Case Study

Coordinated Use of Digital Construction Tools for Renewal Design of Low-Volume Roads: A Norwegian Case Study

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Abstract: The implementation of building information modeling (BIM), enabling the creation of digital database files containing semantic representation of civil structures and infrastructures, also concerns the field of road engineering. Differently from highly trafficked motorways, low-volume roads (LVRs) represent the largest part of the global road network, and this type of transportation infrastructure has received minimal attention in terms of BIM implementation in academic research. This work investigates the coordinated use of digital tools to enable the renewal of LVRs according to an integrated framework comprising georeferencing, alignment tracing, estimation of quantity take-offs, and evaluation of mechanical response as well as service life. This study ascertains a repeatable workflow using five systems: Autodesk InfraWorks, Autodesk Civil 3D, Autodesk Dynamo, COMSOL Multiphysics, and MATLAB. The research considers the rehabilitation of a Norwegian LVR located in Våler municipality as an application case study, the aim of which is to renew the road pavement by employing new aggregates for its reconstruction. This work assumes that the mechanical properties of the road construction materials are evaluated in the laboratory by means of repeated load triaxial tests. In this regard, six scenarios are envisaged: unstabilized, stabilized by a traditional binder (bitumen), and stabilized by four nontraditional polymeric binders (polyurethane, acrylate, styrene butadiene, and acetate). All five stabilization techniques lead to economic savings and improved mechanical performance. Compared with bitumen-treated aggregates, the adoption of nontraditional binders entails a longer road service life, although at a higher cost. **DOI:** 10.1061/AOMJAH.AOENG-0004.

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Introduction

Building Information Modeling

Building information modeling (BIM) is a digital semantic representation of physical and functional features of real objects (Eastman et al. 2008) and has been applied to design, construct, monitor, and maintain built facilities (Cheng et al. 2016; He et al. 2017). As a computer-based workflow, BIM enriches three-dimensional (3D) computer-aided design (CAD) information with additional *n*D dimensions of an asset, such as time, cost, and sustainability (Ding et al. 2014; Lee et al. 2020). The implementation of BIM in the architecture, engineering, construction and operation (AECO) industry has been gaining traction during the last two decades, finally emerging into the mainstream and accruing significant technical and economic benefits (Azhar 2011; Bryde et al. 2013; Jung and Joo 2011; Succar 2009). Moreover, the application of BIM standards is becoming mandatory in many countries around the world, such as the Scandinavian region, the United Kingdom, and Singapore (Shou et al. 2015; Smith 2014; Wong et al. 2010).

As documented by several academic review studies, BIM has been initially implemented in buildings (Volk et al. 2014; Zhao 2017) and then in civil infrastructure belonging to the domains of transportation, energy, utility, and water management, only to name a few (Bradley et al. 2016; Salzano et al. 2023). In this regard, the application of BIM in academic research revolving around transportation infrastructure (e.g., highways, railways, airports, bridges, transit hubs, tunnels, and ports) has been slowly adopted (Moreno Bazán et al. 2020; Costin et al. 2018; Wu et al. 2022). This delay can be ascribed to the major differences existing between the more traditional *vertical BIM* (e.g., schools, high rises)

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and the *horizontal BIM* (e.g., roads, railways, tunnels): design requirements, spatial development, and construction and maintenance processes (Costin et al. 2018).

Low-Volume Roads

Low-volume roads (LVRs) are road pavements characterized by low annual average daily traffic (AADT), in general, AADT < 1,000 vehicles/day (Douglas 2016; Robinson and Thagesen 2004; Silyanov et al. 2020). Worldwide, their importance is obvious, considering that approximately 65% of the global road network, which is roughly 22 million km long, can be classified as LVR (Lay et al. 2021; Meijer et al. 2018; Silyanov and Sodikov 2017).

A traditional flexible road infrastructure includes several layers to transfer vehicle loads to a natural substrate. Starting from the top, the layers are generally classified as wearing, binder, base, and sub-base. Wearing and binder courses are usually bounded by bitumen or cement, while base and sub-base courses commonly comprise only unbound aggregates (unbound granular materials, UGMs) (Huang 2004; Islam and Tarefder 2020; Mallick and El-Korchi 2023; Thom 2014). When it comes to LVRs, the bound layers are often very thin (a few centimeters) or absent; in the latter case, the base layer is directly exposed to trafficking actions. Globally, LVRs often exhibit poor conditions and reduced accessibility mainly because of a lack of maintenance operations (Henning et al. 2014; Jalali et al. 2019; Keller and Sherar 2003; Labi et al. 2019). In Norway, it has been estimated that the backlog in required maintenance exceeds 100 million euros, thus possibly compromising the structural integrity of roads and leading to premature damage (Aursand and Horvli 2009; Barbieri et al. 2017).

As a possible solution to alleviate these problems, binder technologies can be employed to effectively improve the mechanical properties of UGM courses and contribute to environmental and economic savings (Gomes Correia et al. 2016). The stabilization process is an in situ operation consisting of mixing the existing aggregates or soil with the chosen binder technology (and water, if necessary) by means of a cold recycler machine. Currently, several stabilizers are available on the market (Jones 2017) and can be classified either as traditional binders (i.e., bitumen, cement) and as nontraditional binders (Tingle et al. 2007). A remarkable amount of academic field and laboratory research has been performed on traditional technologies (Douglas 2016; Huang 2004; Islam and Tarefder 2020; Mallick and El-Korchi 2023; Robinson and Thagesen 2004; Thom 2014). On the other hand, very few coordinated academic research efforts have focused on achieving a comprehensive understanding on nontraditional ones (Barbieri et al. 2022a, b; Santoni et al. 2002, 2005; Tingle and Santoni 2003), which can be categorized according to five types when it comes to the stabilization of coarse-graded aggregates: brine salt, clay, organic petroleum, organic nonpetroleum, and synthetic polymer.

Research Objective and Literature Review

Considering the current academic literature, the main research gap addressed by this research is to propose an integrated workflow produced by BIM and digital tools that can be used in the engineering design and renewal of LVRs. In this regard, this study refers to the rehabilitation of an LVR in Norway as an application case study. Here, it is important to mention that the identification of such an academic gap may not warrant sufficient knowledge gap definition, especially since BIM and related systems are industry tools and processes. In this research, considerations are made when stabilizing the UGM aggregates constituting the base layer by means of both traditional and nontraditional binders. Overall, the case study addresses the following main topics: road georeferencing and alignment tracing, estimation of material volumes and costs, achievement of road structural analysis, and, finally, evaluation of its service life. Based on these premises, this work offers new perspectives on BIM implementation and broadens its application for road transportation infrastructure, as illustrated in Table 1, for at least three reasons.

First, the existing academic studies have largely focused on the different life stages of high-trafficked roads [high-volume roads (HVRs)], such as highways and motorways. Kim et al. (2014, 2016) developed a system to automatically assess, cut, and fill quantities, costs, and schedules for different road alignments leveraging the computer-interpretable representation format in compliance with the international standard ISO 10303. Zhao et al. (2019) dealt with the identification of the best alignment by means of genetic algorithms integrating BIM tools, such as Autodesk Revit, Autodesk Civil 3D, and Autodesk Navisworks, with geographic information systems (GISs) such as Esri ArcGIS and Esri ArcMAP. When it comes to highway maintenance and management, Jing et al. (2019) used Autodesk Civil 3D, Autodesk Revit, and Autodesk InfraWorks to document the necessary operations for the rehabilitation of road, bridge, and ancillary facilities. Vignali et al. (2021) employed Autodesk Civil 3D and Autodesk Revit to facilitate the upgrade of a new highway segment. Jiang et al. (2022) detailed the operations of road demolition and related costs leveraging a combination of aerial photographs and government statistics to build cross sections based on horizontal and vertical road marking lines. Sankaran et al. (2016) and Zhang et al. (2020) synthetized the major lessons learned during collection, management, and utilization of digital information from an industrial standpoint and academic education perspective, respectively. When it comes to LVRs, Abbondati et al. (2020) showed the potential of Bentley OpenRoads and Bentley LumenRT software tools to achieve parametric modeling of a major rural road. Khalil et al. (2021) and Raya and Gupta (2022) leveraged Autodesk Civil 3D and Autodesk InfraWorks to perform a geometric design and hydraulic study of unpaved roads.

Second, only two academic studies in road engineering have shed light on the potential of visual programming (VP) algorithms and the importance of integrating BIM systems with structural analysis software (Tang et al. 2020a, b). Such research efforts centered on two main areas: (1) the development of an indirect data conversion interface between Autodesk Revit and the modelling software ABAQUS; and (2) the creation of a Python subroutine to enable the structural analysis of road structures parametrically defined in Autodesk Dynamo.

Third, a combination of BIM and innovative construction technologies can reduce the environmental impact of constructing, maintaining, rehabilitating, and demolishing civil infrastructures, which is a key area where the transition to carbon neutrality can benefit from BIM implementation (de Bortoli et al. 2023; Patel and Ruparathna 2023). Only a previous study integrated BIM models with laboratory results, which were derived from testing traditional asphalt concrete (Oreto et al. 2021), but no structural analysis was performed.

Methodology: BIM and Digital Tools

The successful implementation of BIM is closely related to the employment of computational resources (Kim et al. 2014; Sankaran et al. 2016). Among the several software suites currently available on the market, the Autodesk platform is largely used in both

Table 1. Overview of the scientific studies using digital tools for planning construction operations of road infrastructures

Source	Road type		Use of VP algorithms		Georeference road alignment	Material volume analysis	Material cost analysis	Activity schedule analysis	Road structure analysis	Material laboratory tests
	LVR	HVR	Yes	No						
Kim et al. (2014)	—	X	—	X	X	X	X	X	—	—
Kim et al. (2015)	—	X	—	X	X	X	—	—	—	—
Chong et al. (2016)	—	X	—	X	X	—	—	X	—	—
Kim et al. (2016)	—	X	—	X	X	X	X	X	—	—
Vitásek and Matějka (2017)	—	X	—	X	X	X	X	—	—	—
Zhao et al. (2019)	—	X	—	X	X	—	X	—	—	—
Jing et al. (2019)	—	X	—	X	X	—	—	—	—	—
Abbondati et al. (2020)	X	—	—	X	X	X	—	—	—	—
Moreno Bazán et al. (2020)	—	X	X	—	X	X	X	—	—	—
Tang et al. (2020a)	—	X	X	—	X	—	—	—	X	—
Tang et al. (2020b)	—	X	X	—	X	—	—	—	X	—
Khalil et al. (2021)	X	—	—	X	X	X	—	—	—	—
Oreto et al. (2021)	—	X	X	—	X	—	—	—	—	X
Vignali et al. (2021)	—	X	—	X	X	X	X	—	—	—
Raya and Gupta (2022)	X	—	—	X	X	—	X	X	—	—
Han et al. (2022)	—	X	X	—	X	—	—	X	—	—
Jiang et al. (2022)	—	X	—	X	X	X	X	—	—	—
This study	X	—	X	—	X	X	X	—	X	X

Note: VP = visual programming; LVR = low-volume road; and HVR = high-volume road.

industry and academia worldwide, thanks to its effective working environment and competitive cost (Cheng et al. 2016; NBS Enterprises 2020). On a global basis, the early adoption of BIM in the 2000s took place in the Nordic countries, with Norway displaying a highly capillary distribution among designers and professionals (Bui et al. 2019; Smith 2014; Wong et al. 2010). Today, all major public and private players in the Norwegian industry mandate the use of BIM for their projects requiring compliant models (Bane NOR 2022; NPRA 2015; Statsbygg 2023). Moreover, Norwegian universities and research institutes have taken the initiative to promote related education (Barbieri et al. 2023b; Bråthen 2015; Hjelseth 2018; Lassen et al. 2018).

In the light of the above, this study aims at creating a repeatable workflow using five software tools that are commonly employed in engineering consulting companies and research institutes (based in either Norway or worldwide): Autodesk InfraWorks, Autodesk Civil 3D, Autodesk Dynamo, COMSOL Multiphysics, and MATLAB. To assess the relevant mechanical parameters necessary to perform a structural analysis and appraise the mechanical stress–strain state, the results obtained from laboratory repeated load triaxial tests (RLTTs) on stabilized and unstabilized aggregates are considered. Autodesk InfraWorks, Autodesk Civil 3D, and Autodesk Dynamo are the BIM tools, whereas COMSOL Multiphysics and MATLAB are the digital tools employed to perform a structural analysis after considering the outputs of BIM systems. Based on the outcomes deriving from this structural analysis, any needed changes (e.g., road thickness, type of construction materials) can be subsequently defined back into the BIM model, thereby creating an iterative process lasting until the calculated construction cost and mechanical response meet any possible desired requirements. The conceptual diagram of this study is displayed in Fig. 1.

Road Georeferencing

The position of existing transportation infrastructures and their spatial relationships can be defined by Autodesk InfraWorks. This software consents the integration of the GIS and BIM domain for model establishment and rendering (Biancardo et al. 2020a; Bosurgi et al. 2019; Oreto et al. 2021). The geopositioned objects corresponding to structures, water bodies, and terrains are built on a satellite map using OpenStreetMap (OSM), which employs the WGS-84 standard coordinate system. The Model Builder tool provided by Autodesk InfraWorks enables the creation of 3D models with a maximum area of 200 km^2, which are saved with .imx file extension. As the Model Builder leverages the open database source OSM to generate a terrain, the level of precision can vary depending on the area of the project. OSM elevations are fairly accurate on average, while the accuracy and completeness patterns for Norway are high (Haklay 2010; Schultz et al. 2017; Zhou et al. 2022). Field survey data could be used instead to achieve the best possible accuracy. The level of development (LOD) specification indicates the accuracy and completeness of the model geometry and related information. Currently, six different levels (LOD 100, LOD 200, LOD 300, LOD 350, LOD 400, and LOD 500) are defined and these levels display increased clarity and reliability (Bedrick et al. 2020; Latiffi et al. 2015). Autodesk Infraworks enables the creation of models embracing the entire spectra spanning from the conceptual design (LOD 100) to the as-built operational definition (LOD 500). For the considered case study, the related level can be estimated between LOD 300 and LOD 350 because the model includes the creation of details and elements precisely displaying size, shape, and location. However, this aspect does not hinder the general purpose of this work, namely, to employ the necessary digital tools that can define a repeatable workflow in LVR engineering.

Alignment Definition

After the definition of the road position, further construction details can be specified on the terrain model using Autodesk Civil 3D importing the .imx file generated by Autodesk InfraWorks. In this software, a road alignment is represented by a corridor consisting

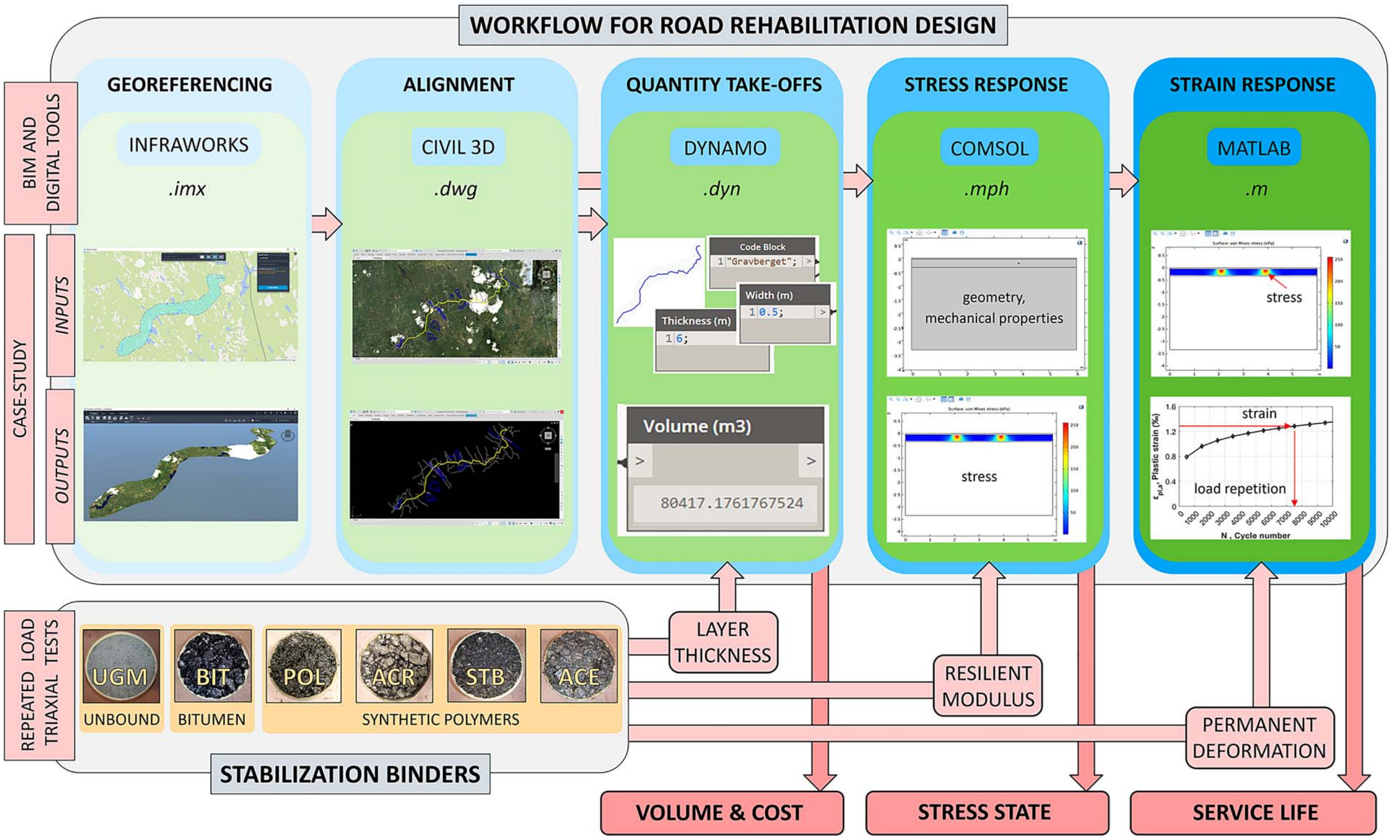

Fig. 1. Conceptual diagram of the study.

of horizontal and vertical alignments as well as cross sections at different stations. Autodesk Civil 3D can be employed to create draft, design, and construction documentation that streamline CAD and BIM workflows; for example, material quantities, work schedules, and operation costs (Kim et al. 2014; Lee et al. 2020; Oreto et al. 2021). From an economic point of view, an evaluation of the bill of quantities based on dimensions and volumes is a highly relevant exercise that exerts a major influence on project realization (Chong et al. 2016; Jiang et al. 2022; Vitásek and Matějka 2017; Zima 2017). Models created with Autodesk Civil 3D are saved with .dwg file extension.

Estimation of Material Volumes and Costs

The evaluation of the volume and cost of the materials needed for road construction is usually achieved in Autodesk Civil 3D. Nevertheless, Autodesk Dynamo represents an innovative plug-in software that can perform these calculations. Autodesk Dynamo is a VP algorithm; that is, it is a visual process chart composed of input and output blocks linked by connectors, which, to some extent, can replace traditional scripts containing code lines (Autodesk 2023). This versatile VP tool simplifies the creation of parametric processes and automatizes repetitive tasks without the need for having advanced programming knowledge (Saito et al. 2017). The visual scripts created using Autodesk Dynamo are saved using .dyn file extension and can be directly uploaded in the chosen host Autodesk suite.

Unlike architectural projects executed with Autodesk Dynamo having Autodesk Revit as the host software, VP tools have been scarcely applied in infrastructure engineering, as testified by academic literature, and they have been mainly used for bridges and tunnels (Collao et al. 2021). Because very few academic studies have shed light on the potential of Autodesk Dynamo in road engineering (Oreto et al. 2021; Tang et al. 2020a, b), this work performs the work of extraction of volume and cost by means of the VP tool instead of Autodesk Civil 3D. Here, it is important to mention that possible discrepancies between academic research and industry practice may exist, because large engineering firms employ VP tools quite extensively for automating various tasks. The main advantage offered by Autodesk Dynamo over Autodesk Civil 3D is that the user can easily leverage the visual script to appreciate the desired outputs (e.g., volume and cost) by modifying the value of the relevant inputs (e.g., road thickness and road width) contained in the corresponding input blocks. On the other hand, the same process performed in Autodesk Civil 3D would require the user to traverse through several lengthy dialog boxes, which can be customized to a much lesser extent.

Assessment of Mechanical Stress–Strain Response

The BIM design workflow and structural analysis are usually regarded as two separate parts. To integrate these, Autodesk developed Autodesk Robot Structural Analysis software, which, however, shows significant limitations (e.g., definition of structure geometry, selection of constitutive model), and its adoption is presented in very few academic studies (Biancardo et al. 2020b; Hasan et al. 2019). COMSOL Multiphysics is created by COMSOL Inc. and can be used to perform advanced numerical analysis also with regard to the mechanical response of road pavements (Barbieri et al. 2019, 2021b; Podolsky et al. 2017); the associated file extension is .mph. Because this software may become overly complicated for everyday engineering practice, this study models a road section with fully controllable parameters (i.e., geometry, mechanical properties) and boundary conditions using the Application

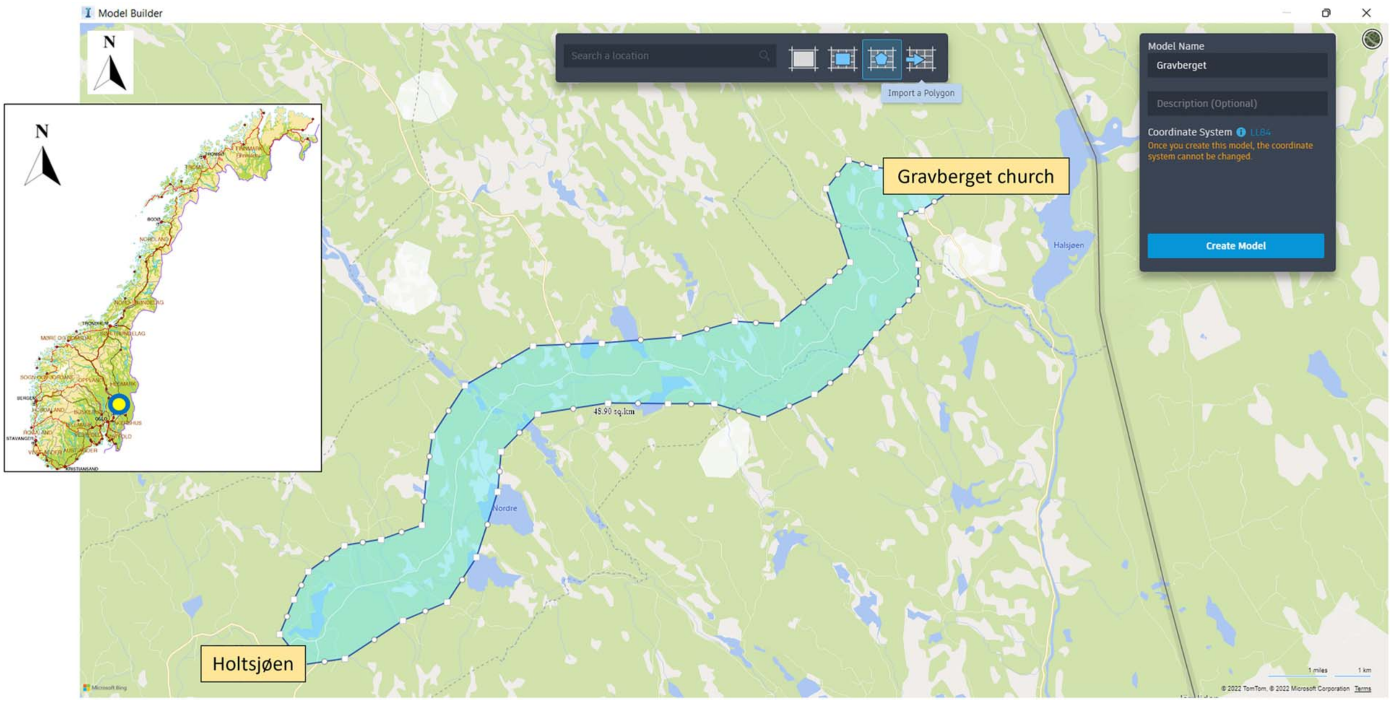

Fig. 2. Geographical position of Gravberget road and adjacent terrain in Autodesk InfraWorks. (Map data © OpenStreetMap contributors, Autodesk screenshot reprinted with permission from Autodesk, Inc.)

Builder: geometrical parameters are specified by the user based on the Autodesk Civil 3D model, whereas the constitutive relationships derive from the results of the laboratory repeated load triaxial tests (RLTTs) performed on stabilized and unstabilized rock aggregates.

For each stress level (i.e., triaxial stress σ_t, deviatoric stress σ_d) obtained in the structural analysis performed with COMSOL Multiphysics, the corresponding experimental dataset of plastic strains measured with RLTTs is considered to estimate the road service life. In this regard, the RLTT data are analyzed according to regression models using MATLAB, which is a software developed by MathWorks. MATLAB is a programming language platform that is widely employed by users having varied numerical computing skills and professional backgrounds (Arif and Khan 2021; Assi 2011; Lu and Lee 2017); the file extension used to save a MATLAB script is .m.

Case Study: Gravberget Road

Description

The LVR considered in this study is the county road Fv 491 Gravberget located in Våler municipality, Innlandet county, Norway. The stretch between the localities (Holtsjøen and Gravberget) church is 6 m wide and has a length of approximately 25 km. Fig. 2 displays the geographical position of Gravberget. The portion of terrain lying in proximity is highlighted using the Model Builder of Autodesk Infraworks and covers 48.9 km^2.

Table 2. Main traffic characteristics of the existing Gravberget road

AADT	AADT$_{\mathrm{HEAVY}}$	Design speed (km/h)	Axial load limit (ton)
150	15	80	10

The road structure is composed of a bituminous bound top surface stratum and an unbound base stratum lying on the natural subgrade. According to the limited historical information available, the road was built during the 1960s without following any precise design code indications, and the thin surface layer has been repaved several times since then. The aggregates used in the base layer were collected directly along the road alignment, and no standard tests were performed to ascertain their conformity with quality.

Recently, the Norwegian Public Roads Administration (NPRA) has started the upgrade of several county roads to accommodate higher trafficking loads, especially heavier timber trucks, in accordance with the project "Gross Weight 74 Tons" (NPRA 2020). As Gravberget is part of this program, some preliminary measurements, also comprising falling weight deflectometer (FWD), have been performed to characterize the geometry and bearing capacity of the existing road. The main information is reported in Tables 2 and 3. FWD measurements indicate an average resilient modulus of a subgrade equal to 300 MPa. The aim of this road renewal is to remove the aggregates currently forming the base layer and replace them with new and certified aggregates, and eventually apply a new asphalt layer on the top. This case study has been selected considering the central position of this road stretch in the project "Gross Weight 74 Tons." However, the procedure discussed and findings obtained in this study can be extrapolated to similar projects; in this way, the proposed framework can also be further validated.

Table 3. Main structural characteristics of the existing Gravberget road

Layer	Material	Thickness (cm)
Top course	Asphalt concrete	4
Base course	Graded rocks	30
Subgrade	Sand	—

Table 4. Denomination, contained water, price estimate, and application rate in the mass of traditional and nontraditional binder technologies

Type	Code	*w* content (%)	Price (€/kg)	Applied rate (%)
Bitumen	BIT	0	0.5	3.0
Polyurethane	POL	0	4.0	4.5
Acrylate	ACR[a]	48	0.6	1.2
Styrene Butadiene	STB	40	3.9	1.2
Acetate	ACE	51	3.6	1.2

Sources: Adapted from Barbieri et al. (2022a, b).
[a]Bicomponent technology.

Traditional and Nontraditional Polymeric Binders

The amount of construction material necessary to renew the base layer of Gravberget can be reduced by employing binder technologies, which improve the mechanical properties of the aggregates (Celauro et al. 2015; Praticò et al. 2011). Bitumen (BIT) is considered as a typical traditional binder. With regard to nontraditional technologies, recent work has thoroughly compared the performance of all the existing types of additives to stabilize coarse-graded aggregates (Barbieri et al. 2022a, b 2023a). Based on the outcomes of these studies appraising the mechanical response of the stabilized material in terms of stiffness, permanent deformation, stripping potential, and resistance to 10 freeze–thaw (FT) cycles, this research considers the technologies that have offered the overall best performance, namely synthetic polymeric binders. These additives can be classified as polyurethane (POL), acrylate (ACR), styrene butadiene (STB), and acetate (ACE); their degree of toxicity varies from none to moderate (Kunz et al. 2022). Table 4 details their most relevant aspects: the amount of water dissolved in each binder, the price estimate excluding transport cost, and the considered application rate.

Repeated Load Triaxial Tests

The main parameters that are necessary to numerically model the unstabilized and stabilized rock aggregates are the resilient modulus M_R and the permanent deformations, which can be evaluated in the laboratory by means of RLTTs (Barbieri et al. 2021a; CEN 2004; Wang et al. 2023). Unlike cyclic triaxial tests, which are cumbersome and time-demanding investigations, Los-Angeles (LA) and micro-Deval (MDE) are two test procedures that are routinely performed (CEN 2010, 2011), although they cannot provide information that is directly related to structural behavior, as in the case of RLTTs.

Table 5. Gradation curve used for base layer renovation

Sieve (mm)	Passing (%)
45	100
31.5	95
22.4	65
16	40
2	16
0.25	6
0.063	4

The construction materials to be used to renew the base layer are crushed rocks originating from the nearest quarry located in Ingeberg, which is a village in Hamar municipality approximately located 70 km away from Gravberget (Hamar Pukk og Grus AS 2023). The LA and MDE values of the aggregates from Ingeberg (LA = 17.3, MDE = 15.0) are very similar to the LA and MDE values of the aggregates from Vassfjell, which is a mountain area close to Trondheim municipality, and these values were investigated in two other previous studies (LA = 18.2, MDE = 14.2) (Barbieri et al. 2022a, b). Furthermore, the density of the crushed rocks from Ingeberg (2,800 kg/m^3) and from Vassfjell (2,950 kg/m^3) are similar. Compounding this with the fact that the LA and MDE values can be efficiently related to the results of RLTTs (Adomako et al. 2021), this study assumes that the RLTT data obtained for the crushed rocks from Vassfjell (Barbieri et al. 2022a, b) are also valid for the ones from Ingeberg. The price of the aggregates is 35 €/t and the gradation considered corresponds to a typical Norwegian base layer (NPRA 2014, 2018), as reported in Table 5. The appearance of the RLTT samples is depicted in Fig. 3.

A multi-stage low stress level (MSL SL) RLTT is composed of five load sequences. In turn, each of them is formed by six load steps, which correspond to a precise combination of deviatoric stress σ_d and triaxial stress σ_t. During each load step, σ_t is kept constant, while σ_d is applied 10,000 times following a sinusoidal pattern with the maximum values listed in Table 6 (Barbieri et al. 2021a; CEN 2004).

The resilient modulus M_R indicates the elastic stiffness of the material and is defined as the ratio between dynamic deviatoric stress $\sigma_{d,\mathrm{dyn}}$ and elastic axial strain $\varepsilon_{el,a}$ (Lekarp et al. 2000a). Considering the RLTT experimental data, M_R can be calculated based on the well-known Hicks and Monismith (1971) formulation

$$M_R = k_1 \sigma_a \left(\frac{\theta}{\sigma_a}\right)^{k_2} \tag{1}$$

where σ_a is a reference pressure equal to 100 kPa, θ is the sum of the principal stresses σ_1, σ_2, and σ_3 ($\sigma_2 = \sigma_3$), and k_1 and k_2 are regression coefficients. As reported in Fig. 4, this study evaluates the resilient modulus as the average trend based on the results obtained by testing the samples both before and after the exposure to 10 FT cycles (Barbieri et al. 2022a, b 2023a).

Considering the models developed to fit the experimental data of permanent strain derived from RLTTs (Lekarp et al. 2000b), the well-known logarithmic formulation proposed by Sweere (1990) is employed to evaluate the accumulation of plastic axial deformation $\varepsilon_{pl,a}$ as a function of the number of load repetition N

$$\mathrm{Log}(\varepsilon_{pl,a}) = a + b \cdot \mathrm{Log}(N) \tag{2}$$

where a and b are regression coefficients. This formulation is used to analyze the permanent deformations measured during each load step independently from the previous ones (Gidel et al. 2001).

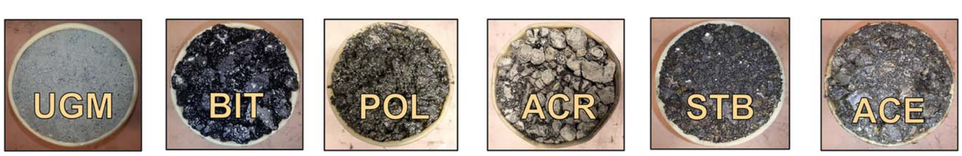

Fig. 3. Appearance of tested RLTT samples. UGB = unbound granular material; BIT = bitumen; POL = polyurethane; ACR = acrylate; STB = styrene butadiene; and ACE = acetate. (Adapted from Barbieri et al. 2022a, b.)

Table 6. Combination of σ_t and σ_d values for an MSL SL RLTT (data in kPa)

	Sequence 1		Sequence 2		Sequence 3		Sequence 4		Sequence 5	
Step	σ_t	σ_d	σ_t	σ_d	σ_t	σ_d	σ_t	σ_d	σ_t	σ_d
1	20	20	45	60	70	80	100	100	150	100
2	20	40	45	90	70	120	100	150	150	200
3	20	60	45	120	70	160	100	200	150	300
4	20	80	45	150	70	200	100	250	150	400
5	20	100	45	180	70	240	100	300	150	500
6	20	120	45	210	70	280	100	350	150	600

Structural Analysis

The Norwegian pavement design code "N200" implements a mechanistic-empirical methodology for road design and requires the definition of several input parameters (NPRA 2018). The stiffening effect engendered by the application of a binder, either traditional or nontraditional, allows for the reduction in thickness of the stabilized base layer, thereby also beneficially reducing the demand for new construction aggregates (de Bortoli 2023). This can be calculated starting from the RLTT results in terms of resilient modulus M_R, as indicated by the pavement design code "N200" (Barbieri et al. 2022b). The values of the base thickness for each stabilization scenario, conceptually depicted in Fig. 5, are reported in Table 7.

The elastic stiffness M_R deriving from RLTTs is a relevant mechanical property needed to perform the structural modeling appraising the stress level of the road pavement (Alnedawi et al. 2022; Ghadimi and Nikraz 2017; Titi and Matar 2018). The objective of the analysis is to characterize the typical stress state in the middle of the base layer, so that the corresponding plastic deformations and service life can be estimated using the Sweere model. The numerical modeling is performed with COMSOL Multiphysics considering a two-dimensional road section. The constitutive relationship implemented for the base layer is the Hicks and Monismith model (Barbieri et al. 2021b). As depicted in Fig. 6, the application builder enables an efficient parametric definition of the geometrical and mechanical inputs, which are specified by the user. Broadly speaking, the proposed framework can take into consideration and analyze different road sections independently. However, this investigation assumes that all possible sections of the selected 25-km road stretch have the same mechanical behavior and service life.

Results and Discussion

The terrain model with the georeferentiation of Gravberget is illustrated in Fig. 7, which depicts the road surface placed on the satellite ground map in Autodesk InfraWorks. It is also worth emphasizing in this section that this case study has been selected in light of the central position of Gravberget road in the project "Gross Weight 74 Tons" (NPRA 2020). However, the findings discussed here can be extrapolated to similar projects related to the renewal of LVRs. In this case, the corresponding terrain models can also be generated based on the satellite map OSM implemented in Autodesk InfraWorks.

Based on these data, Autodesk Civil 3D automatically generates the road stretches covering the entire route of Gravberget. All the stretches are merged into one (highlighted in yellow) using the Kobi Toolkit for Autodesk Civil 3D. Therefore, it is possible to represent both horizontal and vertical alignments, as illustrated in Figs. 8 and 9, respectively.

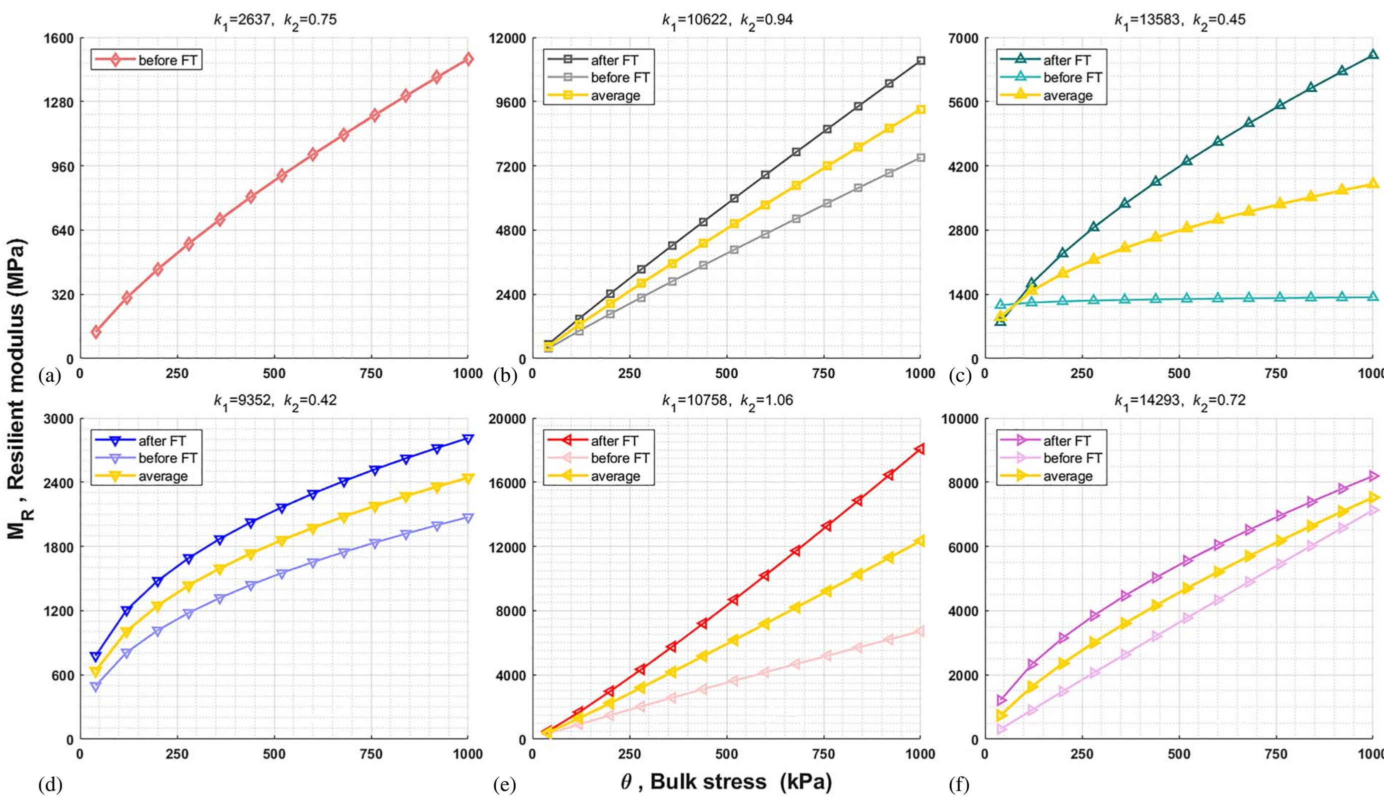

Fig. 4. Resilient modulus M_R of unstabilized and stabilized materials: (a) UGM; (b) BIT; (c) POL; (d) ACR; (e) STB; and (f) ACE. (Adapted from Barbieri et al. 2022a, b, 2023a.)

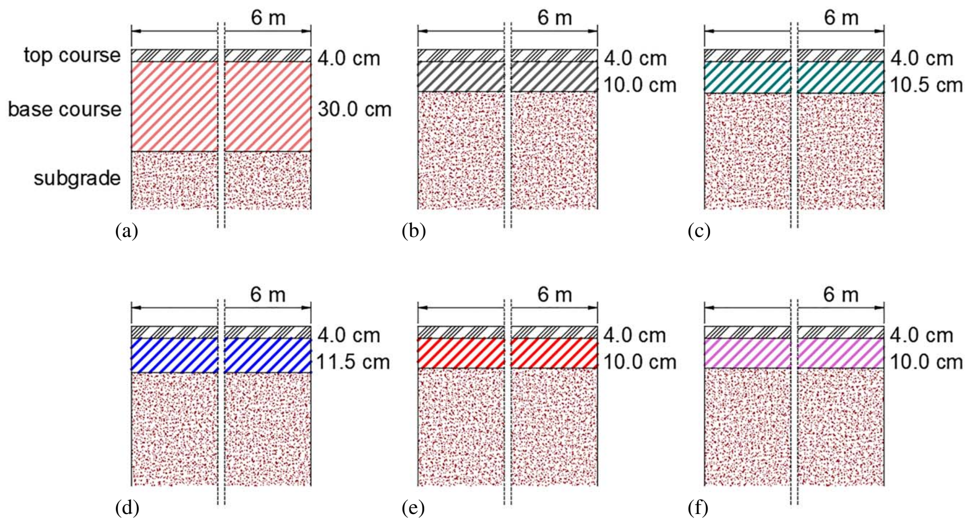

Fig. 5. Typical road cross section for each considered stabilization scenario: (a) UGM; (b) BIT; (c) POL; (d) ACR; (e) STB; and (f) ACE.

Table 7. Thickness of a base layer for different stabilization technologies

Binder type	Thickness (cm)
UGM	30
BIT	10
POL	10.5
ACR	11.5
STB	10
ACE	10

Source: Adapted from Barbieri et al. (2022b).

Material Volumes and Costs

An evaluation of construction volumes is necessary to estimate the cost of the rock aggregates used in the renewal of the base layer. In this regard, the Autodesk Dynamo visual script depicted in Fig. 10 illustrates the code blocks and connections that are created to visualize the road alignment (depicted in blue) and calculate the volume for the specified thickness and width.

The construction volumes are assessed by inputting in the Autodesk Dynamo script the different thicknesses of both unstabilized

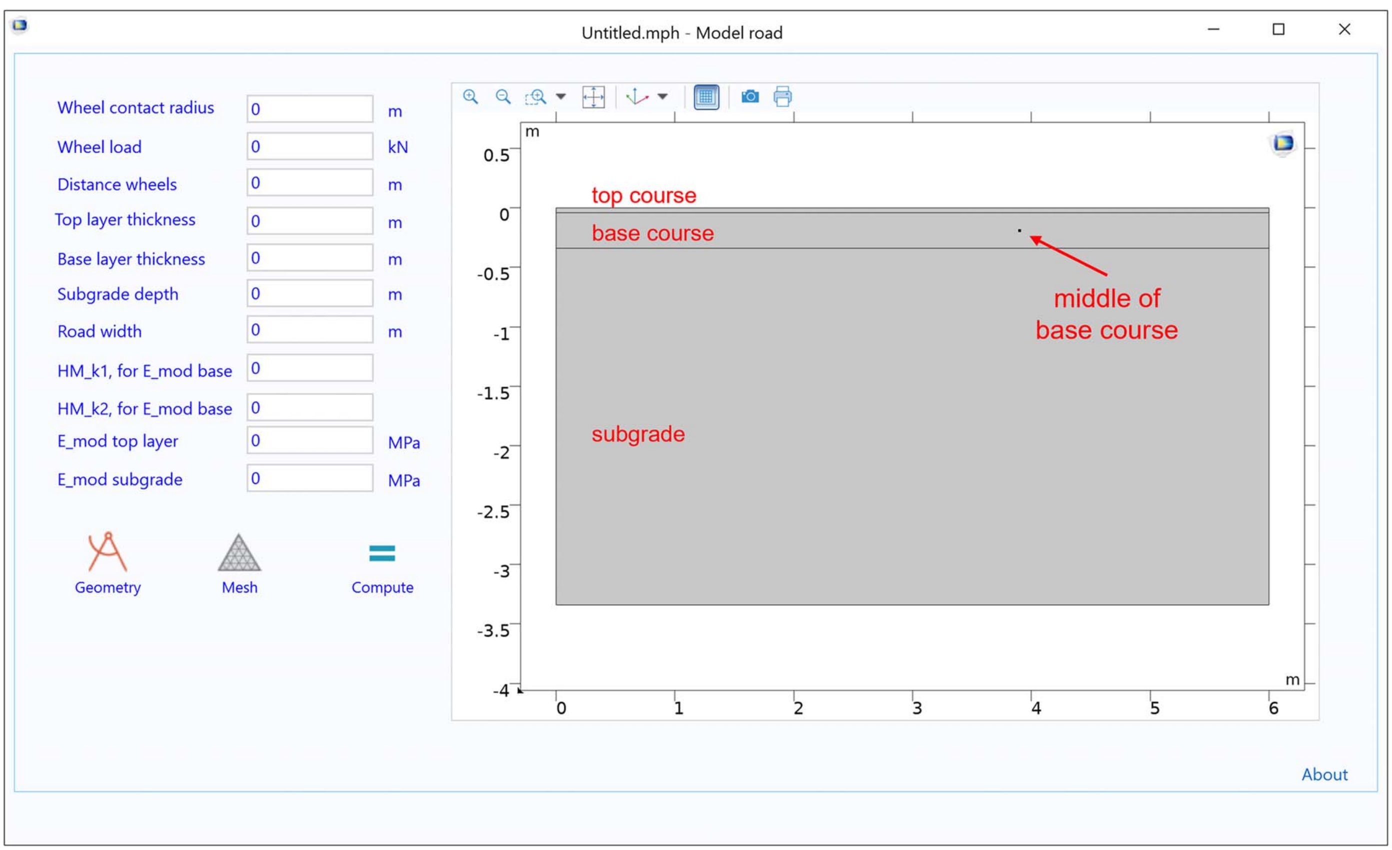

Fig. 6. Parametric modeling of a road structure created with application builder of COMSOL Multiphysics.

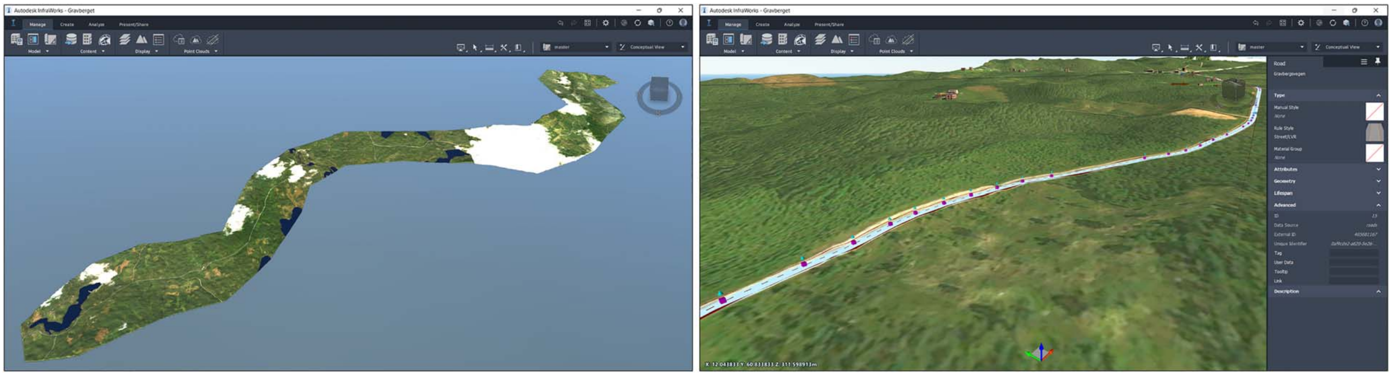

Fig. 7. Terrain model and rendering of Gravberget road. (Autodesk screenshot reprinted with permission from Autodesk, Inc.)

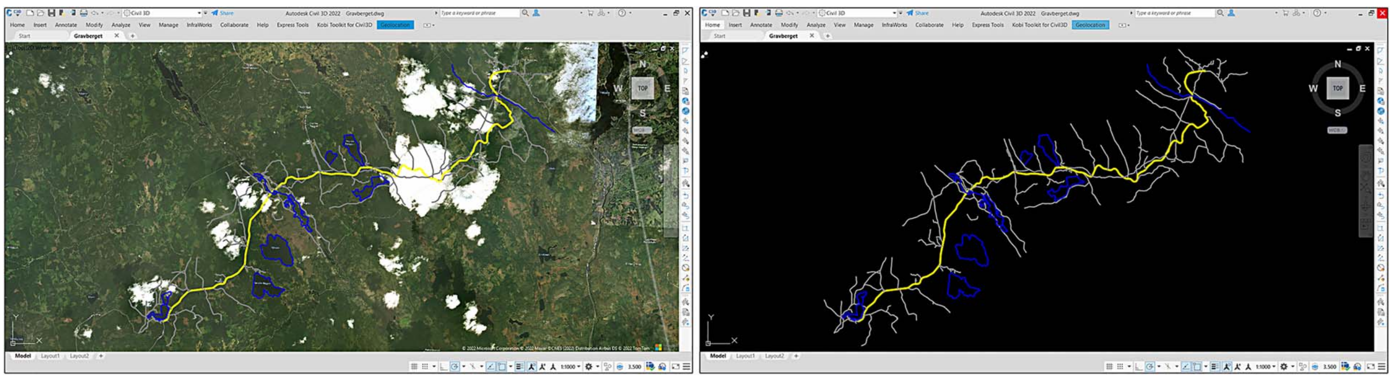

Fig. 8. Horizontal alignment of Gravberget. (Autodesk screenshot reprinted with permission from Autodesk, Inc.)

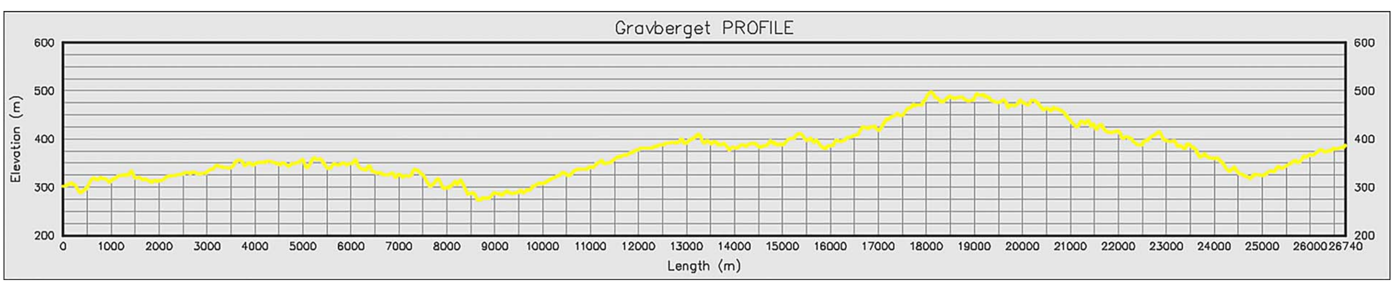

Fig. 9. Vertical alignment of Gravberget. (Autodesk screenshot reprinted with permission from Autodesk, Inc.)

and stabilized base layers, as displayed in Table 7. The material costs consider the prices of both aggregates (35 €/t) and binders applied according to the percentages reported in Table 4. The transport cost calculations are performed using a part of the "HERMES CO_2" spreadsheet tool, which was originally developed to quantify the amount of carbon dioxide emissions and related costs associated with the main stages of a road life span, such as production, construction, and use (Barbieri et al. 2021c). The content of the "HERMES CO_2" tool can be freely edited by the user, for instance by specifying the properties of the desired construction machines, the geometry of each layer course, and traffic volume. This study takes into consideration only the transport cost related to the construction phase assuming a typical medium on-road truck traveling at 50 km/h with average capacity equal to 13 m^3, fuel consumption 0.25 L/km, and operating cost of 200 €/h. These average figures derive from the largest Norwegian companies providing rental equipment including operators (Barbieri et al. 2022b). As already stated, the considered average transport distance is 70 km and corresponds to the stretch between Gravberget and the nearest quarry. The results are reported in Table 8.

The use of binders contributes to a significant reduction in the quantity of needed rock aggregates and therefore envisages positive environmental effects such as reduction in the carbon footprint associated with the production and transport of natural resources

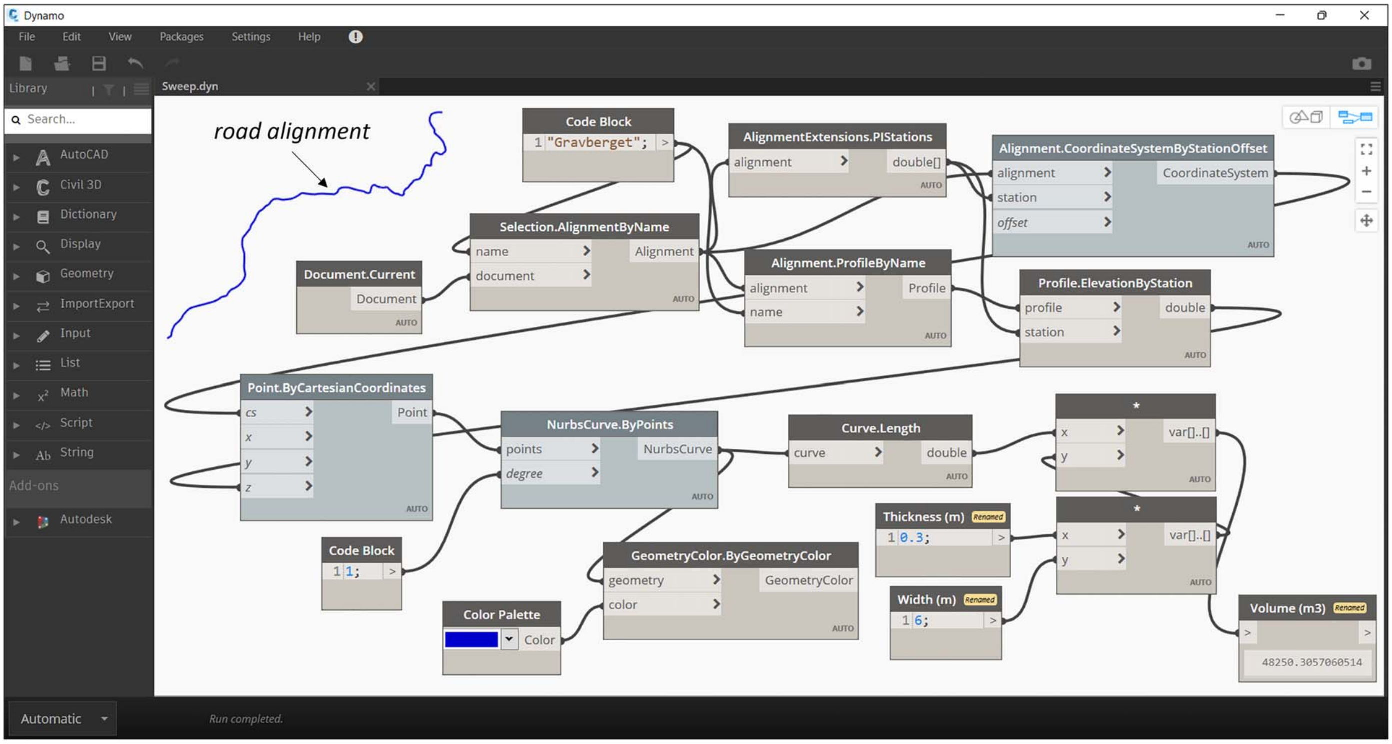

Fig. 10. Dynamo script for visualization of road alignment (depicted in blue) and calculation of base layer volume. (Autodesk screenshot reprinted with permission from Autodesk, Inc.)

Table 8. Volume of aggregates and associated costs (material and transport) for the different stabilization technologies for base layer rehabilitation

Binder type	Volume (m^3)	Material (€)	Transport (€)	Total (€)
UGM	48,250	1,688,778	2,161,636	3,850,414
BIT	16,083	804,180	720,545	1,524,725
POL	16,888	3,630,873	756,573	4,387,445
ACR	18,496	774,196	828,627	1,602,823
STB	16,083	1,817,447	720,545	2,537,992
ACE	16,083	1,980,909	720,545	2,701,454

(Balaguera et al. 2018; van der Merwe Steyn and Visser 2011). From a cost standpoint, all additives contribute to economic savings. In this regard, the only exception is represented by polyurethane POL, because its application is even more expensive than the creation of a base layer using unstabilized aggregates. Compared with the use of other nontraditional polymeric additives, the traditional binder bitumen BIT is the cheapest alternative. This finding is in good agreement with that of other studies, indicating that the higher costs of polymeric technologies are mainly due to the current small commercial scale (Bushman et al. 2005; Khoeini et al. 2019).

Stress State

An estimation of the stress state in the base layer is important for the appraisal of the permanent deformation and associated service life. As illustrated in Fig. 11, the Application Builder in COMSOL Multiphysics allows for a parametric definition of the road geometry, which is composed of a top layer, base layer, and subgrade. The

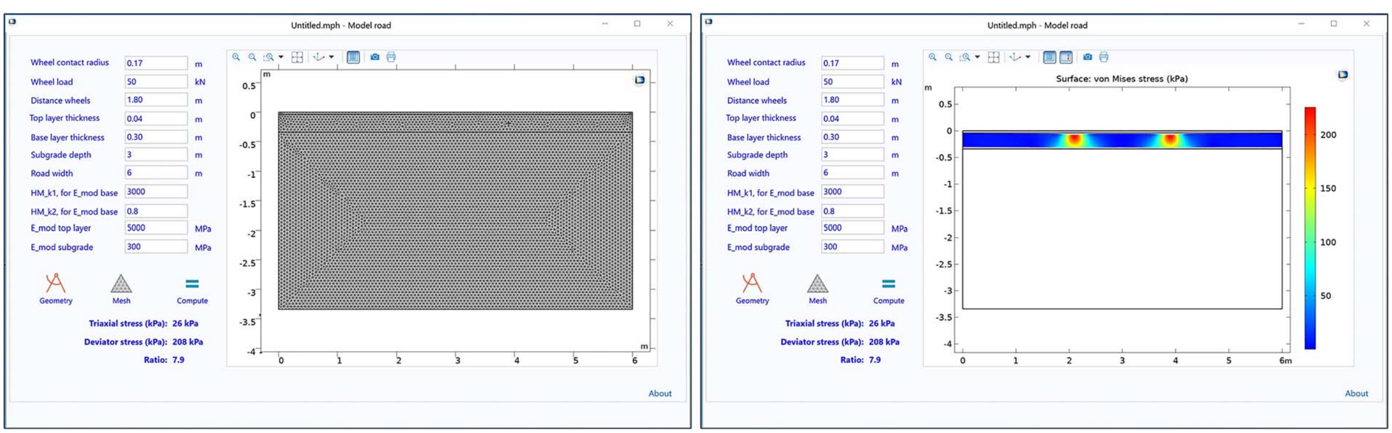

Fig. 11. Meshing of the road structure and computation of stresses in the base layer.

tire pressure is uniformly distributed and the standard axle load corresponds to 10 t (NPRA 2018). The constitutive behavior of the base layer is defined by the average nonlinear elastic relationships represented in Fig. 4. The elastic stiffness of the subgrade E_{sub} is 300 MPa, as already discussed. With regard to the elastic modulus of the top layer E_{top}, this case study considers the recent findings estimating the mechanical properties of the asphalt mixtures typically used throughout Norway (Chen et al. 2022, 2023a, b, c). Referring to this Norwegian dataset and the geographical location of Våler municipality, two extreme values are considered as representative of as many climatic and traffic conditions: $E_{\text{top}} = 2{,}000$ MPa (high temperature, slow loading) and $E_{\text{top}} = 20{,}000$ MPa (low temperature, quick loading).

Table 9. Stress state evaluated using COMSOL Multiphysics for two different values of E_{top} and the corresponding closest stress state achieved during RLTT (data in kPa)

		$E_{\text{top}} = 2{,}000$ MPa		$E_{\text{top}} = 20{,}000$ MPa	
Binder type	Stress	COMSOL	RLTT	COMSOL	RLTT
UGM	σ_t	37	45	17	20
	σ_d	252	210	201	120
BIT	σ_t	69	70	104	100
	σ_d	290	280	309	300
POL	σ_t	67	70	99	100
	σ_d	289	280	304	300
ACR	σ_t	65	70	93	100
	σ_d	283	280	287	300
STB	σ_t	71	70	102	100
	σ_d	293	280	312	300
ACE	σ_t	72	70	104	100
	σ_d	292	280	314	300

Table 9 reports the triaxial stress σ_t and the deviatoric stress σ_d values assessed by COMSOL Multiphysics at the middle of the base layer as well as specifies the closest stress state achieved during RLTT among the ones listed in Table 6. For stabilized base layers, a slightly higher RLTT stress state ($\sigma_t = 100$ kPa, $\sigma_d = 300$ kPa) is associated with a stiffer top layer ($E_{\text{top}} = 20{,}000$ MPa), whereas a softer top layer ($E_{\text{top}} = 2{,}000$ MPa) is associated with a lower RLTT stress condition ($\sigma_t = 70$ kPa, $\sigma_d = 280$ kPa). Considering an unstabilized UGM base course, the deviatoric stress σ_d calculated with COMSOL Multiphysics is significantly higher than the associable σ_d values exerted during the LSL MS RLTT.

Service Life of a Base Layer

The accumulated plastic axial deformations $\varepsilon_{\text{pl},a}$ for the stress states listed in Table 9 are reported in Fig. 12 (for $E_{\text{top}} = 2{,}000$ MPa) and Fig. 13 (for $E_{\text{top}} = 20{,}000$ MPa). The trends obtained by testing the samples both before and after exposure to 10 FT cycles (Barbieri et al. 2022a, b 2023a), as well as the corresponding average trends, are calculated by using a MATLAB script that fits the experimental RLTT in accordance with the Sweere formulation based on the least-squares method.

The service life of the base layer is estimated by assessing the number of load repetition N leading to permanent deformation $\varepsilon_{\text{pl},a} = 1‰$ (CEN 2004), as reported in Table 10. The unstabilized aggregates UGM exhibit the worst performance, because the corresponding N values are at least smaller by two orders of magnitude compared with stabilized materials. The beneficial effect provided by the application of additive binders in terms of prolonged service life and associated reduced frequency of maintenance operations is apparent for all stabilized materials. Acetate ACE is characterized by the best result because the corresponding N values have an

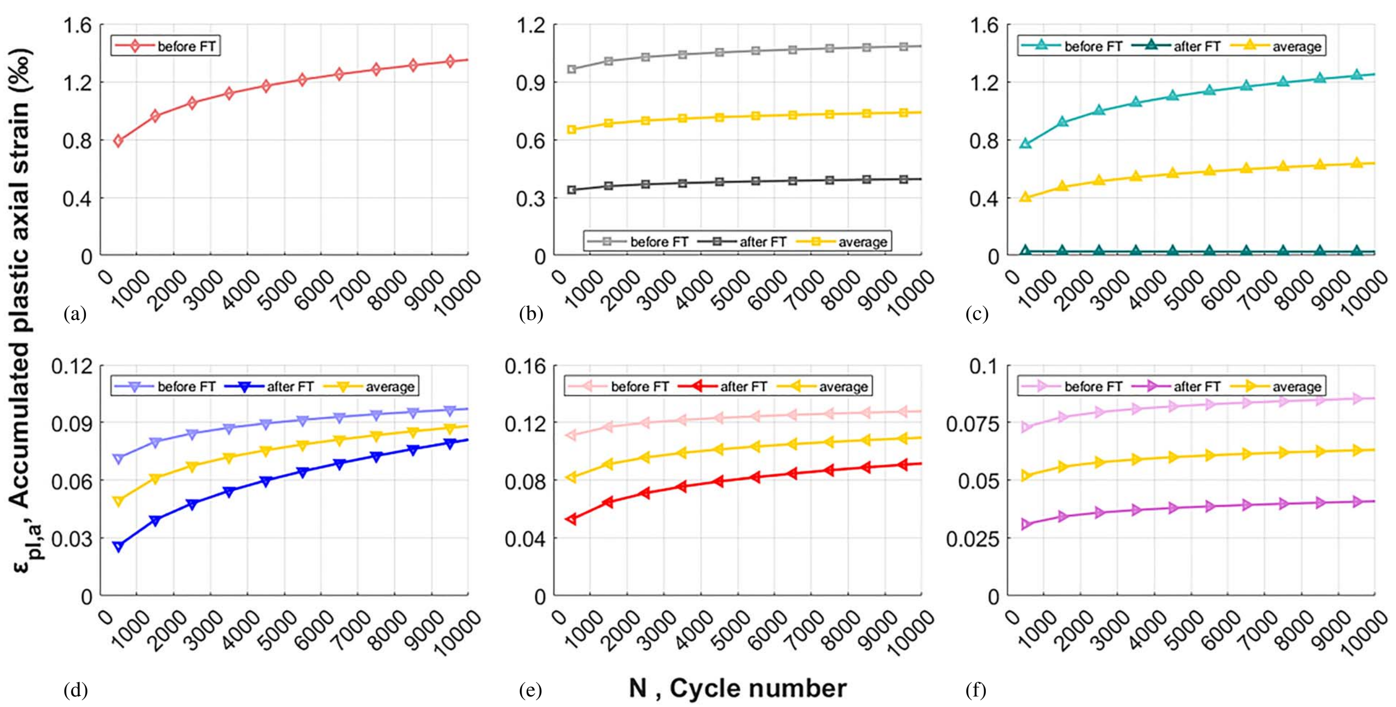

Fig. 12. Accumulated plastic axial deformation of unstabilized and stabilized aggregates for the RLTT steps defined in Table 8 for $E_{\text{top}} = 2{,}000$ MPa: (a) UGM; (b) BIT; (c) POL; (d) ACR; (e) STB; and (f) ACE.

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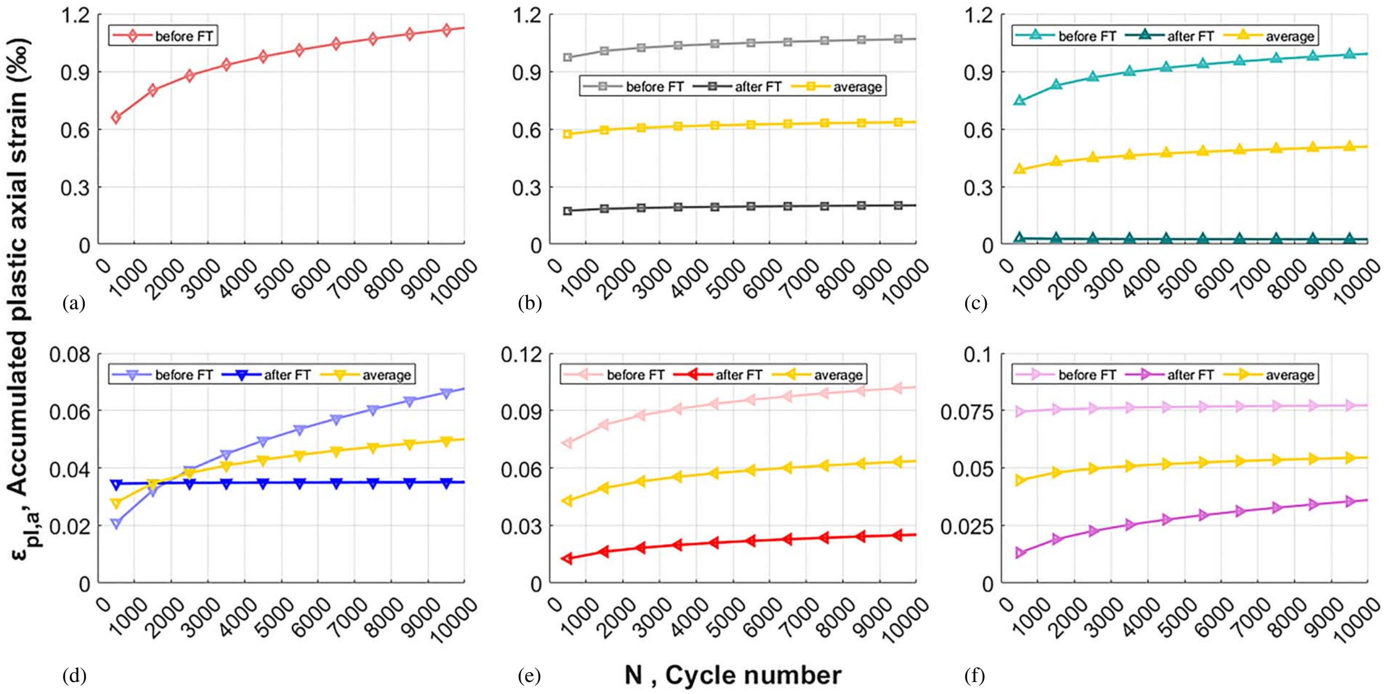

Fig. 13. Accumulated plastic axial deformation of unstabilized and stabilized aggregates for the RLTT steps defined in Table 8 for $E_{top} =$ 20,000 MPa: (a) UGM; (b) BIT; (c) POL; (d) ACR; (e) STB; and (f) ACE.

Table 10. Number of repetitions N of 10 t standard axle load necessary to achieve $\varepsilon_{pl,a} = 1‰$ in unstabilized and stabilized road base layers for two different values of E_{top}

Binder type	$E_{top} = 2{,}000$ MPa	$E_{top} = 20{,}000$ MPa
UGM	1.86×10^3	5.14×10^3
BIT	1.11×10^7	4.51×10^9
POL	1.72×10^5	1.70×10^7
ACR	3.10×10^9	5.49×10^{10}
STB	8.91×10^{13}	1.22×10^{13}
ACE	3.16×10^{22}	7.85×10^{22}

order of magnitude of 22. Except for polyurethane POL, all polymeric binders, that is, acrylates ACR, styrene butadiene STB, and acetate ACE, offer responses that are better than that of the traditional binder bitumen BIT. Nevertheless, the bituminous binder BIT is the cheapest solution among the investigated ones: as already discussed, the costs of polymeric products are likely to diminish over time as the main barriers (e.g., low-scale production and current sales system) are removed (Huang et al. 2021).

Finally, it is worth noting that the experimental data of permanent deformation could have also been analyzed by implementing other regression approaches (Alnedawi et al. 2019; Chen et al. 2020; Pérez and Gallego 2010; Ullah et al. 2021). Based on the findings of these studies, it can be reasonable to assume that the ranking of the stabilization technologies derived adopting the Sweere formulation, as reported in Table 10, is not likely to change when considering other regression models. For instance, the resistance to permanent deformation assessed according to the Hyde model for all the RLTT stress levels reported in a previous study also indicates the better mechanical response of the nontraditional polymeric binders compared with bitumen and unstabilized aggregates (Barbieri et al. 2022b).

Sensitivity Analysis

An important aspect of the research dealt with in this study is represented by the validation of the generalizable workflow. One approach to meet this aim entails the achievement of multiple experiments, which is an analysis of more case studies. On the other hand, another approach involves performing a sensitivity analysis to prove how the algorithms are not sensitive to changing project-based variables. Following the latter path, this section applies the same calculation framework already discussed for the case study to the combinations of the hypothetical values of the two main input parameters, as depicted in Fig. 5, namely, thickness and width of the stabilized base layers. Five values are assumed for the thickness: the actual one detailed in Table 7 as well as the other four corresponding to an increase or decrease by ±1 and ±2 cm. With regard to the road width, three values are considered: 5, 6 (actual case study), and 7 m.

In the first place, the visual script created using Autodesk Dynamo is run for all combinations of width and thickness values to assess the corresponding volume of aggregates needed to rehabilitate the base layer. The total costs including material supply and transport are then derived using the spreadsheet tool "HERMES CO_2." The results displayed in Fig. 14 indicate a linear relationship between inputs (i.e., thickness, width) and estimated outputs (i.e., volume, cost). The red points correspond to the results already found in the case study. The stabilization by means of bitumen BIT is always the cheapest alternative, whereas the most expensive technology is represented by polyurethane POL; this finding agrees with the outcomes of the case study.

Following the proposed workflow, the structural analysis is successively conducted by leveraging the Application Builder and analyzing the parametric two-dimensional road section developed with COMSOL Multiphysics. The considered elastic modulus of

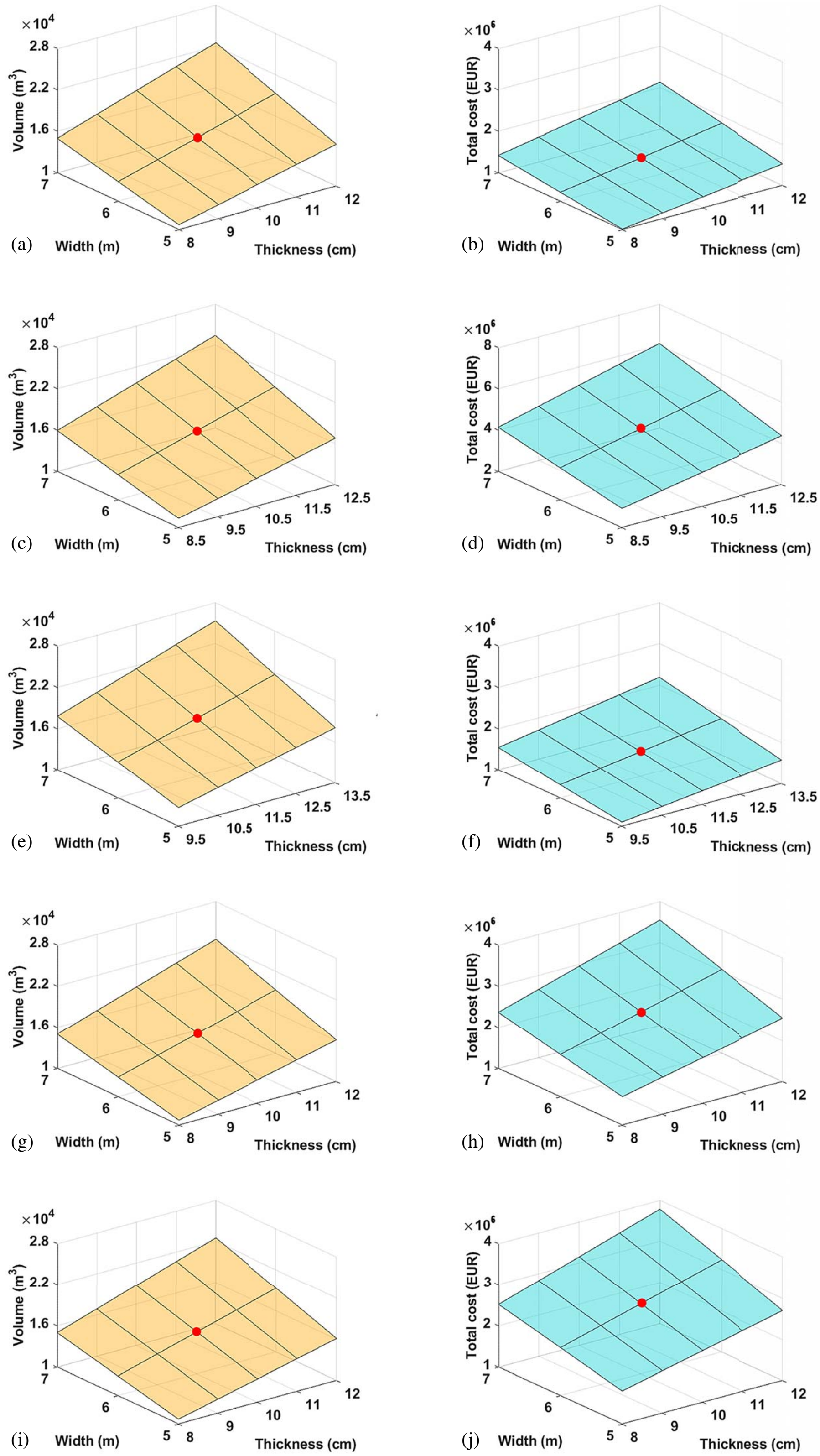

Fig. 14. Volume of aggregates and total costs as functions of stabilization technology as well as the width and thickness of the base layer. The red points correspond to the results considered in the case study: (a and b) BIT; (c and d) POL; (e and f) ACR; (g and h) STB; and (i and j) ACE.

the top layer E_{top} is 2,000 MPa. Based on the obtained values of triaxial stress σ_t and deviatoric stress σ_d displayed in Fig. 15, the closest stress states achieved during RLTT, which are listed in Table 6, are the same ones already identified for the case study reported in Table 9. Therefore, the service life values already computed in Table 10 are also valid for all the parameter combinations considered in the sensitivity analysis. This finding indicates the small influence exerted by changes in width or small variations (a few cm) in the thickness of the stabilized base layer on the estimated service life.

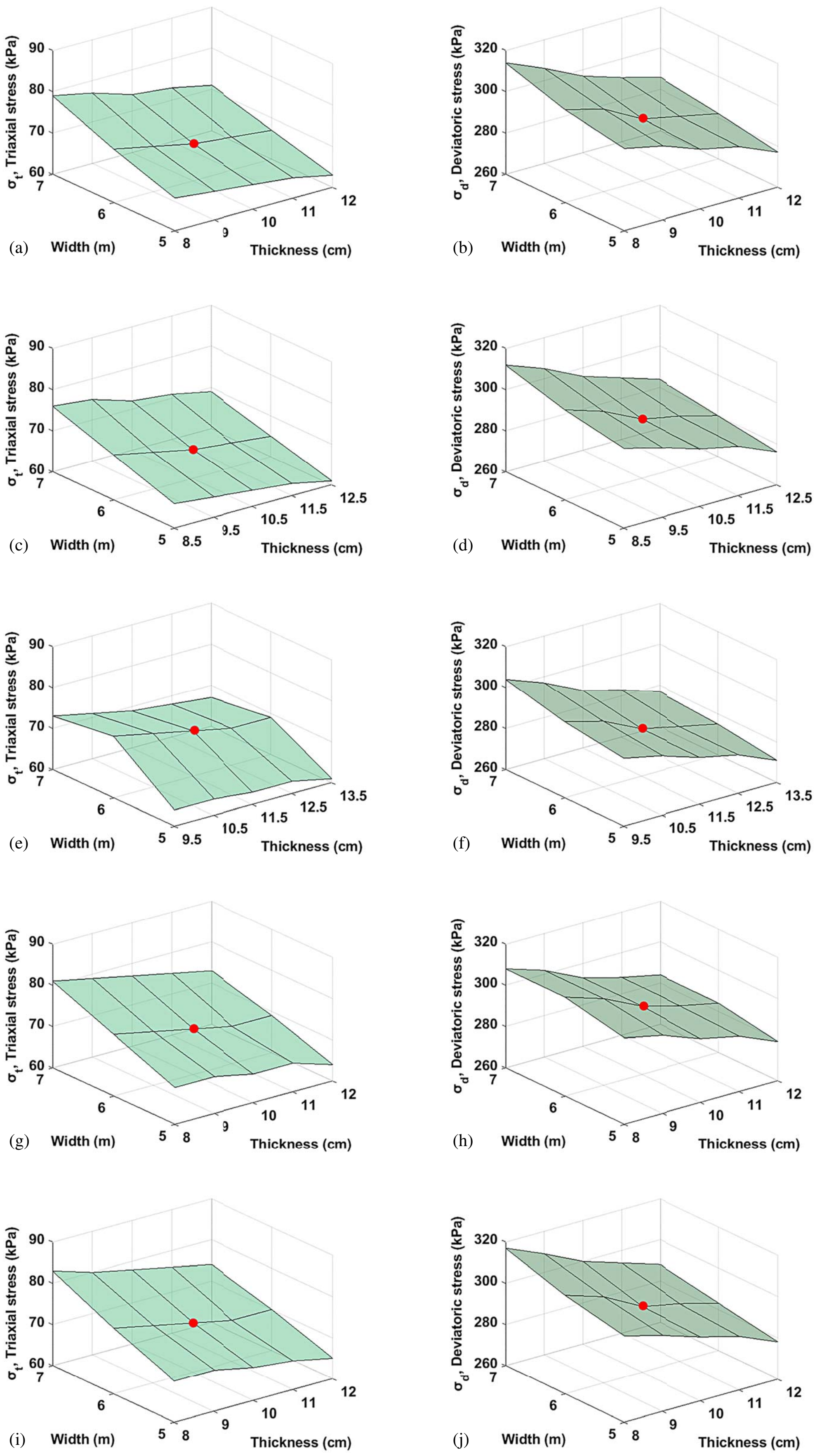

Fig. 15. Values of triaxial stress σ_t and deviatoric stress σ_d as functions of stabilization technology as well as the width and thickness of the base layer for $E_{\mathrm{top}} = 2{,}000$ MPa. The red points correspond to the results considered in the case study: (a and b) BIT; (c and d) POL; (e and f) ACR; (g and h) STB; and (i and j) ACE.

Conclusions

Although the adoption of BIM in the domain of transportation infrastructures is gaining momentum worldwide, the volume of academic studies encompassing road engineering is still limited. Furthermore, BIM software tools commonly lack the function to perform pavement structural analysis and carry out associated appraisals on service life. There is a significant dearth of research efforts dealing with the implementation of BIM in LVRs, notwithstanding the burgeoning need for their maintenance. Pivoting on a case study, this work has shed light on the digital tools that are useful for the engineering design and maintenance of LVRs by aiming at defining a repeatable workflow.

This research has considered the renewal of a county road situated in the central part of Norway as the application case study. The project consists of removing the existing materials and employing new aggregates for reconstructing the base layer. In this regard, six scenarios have been envisaged for the rock aggregates: unstabilized, stabilized by a traditional binder (bitumen), and stabilized by four nontraditional polymeric binders (polyurethane, acrylate, styrene butadiene, and acetate).

This research has highlighted the interoperability of different BIM software packages by Autodesk so as to comprise road georeferencing (Autodesk InfraWorks), alignment definition (Autodesk Civil 3D), and estimation of material volumes and costs (Autodesk Dynamo). Furthermore, this work has also documented the feasibility of employing COMSOL Multiphysics to achieve pavement structural analysis using the Application Builder and compiling a MATLAB script to estimate the road service life. Finally, the research has documented the repeatability of the presented framework by means of sensitivity analysis. The following conclusions can be drawn:

1. BIM implementation can streamline the engineering design and analysis of LVR pavement infrastructures. The workflow presented in this study enables the adoption of a BIM environment with pavement structural analysis and associated appraisal of mechanical performance.
2. The customization achieved by the coordinated use of digital tools with graphical and textual programming languages creates an effective and seamless workflow encompassing all steps necessary for the engineering design and maintenance of LVRs.
3. Compared with unstabilized rock aggregates, the application of binders leads to significant cost savings because only a reduced quantity of construction materials is needed. This further engenders a reduction in the pollution associated with the production and transport of natural resources. Bitumen is the cheapest stabilization solution, whereas polyurethane is the most expensive one.
4. With reference to the performance of traditional and nontraditional binders in terms of accumulated permanent deformations, all polymeric technologies (with the only exception of polyurethane) entail smaller plastic strains compared with bitumen and thus envisage a longer service life. The worst and best performances are, respectively, associated with unstabilized aggregates and aggregates stabilized with acetate binder.

As limitations of this work, it can be said that findings have been reported and discussed only for the considered case study and associated sensitivity analysis; however, the outcomes can be further generalized and validated by considering other engineering scenarios. Besides, it is worth highlighting that the largest part of the systems considered is produced by Autodesk. To gain a more comprehensive understanding of the potential of the digital resources that can be used for LVRs, future research can shed light on other software tools for civil engineering developed by different companies such as Bentley Systems, Nemetschek Group, and Trimble, to name a few. Moreover, as BIM methodology continues to grow in the road engineering sector, further work could focus on the implementation of the findings in a pavement management system (PMS) to rationally plan maintenance operations. Finally, instrumentation installed inside the LVR pavement after its renewal could provide relevant real-time information on traffic volume and the environment, for example, and thus enable the creation of a digital twin model.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Abbondati, F., C. Oreto, N. Viscione, and S. A. Biancardo. 2020. "Rural road reverse engineering using BIM: An Italian case study." In *Proc., 11th Int. Conf. "Environmental Engineering,"* edited by Č. Donatas and R. Vaiškūnaitė, 1–7. Vilnius, Lithuania: Vilnius Gediminas Technical Univ.

Adomako, S., C. J. Engelsen, R. T. Thorstensen, and D. M. Barbieri. 2021. "Review of the relationship between aggregates geology and Los Angeles and micro-Deval tests." *Bull. Eng. Geol. Environ.* 80: 1963–1980. https://doi.org/10.1007/s10064-020-02097-y.

Alnedawi, A., K. P. Nepal, and R. Al-Ameri. 2019. "Permanent deformation prediction model of unbound granular materials for flexible pavement design." *Transp. Infrastruct. Geotechnol.* 6: 39–55. https://doi.org/10.1007/s40515-018-00068-1.

Alnedawi, A., S. Ullah, A. Azam, E. Mousa, I. Obaid, and A. Yosri. 2022. "Integrated and holistic knowledge map of resilient modulus studies for pavement materials: A scientometric analysis and bibliometric review of research frontiers and prospects." *Transp. Geotech.* 33: 100711. https://doi.org/10.1016/j.trgeo.2021.100711.

Arif, F., and W. A. Khan. 2021. "Smart progress monitoring framework for building construction elements using videography–MATLAB–BIM integration." *Int. J. Civ. Eng.* 19: 717–732. https://doi.org/10.1007/s40999-021-00601-3.

Assi, A. 2011. *Engineering education and research using MATLAB*. London: IntechOpen.

Aursand, P. O., and I. Horvli. 2009. "Effect of a changed climate on gravel roads." In *Proc., 8th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields*, edited by E. Tutumluer and I. Al-Qadi, 1091–1099. London: Taylor & Francis.

Autodesk. 2023. "Autodesk Dynamo: Open source graphical programming for design." Accessed August 4, 2022. https://dynamobim.org/.

Azhar, S. 2011. "Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry." *Leadersh. Manage. Eng.* 11: 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127.

Balaguera, A., G. I. Carvajal, J. Albertí, and P. Fullana-i-Palmer. 2018. "Life cycle assessment of road construction alternative materials: A literature review." *Resour. Conserv. Recycl.* 132: 37–48. https://doi.org/10.1016/j.resconrec.2018.01.003.

Bane NOR. 2022. "Krav til informasjonsmodellering (KIM)." Accessed August 4, 2022. https://www.banenor.no/kim.

Barbieri, D. M., J.-G. Dorval, B. Lou, H. Chen, B. Shu, F. Wang, and I. Hoff. 2021a. "Dataset regarding the mechanical characterization of sedimentary rocks derived from Svalbard for possible use in local road constructions." *Data Brief* 34: 106735. https://doi.org/10.1016/j.dib.2021.106735.

Barbieri, D. M., I. Hoff, and C.-H. Ho. 2021b. "Crushed rocks stabilized with organosilane and lignosulfonate in pavement unbound layers: Repeated load triaxial tests." *Front. Struct. Civ. Eng.* 15: 412–424. https://doi.org/10.1007/s11709-021-0700-5.

Barbieri, D. M., I. Hoff, and H. Mork. 2017. "Laboratory investigation on unbound materials used in a highway with premature damage." In *Proc., 10th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields*, edited by A. Loizos, I. L. Al-Qadi, and A.T. Scarpas, 101–108. London: Taylor & Francis.

Barbieri, D. M., I. Hoff, and M. B. E. Mørk. 2019. "Mechanical assessment of crushed rocks derived from tunnelling operations." In *Sustainable civil infrastructures*, edited by W.-C. Cheng, J. Yang, and J. Wang, 225–241. Berlin, Germany: Springer.

Barbieri, D. M., B. Lou, R. J. Dyke, H. Chen, U. Chandra Sahoo, J. S. Tingle, and I. Hoff. 2023a. "Dataset of mechanical properties of coarse aggregates stabilized with traditional and nontraditional additives: Stiffness, deformation, resistance to freezing and stripping." *Data Brief* 46: 108781. https://doi.org/10.1016/j.dib.2022.108781.

Barbieri, D. M., B. Lou, R. J. Dyke, H. Chen, F. Wang, B. Dongmo-Engeland, J. S. Tingle, and I. Hoff. 2022a. "Stabilization of coarse aggregates with traditional and nontraditional additives." *J. Mater. Civ. Eng.* 34: 04022207. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004406.

Barbieri, D. M., B. Lou, R. J. Dyke, X. Wang, H. Chen, B. Shu, U. Gazder, S. Horpibulsuk, J. S. Tingle, and I. Hoff. 2022b. "Design and sustainability analyses of road base layers stabilized with traditional and nontraditional additives." *J. Cleaner Prod.* 372: 133752. https://doi.org/10.1016/j.jclepro.2022.133752.

Barbieri, D. M., B. Lou, M. Passavanti, A. Barbieri, and F. Bjørheim. 2023b. "A survey dataset evaluating perceptions of civil engineering students about building information modelling (BIM)." *Data* 8: 114. https://doi.org/10.3390/data8070114.

Barbieri, D. M., B. Lou, F. Wang, I. Hoff, S. Wu, J. Li, H. R. Vignisdottir, R. A. Bohne, S. Anastasio, and T. Kristensen. 2021c. "Assessment of carbon dioxide emissions during production, construction and use stages of asphalt pavements." *Transp. Res. Interdiscip. Perspect.* 11: 100436. https://doi.org/10.1016/j.trip.2021.100436.

Bedrick, J., W. Ikerd, and J. Reinhardt. 2020. "Level of development (LOD) specification part I & commentary for building information models and data." Woburn, MA: BIM Forum.

Biancardo, S. A., F. Russo, R. Veropalumbo, V. Vorobjovas, and G. Dell'Acqua. 2020a. "Modeling roman pavements using heritage-BIM: A case study in Pompeii." *Balt. J. Road Bridge Eng.* 15: 34–46. https://doi.org/10.7250/bjrbe.2020-15.482.

Biancardo, S. A., N. Viscione, C. Oreto, R. Veropalumbo, and F. Abbondati. 2020b. "BIM approach for modeling airports terminal expansion." *Infrastructures* 5: 41. https://doi.org/10.3390/infrastructures5050041.

Bosurgi, G., C. Celauro, O. Pellegrino, N. Rustica, and G. Sollazzo. 2019. "The BIM (building information modeling)-based approach for road pavement maintenance." In *Proc., 5th Int. Symp. on Asphalt Pavements & Environment*, edited by M. Pasetto, M. N. Partl, and G. Tebaldi, 480–490. Berlin, Germany: Springer.

Bradley, A., H. Li, R. Lark, and S. Dunn. 2016. "BIM for infrastructure: An overall review and constructor perspective." *Autom. Constr.* 71: 139–152. https://doi.org/10.1016/j.autcon.2016.08.019.

Bråthen, K. 2015. "Collaboration with BIM - Learning from the front runners in the Norwegian industry." *Procedia Econ. Finance* 21: 439–445. https://doi.org/10.1016/S2212-5671(15)00197-5.

Bryde, D., M. Broquetas, and J. M. Volm. 2013. "The project benefits of building information modelling (BIM)." *Int. J. Project Manage.* 31: 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001.

Bui, N., C. Merschbrock, B. E. Munkvold, and E. Hjelseth. 2019. "Role of an innovation community in supporting BIM deployment: The case of buildingSMART Norway." *WIT Trans. Built Environ.* 192: 329–342. https://doi.org/10.2495/BIM190281.

Bushman, W. H., T. E. Freeman, and E. J. Hoppe. 2005. "Stabilization techniques for unpaved roads." *Transp. Res. Rec.* 1936: 28–33. https://doi.org/10.1177/0361198105193600104.

Celauro, C., F. Corriere, M. Guerrieri, and B. Lo Casto. 2015. "Environmentally appraising different pavement and construction scenarios: A comparative analysis for a typical local road." *Transp. Res. Part D Transp. Environ.* 34: 41–51. https://doi.org/10.1016/j.trd.2014.10.001.

CEN (European Committee for Standardization). 2004. *Unbound and hydraulically bound mixtures. Part 7: Cyclic load triaxial test for unbound mixtures*. ISO 13286-7. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2010. *Tests for mechanical and physical properties of aggregates. Part 2: Methods for the determination of resistance to fragmentation*. ISO 1097-2. Brussels, Belgium: CEN.

CEN (European Committee for Standardization). 2011. *Tests for mechanical and physical properties of aggregates. Part 1: Determination of the resistance to wear (micro-Deval)*. ISO 1097-1. Brussels, Belgium: CEN.

Chen, H., M. M. Alamnie, D. M. Barbieri, X. Zhang, G. Liu, and I. Hoff. 2023a. "Comparative study of indirect tensile test and uniaxial compression test on asphalt mixtures: Dynamic modulus and stress–strain state." *Constr. Build. Mater.* 366: 130187. https://doi.org/10.1016/j.conbuildmat.2022.130187.

Chen, H., D. M. Barbieri, I. Hoff, H. Mork, P. Wathne, and G. Liu. 2022. "Construction of asphalt mixture master curves for a Norwegian mechanistic-empirical pavement design system." In *Proc., 11th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields*, edited by I. Hoff, H. Mork, and R. Saba, 423–434. London: Taylor & Francis.

Chen, H., R. G. Saba, G. Liu, D. M. Barbieri, X. Zhang, and I. Hoff. 2023b. "Influence of material factors on the determination of dynamic moduli and associated prediction models for different types of asphalt mixtures." *Constr. Build. Mater.* 365: 130134. https://doi.org/10.1016/j.conbuildmat.2022.130134.

Chen, H., I. Hoff, G. Liu, X. Zhang, D. Maria Barbieri, F. Wang, and J. Liu. 2023c. "Development of finite element model based on indirect tensile test for various asphalt mixtures." *Constr. Build. Mater.* 394: 132085. https://doi.org/10.1016/j.conbuildmat.2023.132085.

Chen, W.-B., W.-Q. Feng, J.-H. Yin, J.-M. Chen, L. Borana, and R.-P. Chen. 2020. "New model for predicting permanent strain of granular materials in embankment subjected to low cyclic loadings." *J. Geotech. Geoenviron. Eng.* 146: 04020084. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002334.

Cheng, J. C. P., Q. Lu, and Y. Deng. 2016. "Analytical review and evaluation of civil information modeling." *Autom. Constr.* 67: 31–47. https://doi.org/10.1016/j.autcon.2016.02.006.

Chong, H. Y., R. Lopez, J. Wang, X. Wang, and Z. Zhao. 2016. "Comparative analysis on the adoption and use of BIM in road infrastructure projects." *J. Manage. Eng.* 32: 05016021. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000460.

Collao, J., F. Lozano-Galant, J. A. Lozano-Galant, and J. Turmo. 2021. "BIM visual programming tools applications in infrastructure projects:

A state-of-the-art review." *Appl. Sci.* 11: 8343. https://doi.org/10.3390/app11188343.

Costin, A., A. Adibfar, H. Hu, and S. S. Chen. 2018. "Building Information Modeling (BIM) for transportation infrastructure—Literature review, applications, challenges, and recommendations." *Autom. Constr.* 94: 257–281. https://doi.org/10.1016/j.autcon.2018.07.001.

De Bortoli, A. 2023. "Understanding the environmental impacts of virgin aggregates: Critical literature review and primary comprehensive life cycle assessments." *J. Cleaner Prod.* 415: 137629. https://doi.org/10.1016/j.jclepro.2023.137629.

De Bortoli, A., Y. Baouch, and M. Masdan. 2023. "BIM can help decarbonize the construction sector: Primary life cycle evidence from pavement management systems." *J. Cleaner Prod.* 391: 136056. https://doi.org/10.1016/j.jclepro.2023.136056.

Ding, L., Y. Zhou, and B. Akinci. 2014. "Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD." *Autom. Constr.* 46: 82–93. https://doi.org/10.1016/j.autcon.2014.04.009.

Douglas, R. A. 2016. *Low-volume road engineering*. 1st ed. Boca Raton, FL: CRC Press.

Eastman, C., P. Teicholz, R. Sacks, and K. Liston. 2008. *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. 1st ed. Hoboken, NJ: Wiley.

Ghadimi, B., and H. Nikraz. 2017. "A comparison of implementation of linear and nonlinear constitutive models in numerical analysis of layered flexible pavement." *Road Mater. Pavement Des.* 18: 550–572. https://doi.org/10.1080/14680629.2016.1182055.

Gidel, G., P. Hornych, J.-J. Chauvin, D. Breysse, and A. Denis. 2001. *A new approach for investigating the permanent deformation behaviour of unbound granular material using the repeated loading triaxial apparatus*. Bulletin des laboratoires des Ponts et Chaussées. Washington, DC: The National Academies of Sciences, Engineering, and Medicine.

Gomes Correia, A., M. G. Winter, and A. J. Puppala. 2016. "A review of sustainable approaches in transport infrastructure geotechnics." *Transp. Geotech.* 7: 21–28. https://doi.org/10.1016/j.trgeo.2016.03.003.

Haklay, M. 2010. "How good is volunteered geographical information? A comparative study of OpenStreetMap and ordnance survey datasets." *Environ. Plann. B* 37: 682–703. https://doi.org/10.1068/b35097.

Hamar Pukk og Grus AS. 2023. "Sørli crushing plant." Accessed August 4, 2022. http://www.hamarpukkoggrus.no/?CatID=1166.

Han, C., F. Tang, T. Ma, L. Gu, and Z. Tong. 2022. "Construction quality evaluation of asphalt pavement based on BIM and GIS." *Autom. Constr.* 141: 104398. https://doi.org/10.1016/j.autcon.2022.104398.

Hasan, A. M. M., A. A. Torky, and Y. F. Rashed. 2019. "Geometrically accurate structural analysis models in BIM-centered software." *Autom. Constr.* 104: 299–321. https://doi.org/10.1016/j.autcon.2019.04.022.

He, Q., G. Wang, L. Luo, Q. Shi, J. Xie, and X. Meng. 2017. "Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis." *Int. J. Project Manage.* 35: 670–685. https://doi.org/10.1016/j.ijproman.2016.08.001.

Henning, T. F. P., D. Alabaster, G. Arnold, and W. Liu. 2014. "Relationship between traffic loading and environmental factors and low-volume road deterioration." *Transp. Res. Rec.* 2433: 100–107. https://doi.org/10.3141/2433-11.

Hicks, R. G., and C. L. Monismith. 1971. "Factors influencing the resilient properties of granular materials." In *Highway research record*, 15–31. Washington, DC: Highway Research Board.

Hjelseth, E. 2018. "Experiences from Norway on implementing BIM in existing bachelor engineering curriculum." In *Proc., 12th European Conf. on Product and Process Modelling*, edited by J. Karlshøj and R. Scherer. London: CRC Press.

Huang, J., R. B. Kogbara, N. Hariharan, E. A. Masad, and D. N. Little. 2021. "A state-of-the-art review of polymers used in soil stabilization." *Constr. Build. Mater.* 305: 124685. https://doi.org/10.1016/j.conbuildmat.2021.124685.

Huang, Y. H. 2004. *Pavement analysis and design*. 2nd ed. Upper Saddle River, NJ: Pearson.

Islam, M. R., and R. A. Tarefder. 2020. *Pavement design: Materials, analysis, and highways*. 1st ed. New York: McGraw-Hill.

Jalali, F., A. Vargas-Nordcbeck, and M. Nakhaei. 2019. "Role of preventive treatments in low-volume road maintenance program: Full-scale case study." *Transp. Res. Rec.* 2673: 855–862. https://doi.org/10.1177/0361198119863025.

Jiang, F., L. Ma, T. Broyd, K. Chen, H. Luo, and M. Du. 2022. "Building demolition estimation in urban road widening projects using as-is BIM models." *Autom. Constr.* 144: 104601. https://doi.org/10.1016/j.autcon.2022.104601.

Jing, W., G. Hao, C. Li, W. Wei, and J. Cheng. 2019. "BIM application approach on highway maintenance and management." In Proc., 19th *COTA Int. Conf. of Transportation*, edited by L. Zhang, J. Ma, P. Liu, and G. Zhang, 776–786. Reston, VA: ASCE.

Jones, D. 2017. *Guidelines for the selection, specification, and application of chemical dust control and stabilization treatments on unpaved roads*. Davis, CA: University of California Pavement Research Center UC Davis.

Jung, Y., and M. Joo. 2011. "Building information modelling (BIM) framework for practical implementation." *Autom. Constr.* 20: 126–133. https://doi.org/10.1016/j.autcon.2010.09.010.

Keller, G., and J. Sherar. 2003. "Low-volume roads engineering: Best management practices." *Transp. Res. Rec.* 1819: 174–181. https://doi.org/10.3141/1819a-25.

Khalil, I. G., A. Mohamed, and Z. Smail. 2021. "Building Information Modeling for rural road design: A case study." In *Proc., Int. Conf. on Electronics, Computer and Computation*. Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE).

Khoeini, S., S. Dessouky, A. T. Papagiannakis, L. F. Walubita, S. A. Tahami, and M. Gholikhani. 2019. "Using polymer-based mixes as alternative to asphalt mixes in low volume roads." *Constr. Build. Mater.* 204: 177–183. https://doi.org/10.1016/j.conbuildmat.2019.01.124.

Kim, H., Z. Chen, C.-S. Cho, H. Moon, K. Ju, and W. Choi. 2015. "Integration of BIM and GIS: Highway cut and fill earthwork balancing." In *Computing in civil engineering 2015*, edited by W. J. O'Brien and S. Ponticelli. Reston, VA: ASCE.

Kim, H., K. Orr, Z. Shen, H. Moon, K. Ju, and W. Choi. 2014. "Highway alignment construction comparison using object-oriented 3D visualization modeling." *J. Constr. Eng. Manage.* 140: 05014008. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000898.

Kim, H., Z. Shen, H. Moon, K. Ju, and W. Choi. 2016. "Developing a 3D intelligent object model for the application of construction planning/simulation in a highway project." *KSCE J. Civ. Eng.* 20: 538–548. https://doi.org/10.1007/s12205-015-0463-4.

Kunz, B. K., E. E. Little, and V. L. Barandino. 2022. "Aquatic toxicity of chemical road dust suppressants to freshwater organisms." *Arch. Environ. Contam. Toxicol.* 82: 294–305. https://doi.org/10.1007/s00244-020-00806-y.

Labi, S., A. Faiz, T. U. Saeed, B. N. T. Alabi, and W. Woldemariam. 2019. "Connectivity, accessibility, and mobility relationships in the context of low-volume road networks." *Transp. Res. Rec.* 2673: 717–727. https://doi.org/10.1177/0361198119854091.

Lassen, A. K., E. Hjelseth, and T. Tollnes. 2018. "Enhancing learning outcomes by introducing BIM in civil engineering studies—Experiences from a university college in Norway." *Int. J. Sustainable Dev. Plann.* 13: 62–72. https://doi.org/10.2495/SDP-V13-N1-62-72.

Latiffi, A. A., J. Brahim, S. Mohd, and M. S. Fathi. 2015. "Building Information Modeling (BIM): Exploring Level of Development (LOD) in construction projects." *Appl. Mech. Mater.* 773–774: 933–937. https://doi.org/10.4028/www.scientific.net/AMM.773-774.933.

Lay, M., J. Metcalf, and K. Sharp. 2021. *Paving our ways. A history of the world's roads and pavements*. 1st ed. Boca Raton, FL: CRC Press.

Lee, S. S., K. T. Kim, W. A. Tanoli, and J. W. Seo. 2020. "Flexible 3D model partitioning system for nD-based BIM implementation of alignment-based civil infrastructure." *J. Manage. Eng.* 36: 04019037. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000725.

Lekarp, F., U. Isacsson, and A. Dawson. 2000a. "State of the Art. I: Resilient response of unbound aggregates." *J. Transp. Eng.* 126: 66–75. https://doi.org/10.1061/(ASCE)0733-947X(2000)126:1(66).

Lekarp, F., U. Isacsson, and A. Dawson. 2000b. "State of the Art. II: Permanent strain response of unbound aggregates." *J. Transp. Eng.* 126: 76–83. https://doi.org/10.1061/(ASCE)0733-947X(2000)126:1(76).

Lu, Q., and S. Lee. 2017. "A semi-automatic approach to detect structural components from CAD drawings for constructing as-is BIM objects." In *Computing in civil engineering 2017: Information modeling and data analytics*, edited by K.-Y. Lin, N. El-Gohary, and P. Tang, 84–91. Reston, VA: ASCE.

Mallick, R. B., and T. El-Korchi. 2023. *Pavement engineering. principles and practice*. 4th ed. Boca Raton, FL: Taylor & Francis.

Meijer, J. R., M. A. J. Huijbregts, K. C. G. J. Schotten, and A. M. Schipper. 2018. "Global patterns of current and future road infrastructure." *Environ. Res. Lett.* 13: 064006. https://doi.org/10.1088/1748-9326/aabd42.

Moreno Bazán, Á., M. G. Alberti, A. Arcos Álvarez, and J. A. Trigueros. 2020. "New perspectives for BIM usage in transportation infrastructure projects." *Appl. Sci.* 10: 7072. https://doi.org/10.3390/app10207072.

NBS Enterprises. 2020. *10th annual BIM report*. Newcastle, UK: NBS Enterprises.

NPRA (Norwegian Public Roads Administration). 2014. *Håndbok N200 vegbygging*. Vegdirektoratet, Norway: NPRA.

NPRA (Norwegian Public Roads Administration). 2015. *Håndbok V770 modellgrunnlag*. Vegdirektoratet, Norway: NPRA.

NPRA (Norwegian Public Roads Administration). 2018. *Håndbok N200 vegbygging*. Vegdirektoratet, Norway: NPRA.

NPRA (Norwegian Public Roads Administration). 2020. *Field tests—Comparison of pavement damage caused by timber trucks with gross weights of 60 and 74 tons*. Vegdirektoratet, Norway: NPRA.

Oreto, C., S. A. Biancardo, N. Viscione, R. Veropalumbo, and F. Russo. 2021. "Road pavement information modeling through maintenance scenario evaluation." *J. Adv. Transp.* 2021: 1–14. https://doi.org/10.1155/2021/8823117.

Patel, K., and R. Ruparathna. 2023. "Life cycle sustainability assessment of road infrastructure: A building information modeling-(BIM) based approach." *Int. J. Construct. Manage.* 23: 1837–1846. https://doi.org/10.1080/15623599.2021.2017113.

Pérez, I., and J. Gallego. 2010. "Rutting prediction of a granular material for base layers of low-traffic roads." *Constr. Build. Mater.* 24: 340–345. https://doi.org/10.1016/j.conbuildmat.2009.08.028.

Podolsky, J., J. C. Ashlock, and R. C. Williams. 2017. "Measurement and finite element modeling of the pavement response to superloads." In *Geotechnical Frontiers 2017: Transportation facilities, structures, and site investigation*, edited by T. L. Brandon and R. J. Valentine, 144–153. Reston, VA: ASCE.

Praticò, F., S. Saride, and A. Puppala. 2011. "Comprehensive life-cycle cost analysis for selection of stabilization alternatives for better performance of low-volume roads." *Transp. Res. Rec.* 2204: 120–129. https://doi.org/10.3141%2F2204-16.

Raya, R. K., and R. Gupta. 2022. "Application of BIM framework on rural infrastructure." *Asian J. Civ. Eng.* 23: 249–268. https://doi.org/10.1007/s42107-022-00421-3.

Robinson, R., and B. Thagesen. 2004. *Road engineering for development*. 2nd ed. London: Taylor & Francis.

Saito, D., H. Washizaki, and Y. Fukazawa. 2017. "Comparison of text-based and visual-based programming input methods for first-time learners." *J. Inf. Technol. Educ. Res.* 16: 209–226. https://doi.org/10.28945/3775.

Salzano, A., M. Intignano, C. Mottola, S. A. Biancardo, M. Nicolella, and G. Dell'Acqua. 2023. "Systematic literature review of open infrastructure BIM." *Buildings* 13: 1593. https://doi.org/10.3390/buildings13071593.

Sankaran, B., W. J. O'Brien, P. M. Goodrum, N. Khwaja, F. L. Leite, and J. Johnson. 2016. "Civil integrated management for highway infrastructure: Case studies and lessons learned." *Transp. Res. Rec.* 2573: 10–17. https://doi.org/10.3141/2573-02.

Santoni, R. L., J. S. Tingle, and M. Nieves. 2005. "Accelerated strength improvement of silty sand with nontraditional additives." *Transp. Res. Rec.* 1936: 34–42. https://doi.org/10.1177%2F0361198105193600105.

Santoni, R. L., J. S. Tingle, and S. L. Webster. 2002. "Stabilization of silty sand with nontraditional additives." *Transp. Res. Rec.* 1787: 61–70. https://doi.org/10.3141%2F1787-07.

Schultz, M., J. Voss, M. Auer, S. Carter, and A. Zipf. 2017. "Open land cover from OpenStreetMap and remote sensing." *Int. J. Appl. Earth Obs. Geoinf.* 63: 206–213. https://doi.org/10.1016/j.jag.2017.07.014.

Shou, W., J. Wang, X. Wang, and H. Y. Chong. 2015. "A comparative review of Building Information Modelling implementation in building and infrastructure industries." *Arch. Comput. Methods Eng.* 22: 291–308. https://doi.org/10.1007/s11831-014-9125-9.

Silyanov, V., and J. I. Sodikov. 2017. "Highway functional classification in ICS countries." In *Proc., AIIT Int. Congress on Transport Infrastructure and Systems*, edited by G. Dell'Acqua and F. Wegman, 411–417. London: Springer.

Silyanov, V. V., J. I. Sodikov, R. Kiran, and A. I. Sadikov. 2020. "An overview road data collection, visualization, and analysis from the perspective of developing countries." *IOP Conf. Ser.: Mater. Sci. Eng.* 832: 012056. https://doi.org/10.1088/1757-899X/832/1/012056.

Smith, P. 2014. "BIM implementation—Global strategies." *Procedia Eng.* 85: 482–492. https://doi.org/10.1016/j.proeng.2014.10.575.

Statsbygg. 2023. "BIM." Accessed August 4, 2022. https://www.statsbygg.no/bim.

Succar, B. 2009. "Building information modelling framework: A research and delivery foundation for industry stakeholders." *Autom. Constr.* 18: 357–375. https://doi.org/10.1016/j.autcon.2008.10.003.

Sweere, G. T. H. 1990. *Unbound granular bases for roads*. Delft, Netherlands: Delft University of Technology.

Tang, F., T. Ma, Y. Guan, and Z. Zhang. 2020a. "Parametric modeling and structure verification of asphalt pavement based on BIM-ABAQUS." *Autom. Constr.* 111: 103066. https://doi.org/10.1016/j.autcon.2019.103066.

Tang, F., T. Ma, J. Zhang, Y. Guan, and L. Chen. 2020b. "Integrating three-dimensional road design and pavement structure analysis based on BIM." *Autom. Constr.* 113: 103152. https://doi.org/10.1016/j.autcon.2020.103152.

Thom, N. 2014. *Principles of pavement engineering*. 2nd ed. London: ICE.

Tingle, J. S., J. K. Newman, S. L. Larson, C. A. Weiss, and J. F. Rushing. 2007. "Stabilization mechanisms of nontraditional additives." *Transp. Res. Rec.* 1989: 59–67. https://doi.org/10.3141%2F1989-49.

Tingle, J. S., and R. L. Santoni. 2003. "Stabilization of clay soils with nontraditional additives." *Transp. Res. Rec.* 1819: 72–84. https://doi.org/10.3141%2F1819b-10.

Titi, H. H., and M. G. Matar. 2018. "Estimating resilient modulus of base aggregates for mechanistic-empirical pavement design and performance evaluation." *Transp. Geotech.* 17: 141–153. https://doi.org/10.1016/j.trgeo.2018.09.014.

Ullah, S., B. F. Tanyu, and B. Zainab. 2021. "Development of an artificial neural network (ANN)-based model to predict permanent deformation of base course containing reclaimed asphalt pavement (RAP)." *Road Mater. Pavement Des.* 22: 2552–2570. https://doi.org/10.1080/14680629.2020.1773304.

van der Merwe Steyn, W. J., and A. T. Visser. 2011. "Evaluation of sustainability of low-volume roads treated with nontraditional stabilizers." *Transp. Res. Rec.* 2204: 186–193. https://doi.org/10.3141/2204-24.

Vignali, V., E. M. Acerra, C. Lantieri, F. Di Vincenzo, G. Piacentini, and S. Pancaldi. 2021. "Building Information Modelling (BIM) application for an existing road infrastructure." *Autom. Constr.* 128: 103752. https://doi.org/10.1016/j.autcon.2021.103752.

Vitásek, S., and P. Matějka. 2017. "Utilization of BIM for automation of quantity takeoffs and cost estimation in transport infrastructure construction projects in the Czech Republic." In *Proc., Building up Efficient and Sustainable Transport Infrastructure 2017*, edited by A. Kohoutková. Bristol, UK: IOP Publishing.

Volk, R., J. Stengel, and F. Schultmann. 2014. "Building information modeling (BIM) for existing buildings—Literature review and future needs." *Autom. Constr.* 38: 109–127. https://doi.org/10.1016/j.autcon.2013.10.023.

Wang, C., C. Chazallon, P. Hornych, and S. Braymand. 2023. "Permanent and resilient deformation behaviour of recycled concrete aggregates from different sources, in pavement base and subbase." *Road Mater. Pavement Des.* 24: 2245–2262. https://doi.org/10.1080/14680629.2022.2134048.

Wong, A. K. D., F. K. W. Wong, and A. Nadeem. 2010. "Attributes of building information modelling implementations in various countries." *Archit. Eng. Des. Manage.* 6: 288–302. https://doi.org/10.3763/aedm.2010.IDDS6.

Wu, J., X. Wang, Y. Dang, and Z. Lv. 2022. "Digital twins and artificial intelligence in transportation infrastructure: Classification, application, and future research directions." *Comput. Electr. Eng.* 101: 107983. https://doi.org/10.1016/j.compeleceng.2022.107983.

Zhang, J., C. Zhao, H. Li, H. Huijser, and M. Skitmore. 2020. "Exploring an interdisciplinary BIM-based joint capstone course in highway engineering." *J. Civ. Eng. Educ.* 146: 05020004. https://doi.org/10.1061/(ASCE)EI.2643-9115.0000017.

Zhao, L., Z. Liu, and J. Mbachu. 2019. "Highway alignment optimization: An integrated BIM and GIS approach." *ISPRS Int. J. Geo-Inf.* 8: 172. https://doi.org/10.3390/ijgi8040172.

Zhao, X. 2017. "A scientometric review of global BIM research: Analysis and visualization." *Autom. Constr.* 80: 37–47. https://doi.org/10.1016/j.autcon.2017.04.002.

Zhou, Q., S. Wang, and Y. Liu. 2022. "Exploring the accuracy and completeness patterns of global land-cover/land-use data in OpenStreetMap." *Appl. Geogr.* 145: 102742. https://doi.org/10.1016/j.apgeog.2022.102742.

Zima, K. 2017. "Impact of information included in the BIM on preparation of Bill of Quantities." *Procedia Eng.* 208: 203–210. https://doi.org/10.1016/j.proeng.2017.11.039.