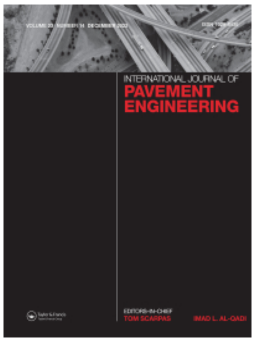

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RESEARCH ARTICLE

Advancing asphalt pavement monitoring and prognostics with physics-informed digital twins: a feasibility study

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ABSTRACT

Asphalt pavements experience progressive deterioration from repeated traffic loads and environmental exposure, leading to premature failure and increased maintenance costs. Traditional monitoring methods fail to provide real-time insights into pavement health, limiting proactive maintenance strategies. This study establishes a framework for the development of a digital twin-enabled cyber-physical platform for the monitoring of asphalt pavements by leveraging the potential of modern sensors and physics engine software. The study combines embedded 'smart rock' sensors capable of capturing real-time mechanical responses of asphalt under varying loads and temperatures with physics informed virtual asphalt models developed using physics engines. Laboratory validation established strong agreement between the virtual model simulations and real asphalt performance data. This alignment provides a foundational breakthrough to correlate changes in mechanical behaviour with emerging distress patterns, enabling early damage detection and failure prediction. Overall, sensor-virtual model fusion can potentially enable proactive, self-updating road performance prediction via cyber-physical systems.

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KEYWORDS
Asphalt pavements; digital twin; physics engine; cyber-physical platform; real-time monitoring

1 Introduction

Road pavements are one of the most important components of transport infrastructure that significantly contribute to overall development (Jiang et al., 2018). The UK's roads support 88% of passenger transportation and 79% of freight transport (Shirley, 2023). Roads are regarded as more important than other modes of transportation due to their accessibility and cost-effectiveness. In addition to facilitating development, roads support societal growth and enhance overall prosperity, productivity, and well-being (Cook, 2011). Among the various types of road pavements, asphalt pavements are the most commonly used due to their excellent performance, easy maintenance, and rehabilitation (Luo et al., 2019). However, asphalt pavements undergo ageing and deterioration over time due to factors such as asphalt binder ageing, repetitive vehicular loading, environmental conditions, climate change related impacts, and poor maintenance (Hu et al., 2022; Hu et al., 2024; Hu et al., 2025; Xue et al., 2014). This deterioration leads to distresses such as cracking, ravelling, and loss of flexibility (Petersen, 2009). Consequently, the lifespan of asphalt pavements is shortened, resulting in the need for frequent repairs and maintenance, which can involve significant costs. Current government allocation and spend on pavement maintenances generally leads to the need to prioritise. In addition, climate change related impacts are visibly accelerating pavement deterioration, complicating the maintenance prioritising process. Hence, monitoring of pavement condition is critical for making efficient maintenance decisions, reducing the likelihood of costly premature failures, and extending service life. Traditional methods of monitoring, such as accelerated pavement testing (APT), falling weight deflectometer (FWD), ground penetrating radar (GPR) technologies, etc., have the disadvantage of being inefficient and time-consuming (Liu

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et al., 2024; Wang et al., 2022a). APT cannot accurately monitor pavement conditions due to the use of controlled, constant load levels. Moreover, the loading speeds of most APT systems are lower than those of conventional traffic, making it difficult to simulate high-speed effects (Harvey, 2009). FWD provides discrete measurements, and the need to close lanes during operation can cause traffic disruptions, the FWD's load does not accurately simulate continuous traffic (Hamidi et al., 2025). The limitations of GPR include signal scattering and backscattering effects, with the depth of penetration strongly influenced by the antenna's centre frequency and the condition of the ground materials (Rasol et al., 2022). Additionally, signal attenuation can be significant in heterogeneous subsurface conditions, which can reduce the accuracy and reliability of the data. To address these issues, increasing attempts have been made to deploy more advanced and efficient monitoring techniques. Various technologies have been developed to monitor pavements, including using pressure cells, strain gauges, thermocouples, accelerometers, fibre-optic sensors, and moisture sensors to predict early damage (Behnia et al., 2018; Braunfelds et al., 2023; Cheng et al., 2020; Ho et al., 2020; Wang, Wang, et al., 2024; Wang, Zhang, et al., 2024). A recent advancement in this field is the development of wireless sensor technologies, which offer the possibility for constant health monitoring and data collection.

Zhang, Wang, Chen, et al. (2025) used fibre optic sensors to track stress variations in the cracking zones of asphalt mixture beams. The study's findings lay a foundation for the broad implementation of distributed fibre optic sensors in monitoring pavement performance under freeze-thaw conditions. Other studies by Zhang et al. have demonstrated that distributed optic fibre sensors in asphalt pavement can accurately identify the origins of cracks and monitor their formation and progression in real time (Zhang, Liu, et al., 2025; Zhang, Wang, Liu, et al., 2025). Ji et al. (2019) fabricated a self-powered damage detection sensor for monitoring cracking in asphalt pavements. It was determined that the acoustic wave attenuation coefficient reduced as the pavement crack width increased, demonstrating the potential of wireless sensors to track the development of cracks in pavement. Hasni et al. (2017) used a self-powered wireless sensor with variable injection rates to precisely identify the onset of bottom-up cracks in pavements. Xue et al. (2014) developed an embedded sensor network using an effective combination of different commercial sensors for monitoring of pavements. The pavement response data captured by this sensor network was employed for predicting the long-term pavement performance, serving as a foundation for the management of pavements. Wang et al. (2018) simulated the movement of aggregates using a sensor termed as 'smart rock', capturing real-time aggregate kinematic behaviour during compaction. The findings revealed a high correlation between aggregate movement and the change in the asphalt mixture density. Furthermore, the utilisation of intelligent aggregates, which is a wireless sensor developed by another study, demonstrated a significant correlation between the degree of compaction, spatial acceleration, and attitude angle during the compaction process (Zhang & Wang, 2021). A key challenge for long-term deployment of such embedded sensors is ensuring a reliable power supply over the multi-decade service life of pavements. While current sensor batteries may not support continuous high-frequency data collection for decades, ongoing rapid technological advancements are anticipated to facilitate the development of self-sustaining power sources in the future (Monagle et al., 2024). Moreover, unlike certain physical assets that necessitate continuous data collection for real-time monitoring, pavement maintenance generally depends on periodic data collection at comparatively low frequencies, thereby reducing power consumption requirements. As the capabilities of wireless sensors advance, their incorporation into pavement monitoring systems will potentially offer reliable, rapid, and cost-effective infrastructure management solutions.

When considering sensor-based health monitoring and visualisation of built infrastructure, the concept of digital twins is emerging as a significant recent advancement as a result of its ability to bridge physical assets with their digital counterparts in real-time (Wang, Zhang, et al., 2024; Wu et al., 2022). A digital twin is a dynamic and data-driven representation of a physical entity or process that leverages the physical model, sensor data, and other information to simulate the physical entity's life cycle through continuous updates and predictive capabilities (Glaessgen & Stargel, 2012; Tuegel et al., 2011). Such digitalisation of pavements is expected to produce favourable results for condition monitoring and performance prediction by obtaining precise, real-time insights into their current service state and future deterioration patterns. However, the application of digital twins in infrastructure systems such as pavements remains challenging due to the factors such as scalability and long-term performance prediction. Recent work by Dai et al. (2024) has shown that leveraging simplified virtual models can capture key properties of physical assets while reducing computational demands and addressing scalability issues. Studies by Shen and Wang (2024) further highlight that simplified numerical modelling approaches, such as the semi-analytical finite element method, can effectively offset computational efficiency with simulation fidelity, thereby improving the feasibility of developing large-scale pavement digital twins. Wang, Zhou, et al. (2024) recently demonstrated the application of data sensing and numerical simulation techniques to develop a digital twin for the asphalt mixing process. In their study, the asphalt mixing was simulated using discrete element method (DEM) by taking inputs from the actual mixing test in the laboratory. Smart rock was employed to collect the real-time response of asphalt in terms of acceleration during mixing. The digital twin developed by combining real-time smart rock data and DEM simulation results showed significant potential for enhancing the workability and optimising the mixing parameters of materials during construction. It should be noted that the digital twin of pavements necessitates the construction of an accurate virtual model, the collection of real-time pavement response data, and the integration of real-time data and virtual model outputs (Wang, Zhang, et al., 2024). However, real-time data collection is challenging due to the difficulties associated with the accuracy and durability of sensor technologies (Rao et al., 2022).

Asphalt pavements are exposed to a variety of environmental and loading conditions. Hence, the sensing technology employed must be resilient to be able to survive rigorous service conditions while simultaneously ensuring accurate data collection. Furthermore, asphalt mixtures, which consist of asphalt binder, aggregates, and filler, exhibit specific physical characteristics as well as a wide range of material properties such as dynamic modulus, relaxation modulus, phase angle, creep compliance, etc (Wang, Zhang, et al., 2024). These properties depend on variables such as composition, binder properties, and mixture volumetrics (Birgisson & Roque, 2005). Thus, accurately designing asphalt mixtures in a digital realm remains a challenging task due to the variables involved and the intricate physical interactions of material constituents with each other. The integration of advanced computational tools such as physics engines presents a promising approach to addressing these complexities by creating detailed virtual representations capable of replicating real-world material behaviour. Physics engines have the potential to develop virtual models of physical entities by simulating physical phenomena (Garcia-Hernandez, Wan, and Dopazo-Hilario, 2021; Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021; Wan et al., 2024). The virtual model could then be updated using data collected by different wireless sensing technologies. Even though physics engines have been employed to simulate the behaviour of asphalt mixtures in the past, no study has so far integrated physics engines with real-time data-driven technologies for the digitalisation of pavements.

Physics engines are primarily used in the gaming industry to create realistic gaming experiences through simulations based on real-world physical parameters (Garcia-Hernandez, Wan, and Dopazo-Hilario, 2021; Ma et al., 2018; Ondercin, 2016). Physics engines consider objects as rigid bodies, meaning they do not deform when forces are applied to them or when they collide (Moravcik, 2025). This assumption is made to significantly minimise computational time compared to other methods, such as DEM (He et al., 2021). The rigid body simulator detects collisions to identify contact pairs between distinct objects, resolves forces and moments, and updates object position and orientation using Newton-Euler equations of motion. The use of physics engines in civil engineering extends to modelling the behaviour of granular materials, including asphalt materials. Research by Pytlos et al. (2015) and He and Zheng (2020) demonstrated the use of physics engines in simulating soil behaviour and granular mechanics. Studies by Garcia-Hernandez, Michot-Roberto, et al. (2021) generated virtual asphalt mixtures using a physics engine, creating virtual aggregates with morphological characteristics akin to those of real aggregates. Furthermore, Komaragiri et al. (2021) demonstrated the capabilities of a physics engine in modelling the compaction process of virtual asphalt mixtures. The findings of the study indicated that the developed virtual model could simulate the asphalt mixture compaction process with reasonable accuracy. Wan et al. (2023) developed virtual models for asphalt mixtures utilising a physics engine. The model's accuracy was demonstrated by accurately predicting the aggregate gradations and characteristics of various mixtures. In addition, a recent study by Awuah et al. (2024) demonstrated that asphalt mixtures designed virtually with physics engines exhibited reasonable accuracy in replicating the mechanical performance of actual pavements in the field.

In terms of advancements in sensing technology, smart rock (SR) is a wireless rock shaped device, equipped with a sensor to collect real-time infrastructure material response data. It has demonstrated significant potential for monitoring the dynamic behaviour of granular materials. In railway engineering, SR has been utilised to study the effects of loading on ballast by recording real-time particle movement in terms of both translational and rotational acceleration (Liu et al., 2017). Additionally, SR has been employed for monitoring stress and strain in granular materials (Liu et al., 2018; Zeng et al., 2022). Studies have shown the potential of SR in monitoring the dynamic response of aggregates during the mixing of asphalt and particle movement characteristics during compaction (Dan et al., 2020; Sha et al., 2023; Wang et al., 2018; Wang, Zhou, et al., 2024). It was demonstrated that SR can effectively analyse the dynamic behaviour of asphalt during mixing and compaction. The findings indicated that the dynamic behaviour of SR could be used to assess the real-time interlocking condition between aggregates. Another study has also shown the potential of SR to assess the vehicle speed for evaluating the dynamic response of pavement (Liang et al., 2023). These studies demonstrate the potential of SR to accurately measure the real-time response of asphalt mixtures. This study proposes a novel integration of physics-engine-driven simulations and real-time wireless sensing (SR technology) to explore the feasibility of developing a physics-informed digital twin-enabled cyber-physical platform for asphalt pavement monitoring. By combining the capabilities of physics-based virtual models with accurate sensor data, this research aims to develop digital technologies that can significantly enhance pavement performance prediction, facilitate proactive maintenance strategies, and ultimately support better infrastructure management decisions.

2 Scope

This study integrates real-time sensor-based technologies and physics engines to investigate the feasibility of developing a digital twin-enabled cyber-physical platform for the condition monitoring of asphalt pavements. This study includes two key aspects: (1) the development of a digital twin for asphalt mixture compaction by integrating real-time smart rock sensor data with physics engine simulations, and (2) the establishment of a framework for the development of a physics-informed platform to capture the post-compaction behaviour of asphalt mixtures. By demonstrating the potential of combining sensor data and virtual model results with other advanced technologies, this framework lays the foundation for the development of a comprehensive digital-twin-enabled platform for the condition monitoring of asphalt pavements. The proposed platform will overcome the limitations of conventional digital twins in pavements by providing a physics-informed insight into their material behaviour. This concept attempts to integrate the physical pavement entity with its virtual model and thus allow virtual models to update with time. To achieve this goal, this study (i) utilises previous research to create realistic virtual asphalt based on the composition of the real asphalt mixture using a physics engine, (ii) collects and processes the real-time data of asphalt behaviour under different conditions of loading and temperature using SR, (iii) compares the outputs from the virtual model with the physical entity data to validate the developed virtual model, and (iv) establishes a conceptual framework for the development of a cyber-physical platform to monitor the time dependent service condition of asphalt pavements.

3 Materials and methods

3.1 Materials

This study used limestone aggregates with an SMA-10 gradation. The aggregate sizes ranged from dust up to 10 mm, the gradation of aggregates is presented in Table 1. The asphalt binder utilised was a penetration grade of 40/60, a standard binder used in the UK roads. The densities of both aggregates and filler were 2700 kg/m^3, while the density of the asphalt binder was 1030 kg/m^3. In the manufacturing process of the asphalt mixtures, both the asphalt binder and aggregates were heated to 160 °C for 3 h. After heating, 5% binder was incorporated into the aggregates in a mixer. The mixture was blended as per BS EN 12697-35: (2016) for 3 min. Subsequently, the asphalt mixtures were compacted, maintaining an air-void content of 7%. Additionally, the kinetic properties of the mixture were monitored during compaction using an SR sensor.

Table 1. Aggregate gradation.

Sieve size (mm)	10.0	8.0	6.3	4	2.8	2	1	0.5	0.25	0.125	0.063
Percent passing	98.6	86.4	70.3	46.3	34.9	27.0	19.5	16.5	14.8	13.2	11.7

3.2 Methods

3.2.1 Compaction of asphalt mixture

In this study, a gyratory compactor was utilised for the compaction process. Compared to other compactors, field compaction is simulated more accurately by gyratory compactor (Komaragiri et al., 2021). During the compaction, loose asphalt mixture was placed in a mould, that rotated at an external angle of 1.25 °C, a compaction pressure of 600 kPa, and a speed of 30 revolutions per minute (rpm). When placing the loose mixture in the mould, the SR was positioned at the mid-level centre. To achieve this, half of the total quantity of the mixture was first placed in the mould as shown in Figure 1. The surface of this mixture was then manually flattened before placing the SR on top. After placing the SR, the remaining asphalt mixture was added to the mould, ensuring that the SR was approximately located at the mid-level centre of the specimen. It is important to note that every SR is equipped with a built-in global coordinate system, that is known to the operator. Regardless of how the SR is positioned within the structure, the orientation represented as a quaternion relative to the global coordinates can be accurately estimated. The external shape and placement of the sensor will not influence the collection of data or determination of orientation, provided that the initial coordinates are recorded as a reference (Wang et al., 2018).

3.2.2 Indirect tensile stiffness modulus test

The indirect tensile stiffness test is commonly used to analyse the behaviour of asphalt under dynamic loads. In this study, a Cooper Universal Testing Machine (UTM NU-10) was utilised to conduct the indirect tensile stiffness test on asphalt mixture specimens at a temperature of 20 °C. Figure 2 illustrates the testing setup used. Prior to the test, asphalt mixture specimens of diameter of 100 mm and a height of 80 mm, containing SR, were placed in a conditioning chamber set at 20 ± 0.5 °C for 12 h. Following BS EN 12697-26: (2012) guidelines, 5 haversine waveform load pulses were applied on the specimen, to achieve a desired horizontal deformation of 5 ± 2 µm. The objective of this test was not to determine the stiffness modulus of the asphalt specimen but rather to evaluate its real-time behaviour under cyclic loading.

3.2.3 Wheel tracking test

Wheel loading was simulated on asphalt mixture slabs using the Hamburg Wheel Tracker Test (HWTT), following the guidelines of BS EN 12697-22: (2020). Each specimen measured 300 × 300 × 80 mm and was compacted using a roller compactor, with SR placed at mid-depth centre of the slab. The same procedure used for compaction of cylindrical asphalt specimens, as discussed previously was followed for placing the SR at the mid-depth centre of the slab. After demoulding, the slab was preconditioned for 8 h at 20 °C. During testing, the specimens were subjected to tracking by a 50 mm wide wheel at various speeds and loadings. Load cycles were set at 26.5 and 30 rpm with loading values of 72 and 65 kg for a total of 300 cycles. The testing setup is shown in Figure 3. It should be noted that this test was not conducted to determine the rutting depth of the asphalt mix slab but to evaluate the real-time behaviour of the asphalt concrete slab under moving wheel loads.

4 Data collection using the smart rock sensor

4.1 Smart rock properties

This study used SR for monitoring the real-time behaviour of asphalt mixture under varying loading conditions. The morphology of SR resembles that of real aggregates as depicted in Figure 4(a), but its size is larger, measuring 28 × 28 × 28 mm. SR is equipped with a waterproof and high-temperature-resistant shell as shown in Figure 4(b), allowing it to withstand very high temperatures, making it suitable for high-temperature pavement construction stages such as paving and compaction (Wang et al., 2022b; Yu & Shen, 2023). One of the key advantages of SR is its wireless design, which makes it easy to install in the field

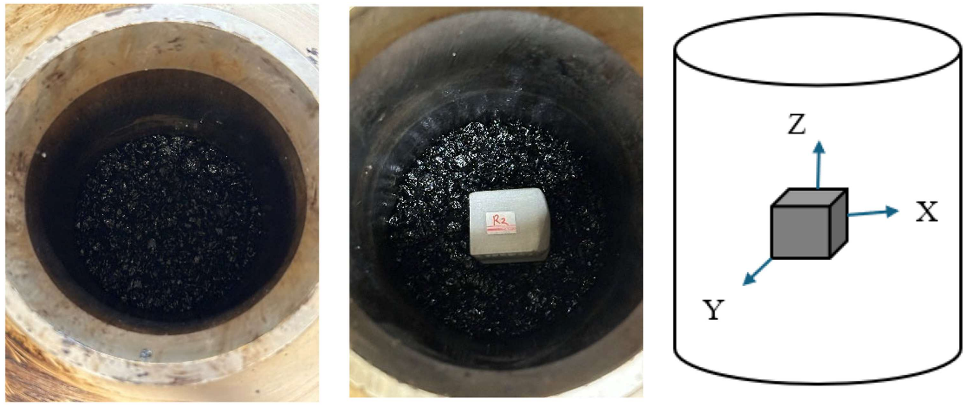


Figure 1. Placement of SR in the asphalt mixture for compaction.

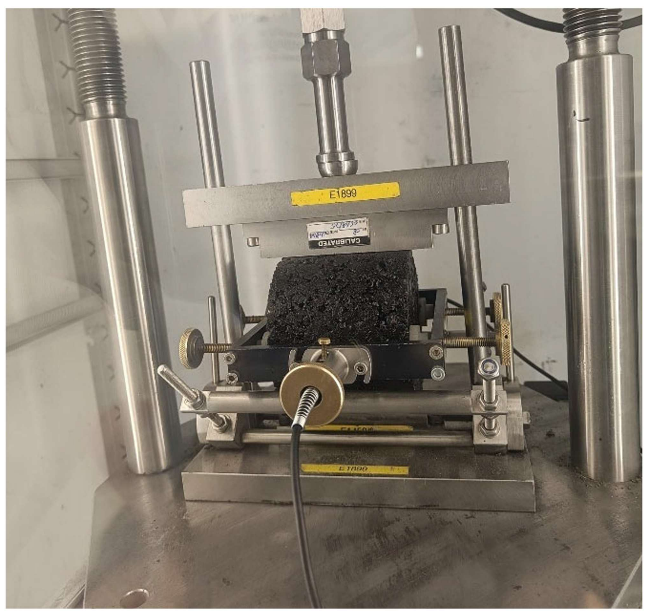


Figure 2. Testing setup for indirect tensile stiffness modulus.

Figure 3. Wheel tracking test setup.

(a) Smart Rock sensor

(b) Smart Rock sensor shell (Wang, et al. 2024)

Figure 4. SR technology components. (a) Smart rock sensor (b) smart rock sensor shell.

compared to conventional sensors. Inside the shell, there are several components, including a stress sensor, a thermometer, a gyroscope, an accelerometer, and a magnetometer. All sensor channels in the SR are connected to a single microcontroller, ensuring synchronised data acquisition from the stress sensor, accelerometer, gyroscope, magnetometer, and thermometer using a common clock. The SR can record internal temperature, rotation, acceleration, and stress in three directions within a Cartesian coordinate system. The core features also include a Bluetooth signal transmitter, a microprocessor, and a battery. SR facilitates real-time data transmission to a receiver through Bluetooth Low Energy technology for further analysis. Additionally, sleep mode can be activated to conserve battery when the collection of data is not ongoing.

The raw data collected from the SR can be processed using software such as MATLAB for further analysis. Table 2 presents the basic properties of the SR. This technology incorporates a wireless data acquisition system, and an algorithm based on data fusion. Data fusion is a process which integrates multiple data or information to produce more efficient and valuable data (Hall & Llinas, 1997). The data fusion algorithm effectively reduces error accumulation in measurements, significantly enhancing the accuracy of data sensing (Wang, Zhou, et al., 2024).

4.2 Smart rock data measuring method

SR measures the real-time data as signals; the built-in accelerometer monitors SR acceleration, while the built-in gyroscope monitors rotation. SR has a global coordinate system and a local coordinate system. The global coordinates can be obtained when Euler angles are set to zero and the direction does not change, and the local coordinate system is connected to the SR and changes when it moves (Wang et al., 2018). The data collected by SR is based on local coordinates; however, local coordinates can be converted into global coordinates. A rotation matrix can be used to perform equivalent conversions between global and local coordinates.

If Z represents a vector in global coordinates, and Z_0 represents the same vector in local coordinates, the following relation (Equations (1) and (2)) holds (Slabaugh, 1999).

$$Z = RZ_{0,} \tag{1}$$

$$R = \begin{bmatrix} \cos\theta\cos\varnothing & \sin\delta\sin\theta\cos\varnothing - \cos\delta\sin\varnothing & \cos\delta\sin\theta\cos\varnothing + \sin\delta\sin\varnothing \\ \cos\theta\sin\varnothing & \sin\delta\sin\theta\sin\varnothing + \cos\delta\cos\varnothing & \cos\delta\sin\theta\sin\varnothing - \sin\delta\cos\varnothing \\ -\sin\theta & \sin\delta\cos\theta & \cos\delta\cos\theta \end{bmatrix}, \tag{2}$$

Table 2. Properties of SR.

Property	Values
Dimensions	28 × 28 × 28 mm
Mass	53 g
Density	2.26 g/cc
Power consumption	0.4–9 mA
Temperature	−20° to 110°
Acceleration accuracy	1 mg
Tilt accuracy	0.1°
Angular velocity accuracy	0.1°/S

where R = rotation matrix and δ, θ, and $\varnothing$ = Euler angles.

The Euler angles, formulated by Leonhard Euler, are three angles that define the orientation of a rigid body relative to a fixed coordinate system (Euler, 1776). Any rotation can be represented through a sequential combination of three coordinate rotations. The SR's data of rotational movement is revealed as quaternions. With the aid of a rotation matrix, the quaternion can be transferred as the rotations in the Euler coordinates (Slabaugh, 1999). Also, the stress measured by SR is in the form of voltage signals. Stress can be calculated from voltage using Equation (3).

$$\sigma = \frac{(V - V_0 - \beta \times \ln(T) - \gamma) \times 10}{\alpha \times A}, \tag{3}$$

where σ = stress (MPa), V_0 = voltage prior to loading, V = voltage during loading, T = temperature (°C), A = stress gauge area (mm^2), and α, β, and γ = regression coefficients.

5 Development of asphalt concrete virtual model

The platform selected for developing the virtual asphalt concrete was Unity 3D, which uses NVIDIA's PhysX physics engine (Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021). This platform was chosen due to its robust physics simulation capabilities, computational efficiency, and flexibility for integration with real-time sensor data. The creation of virtual aggregates followed a previous study conducted at Nottingham transportation engineering centre (NTEC) and involved the generation of a cuboid having dimensions that correspond to the minimum and maximum Feret diameters, and the height of the real aggregates, based on a defined range determined by Weibull distributions (Garcia-Hernandez, Wan, and Dopazo-Hilario, 2021; Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021). The minimum and maximum Feret diameters and height of the real aggregate gradation were obtained using digital image analysis techniques. Subsequently, a set number of points was scattered across the surface of the cuboid and then moved perpendicularly to the surface at different distances. This process was executed to simulate aggregate morphologies that closely resemble those of real aggregates. For the simulations, the virtual aggregates are considered to be rigid and without friction, simplifying the simulations and reducing computational costs. A detailed explanation of the methodology used to develop these aggregates can be found in literature (Garcia-Hernandez, Michot-Roberto, et al., 2021; Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021).

This algorithm produces 250 g of material, with aggregate exceeding 2 mm in size. Aggregates smaller than 2 mm are classified as part of the mortar (Awuah et al., 2024; Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021; Wan et al., 2024). The material is generated within a virtual cylinder that has a diameter of 6.5 cm and a height of 50 cm. This specific diameter is chosen to minimise the number of virtual aggregates generated (Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021). To generate the virtual aggregate gradations, inputs required include the percentage and density of all aggregate types, as well as the percentages of asphalt binder and filler in the mixture. This information allows for the estimation of the masses of the aggregates and the asphalt binder. During the aggregate generation phase, the aggregates are produced randomly within the cylinder. Aggregates are generated until the specified total mass of each aggregate type is achieved. The compaction process is carried out without the influence of gravity to prevent the segregation of materials. The compaction of asphalt consists of two stages. In Stage I, virtual aggregates are created, and they are mixed using a force of 2 N applied to the centroid of every aggregate for 0.01 s every 0.5 s. Subsequently, two pistons are introduced at each end of the cylinder, moving towards one another at a constant speed till the air voids reach 50%. Once the air voids reach 50%, a virtual force is exerted on the pistons in Stage II. This force begins at 0 N and increases at a rate of 0.12 N/s if the piston's moving speed is less than 0.001 m/s, till the air void percentage matches the value determined in the laboratory (Wan et al., 2024). Figure 5 illustrates the development of the virtual asphalt mixture.

6 Results and discussion

6.1 Real-time response of mixtures during compaction

Compaction of asphalt is one of the most important stages in the construction of pavements, which affects pavement performance (Wang et al., 2018; Wang, Chen, et al., 2022; Yu & Shen, 2023). The degree of compaction influences density, air void percentage, etc., and eventually performance and durability (Wang et al., 2018). During compaction, aggregates in the mixture move, rotate, and interact to eventually form a stable structure (Wang et al., 2018). Based on this dynamic behaviour of the aggregates, the state of compaction of the asphalt mixture at any given time can be estimated. It has been reported that the stress and degree of compaction of an asphalt mixture in real time are related (Dan et al., 2020). Hence, this study measured the stress exerted on SR within the asphalt mixture during compaction as displayed in Figure 6.

During the compaction process, SR is compacted with the mixture while monitoring the stress exerted on it in three directions, i.e. X, Y, and Z. The SR records data at a frequency of 16 Hz, which allows it to collect 16 data points per second. Figure 6(a)–(c) show the stress exerted on the SR in X, Y, and Z directions, respectively, during compaction. It can be observed that the SR data is prone to noise, hence, MATLAB was used to de-noise the data. To minimise noise, a moving average filter was applied to the SR data, improving the interpretability and reliability of the stress measurements. This filter averages a certain number of data points within a sliding window and replaces each point with the average value. In Figure 6, raw data is the data measured by SR, and filtered data is the data after de-noising. The results show that stress values fluctuate over time, following a periodic pattern with peak values at regular intervals. Notably, this fluctuation pattern occurs every 2 s, corresponding to the gyratory compactor's rotation speed of 30 rpm. This suggests that the rotation of the compaction mould has a substantial influence on the stress experienced by the SR. Studies by Wang et al. (2018) and Yu and Shen (2023) also reported that the cyclic trend of Euler angle rotation occurs every 2 s, aligning with the gyratory compactor's rotation speed of 30 rpm. The stress values recorded in the X and Y directions are much lower than the stress in Z direction. This implies that the SR experiences more stress in the vertical plane than in the horizontal plane, owing to the varied loading effects of compaction along different directions.

To better understand the stress variation with respect to compaction time, mean stress values were determined in each direction. The mean stress was estimated by taking the average of the maximum and minimum stresses in the asphalt mixture during each gyration cycle. The mean stress curves in different directions are shown in Figure 7. The mean stress in the Z direction is higher than in the X and Y directions. Mean stress increases rapidly during the initial stage of compaction, as the SR receives force from nearby aggregates immediately, resulting in higher mean stress. The mean stress of the asphalt mixture does, however, stabilise as the number of gyration cycles increases. According to the studies conducted by Wang et al. (2018), the compaction process is classified into three distinct stages: the initial stage, the growth stage, and the stability stage. During this process, the accelerated fluctuations of the aggregates progressively stabilise (Chen et al., 2023; Wang, Chen, et al., 2022; Yu et al., 2022). The density curve for the asphalt mixture obtained during compaction is also shown in Figure 7. The mean stress has the same variation trend as the specimen's density. This is because the contact force between the SR and its neighbouring aggregates increases when the asphalt mixture densifies (Sha et al., 2023). As a result, increased contact force can account for increasing mean stress in all three directions. The stress measured along the X, Y, and Z axes of the SR demonstrates a significant correlation with the variation in the mixture's density. The change in the mixture's density can be characterised by the mean stress of the SR during the compaction process. Monitoring compaction in real time appears to be an effective approach

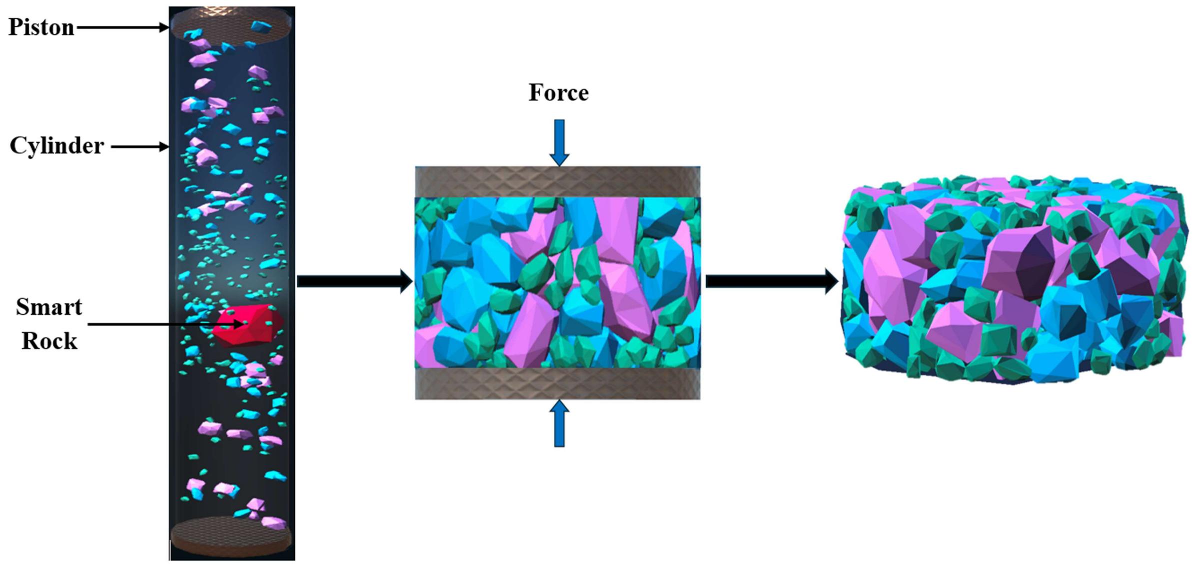


Figure 5. Asphalt concrete virtual model development.

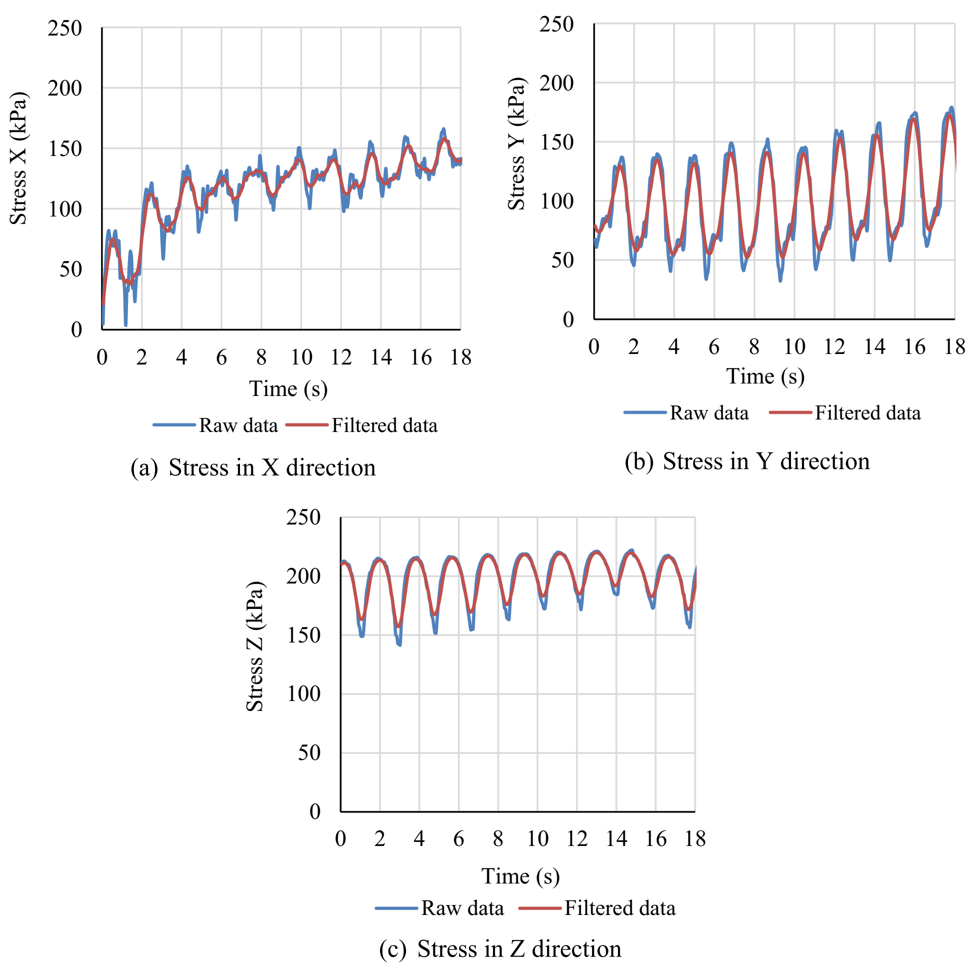


Figure 6. Stress recorded by SR along different directions.

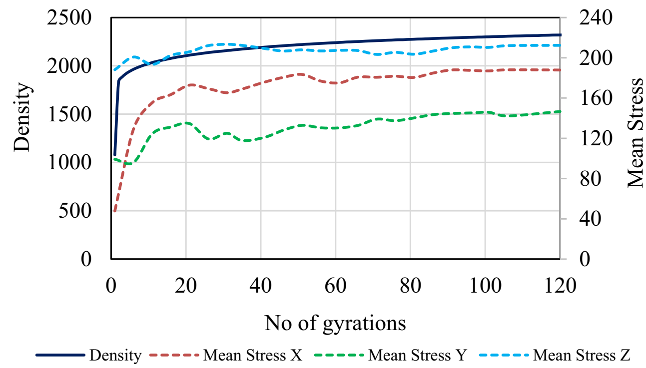


Figure 7. Density and mean stress of asphalt mixture.

for tracking the variation in mean stress and evaluating the compaction condition of an asphalt mixture. Consequently, the real-time stress response of the asphalt mixture during the compaction process can be utilised to monitor its compaction level. This allows for real-time control of compaction, enhancing both efficiency and accuracy in the compaction process by obtaining information about the internal dynamic response of aggregates, which is linked to the internal structure of the asphalt mixture.

Further, from a digital twinning perspective, analysis reveals that the synchronised periodic stress variations measured by the SR could directly feed into a digital twin model to calibrate aggregate interactions and improve the accuracy of virtual compaction simulations. Specifically, real-time variations in stress amplitude and frequency provide quantitative insights into aggregate rearrangements, enabling immediate adjustments in the virtual model parameters such as aggregate stiffness, frictional properties, and compaction force distributions. Additionally, the wireless SR technology's real-time data transmission facilitates immediate data integration and model updating, showcasing its substantial value in advancing digital model accuracy and responsiveness during pavement compaction monitoring.

6.2 Asphalt mixture virtual model validation

To validate the virtual model, the results of actual asphalt concrete manufactured in the laboratory were compared to the virtual model results developed in Unity 3D. During the compaction in the laboratory, the variation in height of the mixture was monitored. Figure 8 illustrates the variation in the height of the asphalt mixture specimen with respect to the number of gyrations. Each gyration takes 2 s to complete, based on the set rotation speed of the mould. As shown in Figure 8, the height of the asphalt mixture decreases as the number of gyrations or compaction time increases. In the initial phase of compaction, the rate of height reduction is quite significant; however, as time progresses, the height decreases more slowly until it reaches the desired height and an air void ratio of 7%.

Also, the change in air voids within the asphalt virtual model during compaction was recorded to verify its consistency with laboratory results. The consistency between the virtual model results and the experimental results is indicative of the accuracy of the virtual model. It is crucial for validation because it indicates that the model accurately reflects the behaviour of the physical entity. Figure 9 illustrates the results of the virtual compaction of asphalt concrete. The air void percentage of the asphalt shows a decreasing trend over time, aligning with the laboratory compaction results depicted in Figure 8. Similar to the changes in height, the air void content also experiences a sudden change in the initial phase of virtual compaction, followed by a gradual change until it stabilises at 7%, which is the designated air void content. However, the air void curve is not as smooth as the height curve. In Figure 9, the air void curve exhibits small peaks, which can be interpreted as the jittering effect caused by the collisions between the SR and the surrounding aggregates. Further details about this effect can be found in the literature (Garcia-Hernandez, Wan, Dopazo-Hilario, et al., 2021). It is important to note that the two curves differ because the virtual compaction of asphalt generates only the aggregates, excluding the mastic component. By comparing the virtual model results presented in Figure 9 to the experimental results presented in Figure 8, a good agreement is observed in terms of the decreasing trend represented by the height curve and air void curve

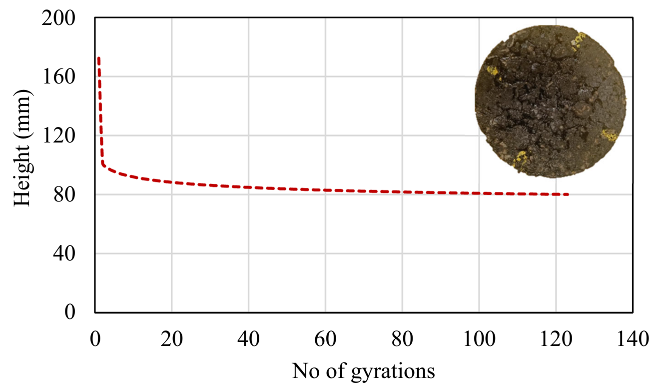


Figure 8. Height of physical asphalt mixture versus number of gyrations.

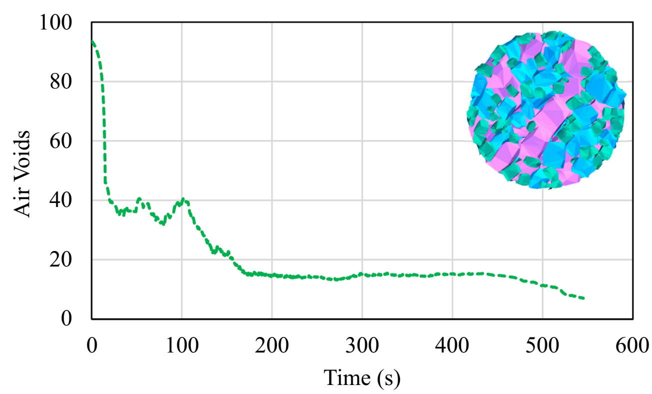


Figure 9. Air voids in virtual asphalt mixture versus compaction time.

as a function of compaction time. This demonstrates the effectiveness of the developed virtual asphalt concrete model.

In addition, the close alignment between the measured and simulated compaction curves underscores the reliability of the physics engine-based approach in capturing the key stages of asphalt densification. By replicating the decreasing trend of air voids observed in the laboratory, the virtual model demonstrates its capacity to mirror the physical asphalt's response throughout compaction. This validation sets the stage for incorporating real-time feedback from the SR sensor directly into the virtual environment, enabling the model to self-adjust its parameters, such as aggregate interaction forces or compaction load settings, in near real time. Such integration would elevate the current model into a more responsive digital twin, facilitating predictive analyses and allowing immediate modifications to compaction protocols based on actual field conditions.

6.3 Real-time response of mixtures under cyclic loading

The mechanical characteristics of asphalt pavement deteriorate under repeated cyclic loads over its service life (Wang, Wang, et al., 2024). Such deterioration of mechanical properties ultimately impacts the quality of the pavement (Wang, Zhang, et al., 2024). As a result, determining the mechanical behaviour of asphalt pavement to cyclic loads is critical for monitoring pavement quality. Thus, to simulate repetitive cyclic loading, an indirect tensile stiffness modulus test was performed on an asphalt mixture specimen containing SR.

Figure 10(a)–(c) illustrate the stress values measured along the X, Y, and Z directions, respectively, by the SR during the indirect tensile stiffness modulus test. It can be observed that the stress values vary over time in all three directions. These variations are periodic and exhibit a specific trend. The pattern of stress fluctuations occurs at regular intervals of every 3 s, corresponding to the duration of each loading cycle

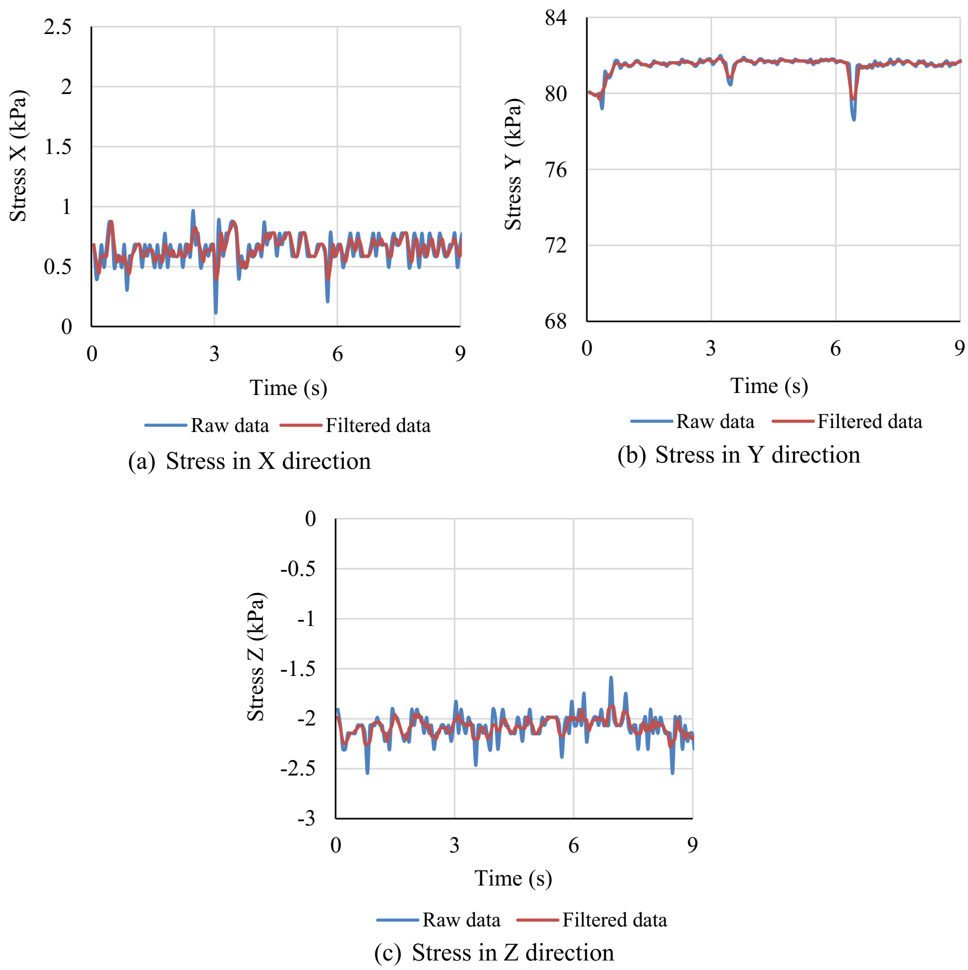
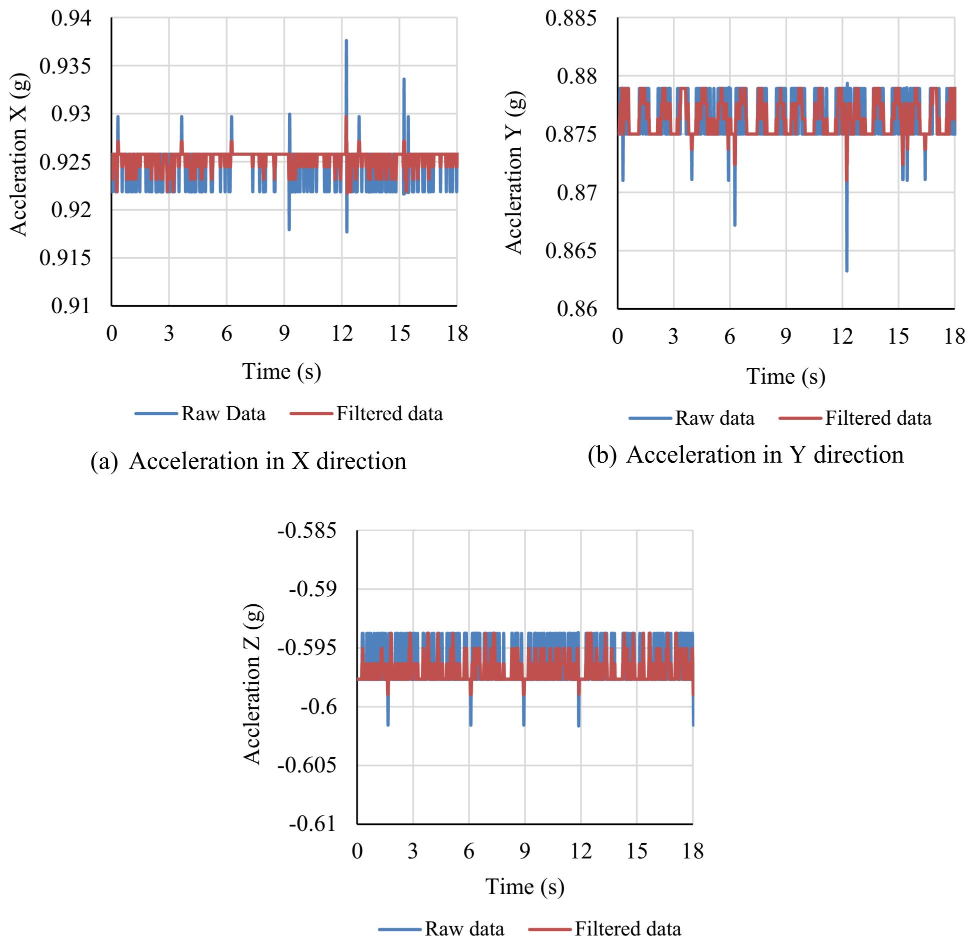


Figure 10. Stress experienced by SR in different directions.

during the dynamic testing. The stress in the Y direction is significantly higher than that in the X and Z directions. This is due to the loading being applied to the specimen along the Y direction of the SR, while the X and Z directions are oriented perpendicular to the load application. During each loading cycle, the stress along the Y direction increases with increasing load and subsequently diminishes in line with the loading pattern applied to the specimen. Throughout the entire loading process, the stresses along the X, Y, and Z axes fluctuate around 0.5, 80, and 2 kPa, respectively. However, the fluctuations in the X and Z directions are more pronounced compared to those in the Y direction. As illustrated in Figure 10(a)–(c), the stress experienced by the specimen under cyclic loading predominantly arises from the Y direction, while there is minimal stress observed in the X and Z directions. Additionally, the stress experienced by SR in all three directions is less than the stress experienced by SR during compaction. This is because the load applied in this test is relatively smaller than the load used during compaction.

During the testing process, applying load to the specimen results in not only a change in stress but also a change in the acceleration of the SR. The acceleration, which is related to the motion over time, is one of the major parameters for determining the motion of aggregates in asphalt mixture under loading (Wang, Wang, et al., 2024), it also exhibits a certain pattern, as illustrated in Figure 11. The changes in acceleration across the three directions exhibit a similar trend; however, the fluctuations in acceleration are smaller in the Y direction relative to the other two directions. This is comparable to the reduced variations in stress response in the Y direction. Throughout the entire loading process, the acceleration along the X-axis, Y-axis, and Z-axis varies around 0.925, 0.875, and 0.597 g respectively. It is important to mention that the acceleration in the X and Y directions exceeds that in the Z direction. No matter the direction, the acceleration graphs fluctuate around a specific value, which suggests that under continuous cyclic loading, the external force exerted by the aggregates in a specific direction consistently remains within a defined



(a) Acceleration in X direction

(b) Acceleration in Y direction

(c) Acceleration in Z direction

Figure 11. Acceleration of SR in different directions.

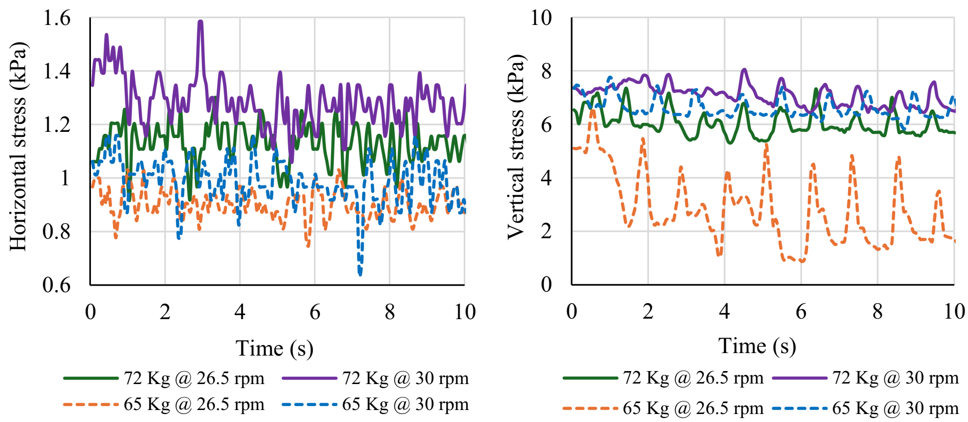
range. In conclusion, the dynamic internal behaviour of SR in asphalt specimens demonstrates the changes in the response of the asphalt mixture under repeated cyclic loading. This, in turn, reflects changes in the mechanical behaviour of the asphalt mixture, which is crucial for determining the present service state of a pavement.

From a digital twin perspective, these sensor-derived stress and acceleration profiles play an essential role in calibrating virtual models for cyclic loading scenarios. In particular, real-time measurements of load-induced deformations captured in distinct axes could be continuously fed into the digital twin to refine its representation of fatigue and rutting behaviours over repeated load cycles. The resultant model updates would enable the system to predict the asphalt mixture's evolving stiffness, potential crack initiation points, and residual service life more accurately.

6.4 Real-time response of mixture under dynamic wheel loading

Under traffic loading, asphalt pavement experiences alternating tensile and compressive stresses, which can result in permanent deformation and cracking (Wang, Zhang, et al., 2024). Such issues drastically reduce pavement service life; thus, comprehending the mechanical behaviour of asphalt pavement to dynamic traffic loads and stress evolution is critical for pavement monitoring. A wheel tracking test was performed on an asphalt concrete slab containing SR to determine its response under vehicular loading.

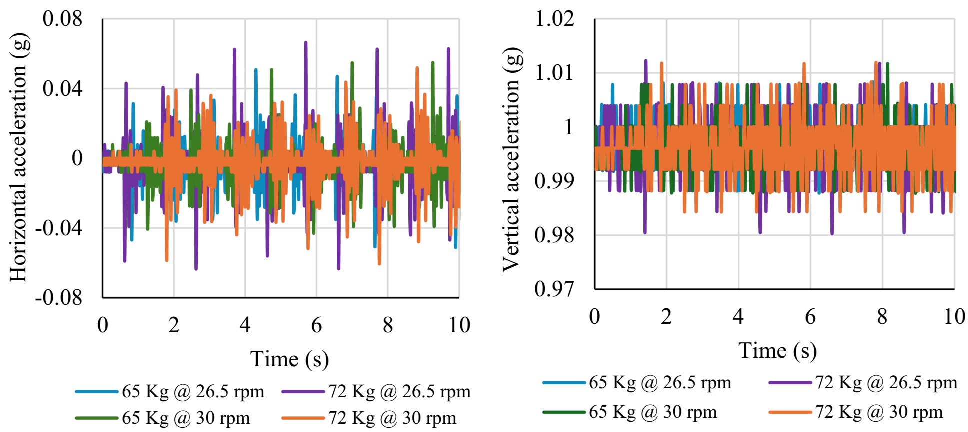
As illustrated in Figures 12 and 13, stress and acceleration along two directions were recorded by SR during the wheel tracking experiment. During the wheel loading application, the stress on SR along the two directions exhibited varying changes. Figure 12 shows that the stress pattern recurs every 2 s, aligning



(a) Stress in horizontal direction

(b) Stress in the vertical direction

Figure 12. Stress experienced by SR in different directions.



(a) Acceleration in horizontal direction

(b) Acceleration in vertical direction

Figure 13. Acceleration of SR in different directions.

with the speed of the load; this holds for the stress in both directions. The stress along the vertical direction is greater than that along the horizontal direction. The lower value of stress experienced by SR seems to occur in the horizontal direction. As stated earlier, two-wheel loads of 72 and 65 kg were simulated, along with two speeds of 26.5 and 30 rpm. It was observed that both the load values and speed values influenced the response of the SR in both directions. Figure 12(b) depicts the vertical stress applied to the asphalt mixture, representing the stress perpendicular to the direction of wheel motion. A load of 72 kg moving with a speed of 30 rpm generated the highest stress, followed closely by a load of 72 kg moving with 26.5 rpm speed. Thus, for a specific load value, a higher loading speed generates more stress than a lower speed. Studies by Shi et al. (2021) also showed that a higher vehicle speed generates higher vertical compressive stress than a lower speed for a specific value of load. The stress experienced by the asphalt mixture in the horizontal direction is depicted in Figure 12(a). It is evident that a load value of 72 kg with speeds of 30 and 26.5 rpm generates greater stress than the other two load and speed combinations.

The acceleration of SR across the two directions exhibits variation. It can be noticed that the acceleration along both directions shows peaks after a specific duration. Furthermore, the acceleration pattern recurs every 2 s, aligning with the speed of the load. The SR's acceleration in the horizontal direction varies around 0 g, whereas the acceleration in the vertical direction varies at 1 g throughout the loading process. Studies by Wang et al. (2024) has also reported that the sensor acceleration fluctuates around a particular value under repetitive loading. The acceleration of SR along the vertical direction exceeds the acceleration value along the horizontal direction, suggesting that aggregate movement along the horizontal direction is less influenced by the load of the test wheel. Thus, the overall movement seems greater in the vertical plane and lesser in the horizontal plane. This aligns with the findings from Gong et al. (2024). The vertical movement of aggregates can be related to the deformation buildup of the asphalt pavement due to prolonged vehicle loading, resulting in rutting. Rutting is among the most significant types of pavement deformation, and to understand its development, investigating the accumulation of deformation in the asphalt mixture is critical (Wang, Zhang, et al., 2024). Therefore, the real-time response of asphalt mixtures can significantly contribute to the monitoring and prediction of critical pavement failures before they occur.

From a digital twin standpoint, incorporating sensor data from dynamic wheel tracking tests allows the virtual model to capture the load-speed-acceleration relationships associated with vehicular traffic. By mapping recorded stress peaks and acceleration patterns to different load-speed conditions, the digital twin can dynamically adjust material parameters such as stiffness, damping, and viscoelastic properties to better approximate the long-term deformation behaviour of asphalt mixtures and enhance the model's predictive accuracy for rutting, cracking, and other traffic-induced failures.

6.5 Development of a cyber-physical platform

There is a considerable interest in developing next-generation platform-based technologies, such as digital twins, for autonomous real-time evaluation of pavement conditions. To achieve this goal, an integration of technologies including distributed sensor networks, AI-driven predictive analytics, IoT-enabled edge computing, and high-fidelity computational modelling must be implemented. However, the fully transformative potential for these technologies to transform road infrastructure development and management has yet to be fully explored.

One possibility of using sensor based data from pavements is the visualisation of stress distribution within asphalt to model its deterioration with time. As an illustration half-slab model of asphalt mixture (Figure 14) was developed using Abaqus software to visualise the stress distribution under wheel loading. In this model, the wheel was treated as a rigid body, and the central part of the asphalt concrete slab was replaced with a heterogeneous asphalt mixture model. In the heterogeneous asphalt model, aggregates were created using the random aggregate generation method. Aggregate particles larger than 6 mm were represented as polyhedra and generated based on the mixture's gradation, which is SMA-10. The model also included air voids ranging in size from 3 to 5 mm, comprising 7% of the asphalt mixture. Asphalt mixtures not only contain aggregates but also binder as well, hence material property such as viscoelasticity is very important and should be taken into account. Hence, the viscoelastic properties of the asphalt mixture and the fine aggregate matrix (FAM) were applied to the homogeneous slab and the matrix phase of the heterogeneous model, respectively. The aggregates were modelled as elastic materials having elastic modulus of 80 GPa and Poisson's ratio of 0.2. In the modelling process, a vertical load of 650 N was applied to the wheel, which rolled with an angular velocity of 2.65 radians per second.

Following this, the analyses were performed, and von Mises stress and maximum principal strain values were obtained. Figure 15 presents the von Mises stress and maximum principal strain as the wheel rolls to the centre of the slab. Under the applied wheel load, the region beneath the wheel experiences heightened von Mises stress and compressive stress, while the area behind the wheel is under tension, displaying elevated maximum principal strain. The higher compressive stress beneath the wheel is consistent with the stress results captured by SR. The results indicate significant variation in stress within the heterogeneous asphalt model. Analysing the mechanical response of asphalt at the scale of its constituents, the aggregate phase exhibits substantially higher stress levels than the fine aggregate matrix phase. This can be attributed to the interactions between the aggregates, which lead to the development of contact forces within the aggregate skeleton. The insights gained from this finite element analysis highlight the critical role of multiscale modelling in developing accurate digital twins for asphalt pavements. By capturing the heterogeneous nature of asphalt mixtures, including aggregate interactions, air voids, and viscoelastic binder properties, this approach enables a more realistic simulation of pavement behaviour under dynamic loading conditions. This model demonstrates the potential of computational techniques to aid in the development of digital twins of asphalt pavements by providing the visualisation of the behaviour of asphalt concrete under wheel loading.

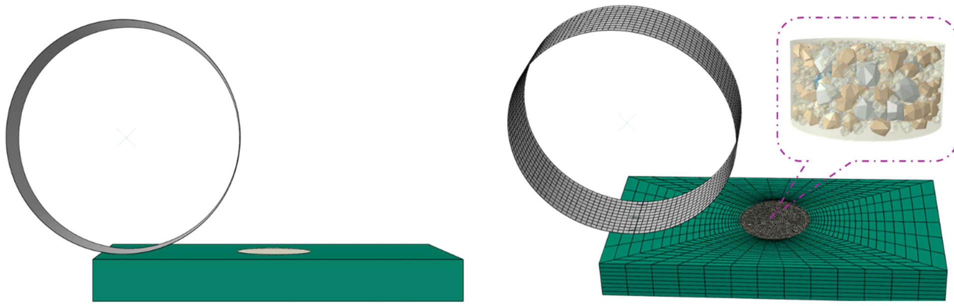


Figure 14. Asphalt concrete numerical model.

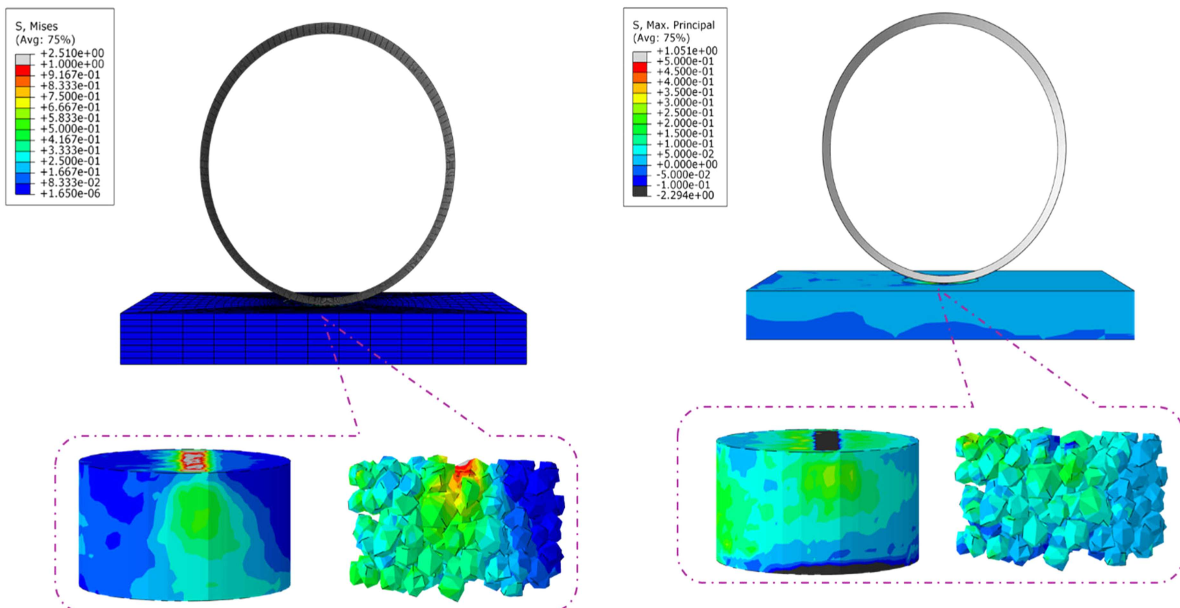


Figure 15. von Mises stress and maximum principal strain.

In this study, a digital model of a real asphalt specimen was created using physics engine, and the model was validated using findings from the compaction of real asphalt mixtures. Furthermore, the real-time response of asphalt mixtures under various loading conditions was explored using the SR sensor. However, the asphalt mixture virtual model was not updated based on the real-time data from sensors. When considering scaling up and developing a cyber-physical based platform for the management of road networks, it is essential to periodically monitor the physical asphalt pavement by collecting real-time data. This information should be utilised to update the existing virtual model of the asphalt pavement. The real-time information on the behaviour of pavement allows the virtual model to accurately reflect its current state. This continuous exchange of data between physical and virtual pavement is a crucial aspect of digitalisation. Figure 16 illustrates the conceptual framework of the cyber-physical platform.

A theoretical cyber-physical platform for a road network would consist of four integrated phases:

(1) Data Collection Phase: This phase involves a physical pavement equipped with an embedded sensor network that monitors real-time behaviour, including mechanical responses and pavement conditions such as temperature, moisture, etc. These sensors should be capable of resisting harsh environmental conditions and transmitting data in real-time. Additionally, specialised sensors (e.g. strain gauges or fibre-optic sensors) can be embedded at different depths within the asphalt to capture more granular data on stresses and strains. Integrating weather stations and traffic counters further enriches the dataset, helping to correlate pavement degradation with climatic and loading factors.

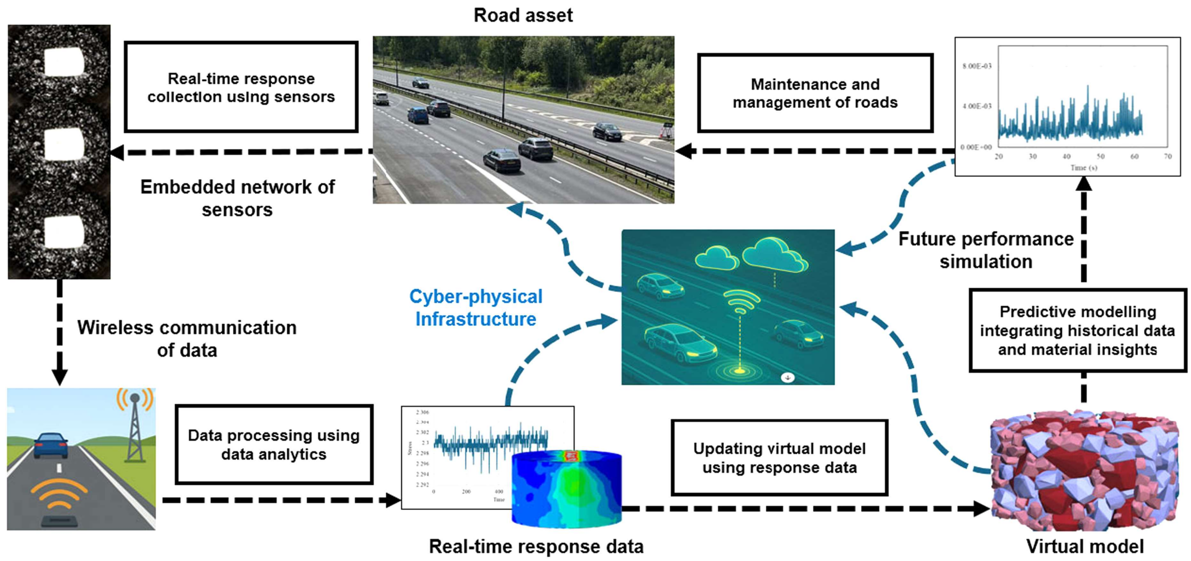


Figure 16. Cyber-physical platform framework.

(2) Data Analysis and Processing Phase: In this stage, it is crucial to remove irrelevant data and retain only valid information to minimise the load associated with data processing. Advanced data analytics techniques could be employed to implement filtering algorithms, allowing for better interpretation of the collected data. For example, machine learning-based anomaly detection can remove outliers or sensor errors, while predictive analytics can reveal patterns in pavement distress. Moreover, leveraging distributed computing or cloud resources can speed up the processing of large, continuous data streams.

(3) Virtual Model Updating Phase: The virtual model would represent the physical road asset that is continuously updated with the latest information to accurately reflect the real-time state of the pavement. This would be achieved by optimising the model parameters to the real-time condition of the physical pavement using an iterative process based on machine learning algorithms, etc. The updated model can then make predictions based on historical data and material characteristics with a high level of accuracy. Incorporating high-fidelity finite element simulations, along with periodic recalibration using sensor inputs, ensures that the digital twin remains responsive to changing pavement conditions. Furthermore, employing advanced calibration techniques (e.g. genetic algorithms, Bayesian updating) can systematically refine material properties, thus enhancing predictive capabilities.

(4) Asset Management Phase: Following the update of the virtual model, the predictions generated regarding the future performance are used for the optimal maintenance and management of the road infrastructure. By integrating reliability-based assessments and life-cycle cost analysis, decision-makers can prioritise maintenance tasks according to both pavement risk factors and budget constraints. The ability to forecast potential failure points or critical distresses facilitates proactive interventions, minimising downtime and extending overall pavement service life.

7 Findings and conclusions

This study investigated the feasibility of developing a digital twin-enabled cyber-physical platform for condition monitoring of asphalt pavements by integrating physics engine and smart rock sensor technologies. The integration of these technologies showed excellent potential for monitoring the construction and service state of pavement infrastructure. The following key findings can be drawn from this study.

(1) SR based sensors can effectively monitor the compaction process of an asphalt mixture by collecting variations in the stress experienced over time. The SR's real-time response in terms of stress in the X, Y, and Z directions is a promising indicator for characterising and optimising the asphalt mixture compaction.

(2) The validation of the asphalt virtual model demonstrates its potential to be updated using SR data to reflect the real-time condition of the physical entity. This presents a novel approach integrating physics engines with data-driven technologies for the real-time monitoring of pavements.
(3) During repetitive cyclic loading, the responses gathered by the SR in terms of acceleration and stress in the X, Y, and Z directions demonstrate changes in the dynamic internal response of the asphalt mixture with loading time.
(4) The real-time response to dynamic wheel loading conditions in terms of stress displays the evolution of stress within the asphalt mixture. Also, the SR's real-time acceleration data represents aggregate motion, which can be linked to the accumulation of deformation in asphalt pavement layers. The response captured by SR is dependent on the speed and loading values simulated over the asphalt concrete.
(5) The integration of SR data with virtual model simulation results and other advanced technologies establishes a framework for the development of a cyber-physical platform for a road network. It is anticipated that the platform will ultimately aid in managing the pavement construction process and condition monitoring by providing real-time information about the service condition of the pavement.

8 Limitations and future work

While the proposed framework demonstrates promising results for pavement condition monitoring, there are several research gaps that need to be addressed including scaling issues and environmental variability. The developed virtual model does not currently consider the asphalt binder characteristics; therefore, it differs from real asphalt in terms of viscoelastic behaviour.

Future research will focus on using a network of sensors to collect a database of pavement response under different environmental and loading conditions at various locations in a specimen. The stresses generated from the applied loads will be compared with the stresses recorded by the sensors to validate the accuracy and potential of the sensors within the digital twin system. Complementary research will also focus on improving the virtual model by considering the time-dependent material behaviour (viscoelasticity) to simulate asphalt concrete response under dynamic loading conditions, as well as updating the model to reflect the real-time state of actual asphalt using SR data.

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Disclosure of LLMs usage

No large language models (LLMs) were used in the preparation of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

All data, or codes used in this study may be made available from the corresponding author upon reasonable request.

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