 МПа және 1,48 МПа, сондай-ақ 1,41 МПа және 1,59 МПа. Конструкцияның беткі қабатқа сезімталдығы дәрежелік заңмен сипатталады: колея тереңдігі серпімді модель жағдайында жабынның жоғарғы қабатының модуліне -0,08 дәрежесіне, ал тұтқыр-серпімді модель жағдайында -0,10 дәрежесіне пропорционал; ең жоғары кернеу +0,27 дәрежесіне сәйкес өзгереді. Осылайша, беткі қабаттың қаттылығының 36 %-ға төмендеуі конструкцияның жауап реакциясын 5 %-дан аз мөлшерде өзгертеді. Екі жолақты жүріс бөлігінің 1 км жоғарғы қабатында табиғи ұсақталған тастың шамамен 800 тоннасын алмастыруға болады. Сондықтан BOF қожын жоғарғы қабат қоспалары үшін техникалық тұрғыдан жарамды және тұрақты толтырғыш алмастырғыш ретінде қарастыруға болады, алайда оны жол жабынына төсеу алдында қождың көлемдік тұрақтылығын міндетті түрде тексеру қажет.

Түйінді сөздер: негізгі отттық пеш қожы, асфальтбетон жабыны, ақырлы элементтерді талдау, тұтқыр-серпімді мінез-құлық, колея түзілуі, тұрақты жол-құрылыс материалдары

ОЦЕНКА ЭФФЕКТИВНОСТИ АСФАЛЬТОБЕТОННЫХ ПОКРЫТИЙ С ПРИМЕНЕНИЕМ МЕТОДА КОНЕЧНЫХ ЭЛЕМЕНТОВ ПРИ ЗАМЕНЕ КРУПНОГО ЗАПОЛНИТЕЛЯ ШЛАКОМ ОСНОВНОЙ КИСЛОРОДНОЙ ПЕЧИ

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Аннотация. Использование побочных продуктов сталеплавильного производства в дорожном строительстве снижает потребность в первичных природных заполнителях и способствует развитию принципов циркулярной экономики в дорожной отрасли. В данной работе проведена оценка конструкционной эффективности асфальтобетонного дорожного покрытия, в котором крупный заполнитель верхнего слоя заменен шлаком основной кислородной печи (Basic Oxygen Furnace, BOF). Четырехслойная конструкция нежесткого дорожного покрытия была смоделирована в ABAQUS 2021 с использованием линейно-упругого и линейно-вязкоупругого законов поведения материала. При вязкоупругом моделировании применялся четырехчленный ряд Пронни с функцией сдвига Williams–Landel–Ferry, аппроксимированной по лабораторным данным. Модель была валидирована по опубликованным эталонным результатам; отклонение по максимальной глубине колеи составило 1,32 %. Традиционное покрытие со слоем из мелкозернистого гравия (E = 3340 МПа при 20 °C) сравнивалось с покрытием, модифицированным BOF-шлаком (E = 2135 МПа при 20 °C). Глубина колеи составила 2,49 и 2,58 мм при упругом допущении (3,6 %) и 2,42 и 2,53 мм при вязкоупругом допущении (4,5 %) соответственно. При этом пиковое напряжение по Мизесу в покрытии с BOF-шлаком было ниже в обоих случаях: 1,31 МПа против 1,48 МПа и 1,41 МПа против 1,59 МПа соответственно. Чувствительность конструкции к свойствам поверхностного слоя описывается степенным законом: глубина колеи зависит от модуля верхнего слоя покрытия в степени -0,08 при упругом и -0,10 при вязкоупругом допущении, тогда как пиковое напряжение изменяется в степени +0,27. Таким образом, снижение жесткости поверхностного слоя на 36 % изменяет конструкционный отклик менее чем на 5 %. На масштабе двухполосной проезжей части такая замена позволяет заменить около 800 т природного дробленого камня на каждый километр верхнего слоя покрытия. Следовательно, BOF-шлак может рассматриваться как технически пригодный и устойчивый заменитель заполнителя для смесей верхнего слоя при условии предварительной проверки его объемной стабильности перед укладкой.

Ключевые слова: шлак основной кислородной печи, асфальтобетонное покрытие, анализ методом конечных элементов, вязкоупругое поведение, колееобразование, устойчивые дорожные материалы