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From a test case to a trusted tool: Lithuania's evolving SWAT system for water and agricultural management

Keywords: modelling system, model management, water management, institution, decision support

Introduction

Agricultural activities are among the major sources of greenhouse gases (Chataut et al., 2023), biodiversity loss (Tsiafouli et al., 2015) and water pollution around the globe (Food and Agriculture Organization of the United Nations [FAO], 2017). According to the studies, agriculture is the leading culprit behind river and lake pollution in the United States (Evans et al., 2019), China (FAO, 2013), where it is estimated to render a staggering 90% of shallow groundwater unfit for human consumption (Lu & Villa, 2022), and the EU (European Environmental Agency [EEA], 2018) severely affecting around 38% of EU water bodies. As expected, population growth, rising per capita food consumption (FAO, 2017) and changing climate is putting even more pressure on water ecosystems (Heathwaite, 2010).

The need to protect and restore water bodies from deterioration has been recognized for nearly half-century in the USA with a major amendment of the Federal Water Pollution Control Act in 1972, to be shortened as Clean Water Act (Laitos

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& Ruckriegle, 2012). In the EU, the same has been done with major water protection legislations such as the Nitrate Directive (Directive 91/676/EEC) and the Water Framework Directive – WFD (Directive 2000/60/EC). Intergovernmental bodies such as the Helsinki Commission (HELCOM, 2023a), bridging the gap between scientific research and policy to safeguard specific water bodies, were established in 1974 (HELCOM, 2023b). These instruments set out standards for the quality of water in the environment and the maximum levels of pollution allowed, aiming to safeguard or improve the condition of water bodies to a "good" state.

However, achieving these objectives has proven to be challenging, especially difficult is addressing diffuse pollution coming from agriculture (EEA, 2020). Recent studies indicate that despite extensive efforts to implement the WFD and other water regulations, nutrient loads from agriculture, especially nitrogen, are on the rise (Nõges et al., 2022; Vigiak et al., 2023). Implementing agricultural pollution control measures have been largely ineffective due to poorly designed policies, lack of targeted approaches, low prioritization, and insufficient integration with farming practices (Brady et al., 2021; Thorsøe et al., 2021). Furthermore, water policy and management design lacks consideration of cost-effectiveness and fails to simultaneously address multiple objectives, such as reducing water pollution, mitigating greenhouse gas emissions, protecting soils, and enhancing agricultural resilience to droughts (Andersson et al., 2022). Addressing such issues requires the utilization of advanced modelling techniques.

The soil and water assessment tool (SWAT) model is one example, which is a powerful tool used worldwide to assess hydrology, water quality, soil health, agricultural or climate impacts (Gassman et al., 2014; Gassman & Yingkuan, 2015; Tan et al., 2019, 2020). Over 6,500 scientific articles document its capabilities in the SWAT Literature Database (Center for Agricultural and Rural Development and Iowa State University, 2023), with the history of development spanning over several decades (Arnold et al., 1998). However, the benefits of using the SWAT model extend far beyond academia. For example, the United States demonstrated its successful application for calculating total maximum daily loads (Borah et al., 2006), evaluating conservation programs (White et al., 2014) or environmental decision-making (White et al., 2022).

Yet, documented examples of the SWAT use in water management institutions in scientific literature outside the US are scarce. There are plentiful sources evaluating the SWAT model's suitability for solving questions related with implementation of the WFD (Bärlund et al., 2007; Kronvang et al., 2009), objectives of the Helsinki convention (Nasr et al., 2007; Piniewski et al., 2020) or even society's development paths (Carstensen et al., 2023), however, only a few articles were available describ-

ing the model development within institutions. For instance, one study for Uruguay (Mer et al., 2020) described a multi-agency effort to build a SWAT model application within a participatory modelling project. Another study (Arnold et al., 2020) introduced the conceptual framework of modelling and model management issues associated with using and developing models within catchment management agencies. In this paper, the authors present cases and lessons learnt from managing catchment models in national or regional institutions in Denmark, the UK, the Netherlands and Canada. Another work (Fu et al., 2020) examined the challenges and actions needed to support and improve water quality modelling within organizations. The study by Vervoort et al. (2024) provided an overview of the integration between science and policy development facilitated by integrated watershed models. However, we have not been able to find a specific example that describes the case of an advanced water modelling tool being developed and used for many years by a single water management institution. This article aims to remedy this situation by providing an insight into the case of Lithuania, where the main water management institution has been using a SWAT-based water modelling system for more than a decade.

Material and methods

In the preparatory phase for EU compliance (i.e. before 2004), it became evident to the Lithuanian Environmental Protection Agency (EPA) and the Ministry of Environment that advanced water modelling tools were essential to address the environmental management and data reporting inquiries mandated by EU regulations. Several trials have been conducted initially with different tools. In 2003, the Danish Hydraulic Institute (DHI) proposed to conduct a comprehensive study to identify optimal modelling options for EPA (Lawson, 2021). This study was completed in 2004 and recommended the use of the MIKE BASIN model (no longer available as of 2014, replaced by MIKE HYDRO Basin) developed and sold by the DHI. MIKE BASIN, an empirical, lumped parameter, continuous time scale, river basin model designed primarily for water allocation issues, has additional capabilities for assessing nutrient loads from multiple sources (Danish Hydraulic Institute Water & Environment, 2003). This model was employed in the initial phase of preparing river basin management plans (RBMPs) across Lithuania, culminating in 2010. However, significant constraints were encountered during the RBMPs preparation projects. For example, the water quality component of the model could only generate information on total watershed loads based on statistical data, and its coefficients have no physical meaning, making predictions highly questionable. In addition, this

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model does not take into account crucial factors influencing diffuse pollution, such as land use, soil characteristics and slope, indicating unreliable results for, among others, modelling non-point source pollution generated by agriculture, which constitutes the main cause of water ecosystem degradation in the country (Aplinkos apsaugos agentūra [AAA], 2009). These limitations implied the need to change the model selection and the modelling approach. Several criteria (Saloranta et al., 2003) were identified in this process:

– Ability to evaluate non-point source pollution in inland water bodies and the environmental effect of implementing mitigation strategies;
– Adaptable for answering WFD questions;
– Compatibility with existing data sources;
– Seamless integration with geographic information systems (GIS);
– Low costs;
– Comprehensive documentation;
– Documented history of successful model applications and extensive development timeline;
– Strong technical support system.

The SWAT model checked all the required boxes and was selected as a tool to be examined with a national test case. The small catchment (14.2 km^2) of the Graisupis river was chosen as a pilot area. Situated in the center of Lithuania, this catchment is predominantly agricultural, covering over 71% of its area. It was selected due to the presence of a long-term monitoring program dedicated to assessing agricultural pollution within the region. Consequently, an abundance of valuable data pertaining to water quality and agricultural practices was readily accessible for analysis. The model application in the Graisupis river catchment was successfully demonstrated for different water management purposes (Plunge, 2009, 2011). This allowed the EPA to proceed with the preparation of the modelling system covering all of Lithuania, as well as areas outside the country that generate flows into Lithuania (Fig. 1).

The development of the national model involved three iterations within three consecutive projects. The first one started in 2011 and was completed in 2012 (Procesu analīzes un izpētes centrs [PAIC] & Estonian, Latvian & Lithuanian Environment, 2012). The second one was completed in 2015 (PAIC, 2015), and the third one in 2022 (PAIC, 2022). During the first iteration, the national model was created and tested with available data. The aim of the second project was to build a modelling system fully based on the Python script library. Additionally, the model was extended to cover the entire Nemunas basin (e.g. areas in Belarus and Poland draining into Lithuania). The third project was designed to migrate the existing system from SWAT2012 to the SWAT+ model, re-calibrating, updating input data, upgrad-

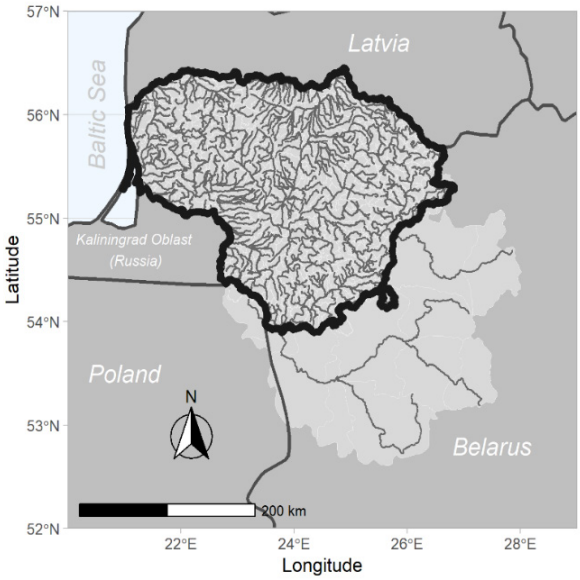

FIGURE 1. Area covered by the model (bold line marks territory of Lithuania, light gray – area covered by the model, thin gray lines – water bodies represented in the model)

Source: Plunge et al. (2022b).

ing the system to model small river water bodies and the modelled network to align with WFD water bodies, upgrading the script library to include automatic building of scenarios for measures, extraction of results and adding new data sources such as rainfall radar (PAIC, 2022). SWAT+ is a new model version characterized by a comprehensive restructuring of inputs and code (Bieger et al., 2017), integrating novel concepts, such as enhanced flexibility in water routing across landscapes (Bieger et al., 2019), decision table (Arnold et al., 2018), etc. Additionally, all the modelling systems were fully transferred to the open source tools using Python (Python Software Foundation, 2023) as the main scripting language, PostgreSQL (The PostgreSQL Global Development Group, 2024) – for database related tasks, PostGIS (PostGIS PSC & OSGeo, 2024) – GIS-related and R (R Foundation, 2024) for some *ad-hoc* input, output data processing tasks.

The constructed system was called the river modelling system (RMS). It has options to be run in two resolution levels (PAIC, 2022). The coarse level, separating the country into 1,335 catchments (individual size does not exceed 80 km^2), corresponds to water bodies defined for the WFD purposes. The detailed level separates the model into 11,490 catchments corresponding to the river, lake and reservoir cadaster data (AAA, 2024). The most detailed recent national and international

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datasets were processed and integrated as SWAT model inputs. Data were provided by multiple institutions as well as experts in specific fields (agriculture, soil, etc.). The main data sources used in the RMS preparation included (Plunge et al., 2022b):

- GIS data of the Rivers, Lakes and Ponds Cadastre of the Republic of Lithuania (EPA) [scale 1:10 000];
- Digital terrain map generated from land surface laser scanning point – SEŽP_0,5LT data (National Land Service) [two-meter spatial resolution];
- Soil data from a soil database – DIRV_DR10LT (National Land Service) [scale 1:10 000];
- Forest Cadastre data (Forest Service) [scale 1:10 000];
- Declared crops data (Agriculture Information and Rural Business Center) [scale 1:1000];
- Abandoned land data – AZ_DR10LT (National Land Service) [scale 1:10 000];
- National geospatial data – GDR10LT (National Land Service) [scale 1:10 000];
- The high-resolution Imperviousness Layer (Geoland2) [10-meter spatial resolution];
- Quaternary geology data (Lithuanian Geological Survey) [scale 1:200 000];
- Soil properties' table (soil expert) [parameter values for the profiles of different soil types existing in DIRV_DR10LT and Forest Cadastre data];
- Meteorological data (Hydrometeorological Service) [mean daily and hourly measurements];
- Point source pollution data (EPA) [yearly means and monthly for big sources (monthly only available for periods of 2006–2016)];
- Water quality monitoring (EPA) [monthly values];
- Water flow data (Hydrometeorological service) [daily flow means];
- Agricultural statistics (Department of Statistics) [yearly statistical data];
- Water extraction (EPA) [yearly data];
- Crop fertilization data (agricultural expert) [amounts for different crops, application methods and timing];
- Belarus data [scale 1:500 000] (Holmlund & Hannerz, 2007);
- EU-DEM v1.17 from Copernicus Land Monitoring Service [30-meter spatial resolution];
- Bathymetry of water bodies (EPA) [one-meter spatial resolution];
- Groundwater pollution (EPA) [modelled mean concentrations];
- Tile drain data – MELDR10LT (National Land Service) [scale 1:10 000];
- Reservoir storage capacity (EPA) [fixed values from reservoir operation rules];
- Atmospheric deposition (European Monitoring and Evaluation Program) [0.1-degree grid].

Results and discussion

The main result of these multi-year efforts is the developed river basin modelling capacity within the EPA. This capacity is now being applied (or in the process to be applied) to address various water management questions. The EPA takes charge of these questions, which encompass tasks arising from the WFD, the Baltic Sea Action Plan (BSAP) for implementing the Helsinki Convention, the Nitrates Directive, the Common Agricultural Policy (CAP), the Environmental Impact Assessment Directive (Directive 2011/92/EU), the Climate Change Convention (greenhouse gas reporting), the Flood Directive (Directive 2007/60/EC), the Marine Strategy Directive (Directive 2008/56/EC), and various reporting requirements for both the European Environment Protection Agency (EEA) and national reporting needs.

The RMS has been calibrated, validated and tested during the preparation of the river basin management plans. Statistical performance evaluation is presented in Figure 2. Soft calibration was utilized to ensure that hydrology and nutrient processes conformed to the available data, including yields and subsurface flow. The model was calibrated/validated using a total of about 62 hydrological stations and 130 stations for water quality data. However, extensive calibration/validation was carried out on representative stations representing 14 regions according to hydrological and pollution generating conditions (Plunge et al., 2022b). Results show that the RMS performs well compared to the observation data. Similar performance levels were kept while transitioning from SWAT2012 (PAIC, 2015) to SWAT+ models (PAIC, 2022).

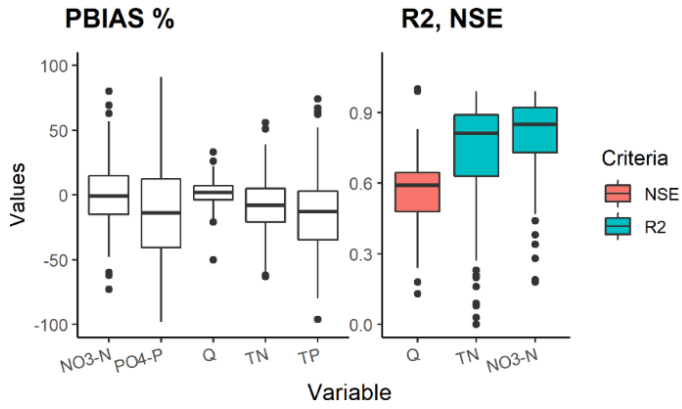

FIGURE 2. Model performance results for daily flows and monthly concentrations
Source: Plunge et al. (2022b).

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In addition to the preparation of RBMPs (AAA, 2021), this system has already been used for the preparation of HELCOM periodic reports on pollution loads, which are used to assess the implementation of the BSAP and the compliance of member countries with the nutrient input ceilings (NIC) for the protection of the Baltic Sea (HELCOM, 2023a). The RMS is also applied for the national state of environment reporting (AAA, 2022), reporting emissions for the EEA (2024). This system was also used to fulfil various other EPA needs. For example, evaluating the potential of best management practices (BMPs) to reduce diffuse pollution from agriculture (Plunge, 2020), assessing the climate change impacts (Gudas & Plunge, 2021), to name a few.

It has also been applied in multiple scientific works. One study (Plunge et al., 2022b) has evaluated consequences of climate change on surface water bodies in Lithuania. Another one, utilizing the RMS, investigated how the effectiveness of BMPs changes with the advancement of climate warming (Plunge et al., 2022a). The costs of agricultural diffuse water pollution abatement to reach water protection goals for Lithuania with changing climate has also been evaluated and published in a scientific paper (Plunge et al., 2023a). In addition, the developed RMS was used to test various tools developed to support SWAT+ modelling efforts (Plunge et al., 2024; Plunge et al., 2023b).

There are also many initiatives and further work planned with this system. For example, a project "Integrated water management in Lithuania" funded within the EU LIFE program will run from 2024 to 2033 (European Commission [EC], 2024). Part of the project's activities is related to updating, improving and applying the RMS for Lithuania, as well as transferring it to selected river basins within the Nemunas river basin in Poland. Another LIFE project is currently underway in Latvia (LIFE GoodWater IP, 2020), which includes the transfer and application of the RMS for the Latvian territory among its activities. This project will continue until 2027.

This work with the RMS is not a unique attempt to apply the SWAT or SWAT+ model in Lithuania or neighboring countries. Different studies have employed this model in large scale applications in Lithuania (Čerkasova, 2019; Čerkasova et al., 2018, 2021, 2024), neighboring Poland (Kundzewicz et al., 2018; Marcinkowski et al., 2022), Estonia (Tamm et al., 2018) and Ukraine (Osypov et al., 2023; Kryshtop et al., 2024). However, there is an important distinction. The RMS is an ongoing project within a decision-making institution that aims to provide river basin modelling capabilities to water and agricultural management institutions. It is intended to be open-source and freely shared so that scientific institutions can benefit from this investment, as well as test and improve the system. Certainly, water management institutions in other countries have authoritative national-scale models, often sup-

ported by academic organizations or earth system modelling agencies (Arnold et al., 2020). However, to the best of our knowledge, this case is quite unique in the Central and Eastern European countries, where governmental agencies with very limited resources would embark to develop and manage such an advanced river basin modelling system.

There are multiple issues which have been noticed a decade ago when embarking on this challenge (Plunge, 2013). Several of them still persist, such as access to reliable data on pollution sources, attracting and retaining skilled specialists within national institutions, and adapting to new versions and revisions of SWAT. However, because this is an ongoing and integrated effort within the institutions, there are many ways to overcome these problems. This might not be the case for a short-term project focused on a single question, which might require a sophisticated model. Unfortunately, after such projects or thesis work is finished, the investment in developing these tools is often lost because the funding, specialists, or both are gone.

While the RMS has been relatively successful on the practical management level, it remains a challenge to meet the most pressing practical or policy needs. This is due to the variety of needs that cannot be addressed by the SWAT model without prior preparation and parameterization of specific scenarios. This is very time-consuming, and time and other resources may be scarce in critical situations. While SWAT is a versatile tool, it may be inappropriate for handling some types of mitigation measures realistically, e.g. channel and floodplain restoration. These limitations are hard to apprehend for policymakers, who do not have much knowledge about the efforts required for model adjustments and nuances. The effective and user-friendly operation of the RMS requires simpler and more accessible tools for data preparation, extraction and presentation in order to maintain its effectiveness and relevance for policy makers and the general public. This could serve as a potential direction for further development in the future.

Conclusions

Lithuania's river modelling system (RMS) has evolved from a test case for a valuable tool for water and agricultural management. Developed to help with European regulations, the RMS is now a part of environmental decision-making. Its integration of the SWAT model and extensive data sources enables comprehensive analysis and informed policy formulation. The RMS has demonstrated its reliability and effectiveness in various applications, including preparing management plans, compiling pollution reports, and supporting scientific research on climate change

and effectiveness of pollution abatement measures. Ongoing initiatives such as the LIFE Integrated Water Management project underscore its continued relevance and potential for regional impact. Despite challenges such as data reliability and retention of skill within the institution, the RMS persists due to institutional commitment and collaborative efforts. Lithuania's experience with the RMS highlights the value of continuous investment in integrated modelling systems for sustainable environmental governance. Through collaboration and innovation, the RMS represents a paradigm shift towards more resilient and advanced water and agricultural management practices. Furthermore, the open-source nature of the developed modelling system presents the potential for it to be adopted by other countries creating more opportunities for cooperation.

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Summary

From a test case to a trusted tool: Lithuania's evolving SWAT system for water and agricultural management. Lithuania's development of the river modelling system (RMS) exemplifies an institutional development and application of integrated modelling for water and agricultural management. What started as a test case, continued to develop focusing on environmental compliance with the EU regulations. Currently, the RMS is a part of decision-making. By incorporating the soil and water assessment tool (SWAT) model and comprehensive data sources, the system facilitates in-depth analysis and policy formulation. Applications in water management plans, pollution assessments, and climate change studies demonstrate the reliability of RMS. Despite data quality and skill retention challenges, institutional commitment and collaboration ensure the RMS's persistence. This experience emphasizes the value of sustained investment in integrated modelling systems for achieving sustainable environmental governance and signifies Lithuania's shift towards data driven green transition practices.

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Ash from gasification of poultry feathers for heavy metal immobilization under assisted phytostabilization in soils

Keywords: *Dactylis glomerata* L., soil contamination, soil amendment, land restoration

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Introduction

Progressing degradation of the soil environment on a global scale has led to the recultivation of contaminated areas gaining a greater role, as well as setting new trends when it comes to scientific research (Santini & Miquelajauregui, 2022). The search for complex solutions in terms of strategies for protecting soil resources, the purpose of which is returning the degraded terrain, including that contaminated with heavy metals, to its renewed use, is the greatest challenge of modern times. In this context, the method of assisted phytostabilization, which is included among gentle remediation options and interferes the least in the environment, finds application (Zhang et al., 2024). The method of assisted phytostabilization, in addition to its main role, i.e., immobilizing contaminants in the root zone, can also be used to reconstruct the grass-legume sward in zones where it was found to have disappeared in connection with the occurrence of high values of heavy metal concentrations (Lacalle et al., 2023). This multifaceted strategy not only addresses soil contamination but also contributes to ecosystem rehabilitation, offering a holistic approach to mitigating the pervasive impacts of soil degradation on a global scale.

Until now, aided phytostabilization has been the subject of many studies on the application in vast spreading post-mining areas, excavation sites, and closed waste disposal sites (Bidar et al., 2016; Teodoro et al., 2020). However, the topic undertaken in the article pertains to the terrain which is located close to urban areas, such as industrial plants involved in the recycling of metal and steel waste on various scales, where waste is very frequently stored directly on the ground without any safety measures, and it is these areas that currently present a challenge due to the need to return them to operational use. In such urban-adjacent environments, the presence of metal and steel waste without proper containment measures poses not only environmental hazards but also potential health risks to nearby communities (Abdulsalam et al., 2020; Dodd et al., 2023).

The global growth of poultry production has resulted in the generation of by-products, with feathers accounting for around 10% of the waste from the poultry sector (Kwiatkowski et al., 2013). In the face of the increasing interest in technologies for the thermal processing of waste, an effective method of utilizing this type of waste is turning feathers into energy with the use of thermochemical processes (Dalólio et al., 2017). Taking into account the fact that poultry feather ash (AGF) is a side product of the thermochemical transformation of feathers, it is necessary

to find a method for its management. One potential method involves using additives to assist in the phytostabilization of soil polluted with metals (Radziemska et al., 2021). The AGF demonstrates a notable adsorption capacity, characterized by an alkaline pH and a nutrient-rich composition (Fahimi et al., 2020). Consequently, it is capable of effectively immobilizing heavy metals within soil that has been contaminated by pollutants. This multifaceted approach not only mitigates metal toxicity to plants, but also enhances soil fertility, promoting the establishment of vegetation in metal-contaminated areas. Incorporating poultry feather ash as an additive in phytostabilization strategies offers a sustainable and cost-effective means of addressing metal pollution while facilitating ecosystem restoration and land remediation efforts (Jagadeesan et al., 2023). In this case, we can speak of the concept of a closed circuit model of the economy, where recovery and reuse in new processes, but also reducing the negative influence of waste materials on the environment, is crucial. Such an idea of the circular management of goods as an element of the strategies of the European bioeconomy poses a challenge of finding other applications of products or waste than those known to date. In connection with the above, the objective was to establish the usefulness of AGF on the soil phytostabilization polluted with metals by evaluating the produce of *Dactylis glomerata* L. as well as Cd, Cu, Pb, and Zn contents in its shoots and roots, at the same time indicating the pH and total exchangeable forms of Cd, Cu, Pb, and Zn contents.

Material and methods

Soil and properties poultry feather ash (AGF)

The soil was taken from the area storing various types of steel waste located in the northeast of Poland, which has been exploited for nearly 80 years, according to the methodology specified in Radziemska et al. (2021). The soil collected exhibited a slightly alkaline pH of 8.4 ±0.1 and a low organic matter content of 1.1 ±0.1%. The soil's cation exchange capacity (CEC) was measured at 56.8 ±0.1 cmol·kg^{-1}. The recorded metal concentrations are as follows (in mg·kg^{-1}): Cd – 13.6 ±1.4, Cu – 396.8 ±10.3, Pb – 10115.4 ±65.1, Zn – 3620.1 ±40.2.

The AGF was generated through the gasification of turkey feathers in a fixed bed gasifier operating at temperatures ranging from 1,000 to 1,200°C, using

wood pellets. The AGF underwent a milling process prior to the experiments to achieve particles with a size of 0.5 mm or smaller. Selected parameters of AGF used as a soil supplement in the method of assisted phytostabilization are compiled in Table 1.

TABLE 1. Selected properties of poultry feather ash (n = 3, ± standard deviation)

Characteristic	Unit	Value
Surface area (Brunauer, Emmett & Teller)	$m^2 \cdot g^{-1}$	1.19
Total area in pores		0.618
pH	–	12.9 ±0.4
Volatile matter	%	1.02 ±0.03
Cd concentration	$mg \cdot kg^{-1}$	< LOD
Cu concentration		2.4 ±0.09
Pb concentration		< LOD
Zn concentration		0.3 ±0.03

< LOD – less than the limit of detection.

Source: own elaboration.

Greenhouse study

Before commencing the experiment, AGF was mixed with soil at a 3.0% (w/w) concentration and subsequently placed in polyethene pots. A series without AGF (0.0%, w/w) was also prepared and designated as the control. The soil-filled pots were located in a completely darkened room for 14 days to ensure the soil mixture was fully stabilized. *Dactylis glomerata* L., with five seeds sowed per pot, was chosen as the test plant (sourced from an authorized seed production center located in Olsztyn, Poland). The plants were watered on alternate days and were harvested after a period of 51 days. The plants were watered with distilled water, ensuring they reached 60% of the maximum water-holding capacity of the soil. Soil moisture content for each pot was regularly maintained at field capacity every three days. It is worth noting that fertilizers were not utilized in this process to prevent any potential interactions with the amendments. After this, they were weighed, divided into their respective parts, namely shoots and roots, and thoroughly cleansed with distilled water.

Physicochemical properties of plants soil and AGF

Soil samples and AGF were pH-tested in distilled water (1 : 2.5 w/v) via HI 221 pH meter. Organic matter in soil and volatile matter were determined by sample ignition in a muffle furnace at 550°C for 4 h (Jeong & Kim, 2001). Volatile matter in ash was determined in a muffle furnace at 950°C for 6 min (Liu et al., 2014). The samples were mineralized in a concentrated mixture of HCl (concentration: 1.16 $g \cdot cm^{-3}$, 38%), HNO_3 (concentration: 1.40 $g \cdot cm^{-3}$, 65%), and H_2O_2 (concentration: 30%) using a microwave oven. Total concentrations of Cd, Cu, Pb, and Zn were estimated with a spectrometer Varian, AA28OFS. The exchangeable soil metal fractions were determined according to Pueyo et al. (2004). The shoots and the roots of the tested plant were mineralized in HNO_3 p.a. and 30% H_2O_2 using a microwave oven.

Statistical evaluation

Statistica 13.3 (StatSoft) was used to conduct the statistical analysis. ANOVA was used to calculate significant differences between the groups (control and AGF) for the Cu, Cd, Pb, and Zn concentrations and in the average values of plant biomass for these same groups. Upon carrying out ANOVA, Tukey's test was conducted to identify significant differences. All analyses were carried out at a significance level equal to 5%.

Results and discussion

Chemical parameters of soil after phytostabilization

The main aim of treatments used to immobilize heavy elements in the soil is to increase the pH value, thereby decreasing their bioavailability (Alvarenga et al., 2009; Radziemska et al., 2022). Upon carrying out the AGF-assisted phytostabilization experiment, soil pH was found to be slightly alkaline (pH 8.5–8.1) in both amended and control soils (Fig. 1). This alkaline pH can be attributed to the presence of alkaline compounds, such as calcium carbonate and calcium oxide, in AGF (Fahimi et al., 2020; Gusiatin et al., 2020). When AGF is applied to the soil, these alkaline compounds dissolve and react with soil moisture, releasing hydroxide ions (OH-) into the soil solution, consequently raising the soil pH towards the alkaline

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range. Additionally, AGF may also act as a buffer, neutralizing soil acidity resulting from metal contamination (Hedayati, 2022). This proves the usefulness of applying byproducts of the thermochemical conversion of feathers in the context of increasing the value of soil pH subjected to aided phytostabilization treatments. Positive results were also obtained in studies where this type of soil amendment was applied to soils that had undergone long-term contamination with Cu, Ni, Cd, Pb, Zn, and Cr, where *Lupinus luteus* L. was the test plant, in which pH increased by 1.42 units upon completion of the experiment (Radziemska et al., 2021).

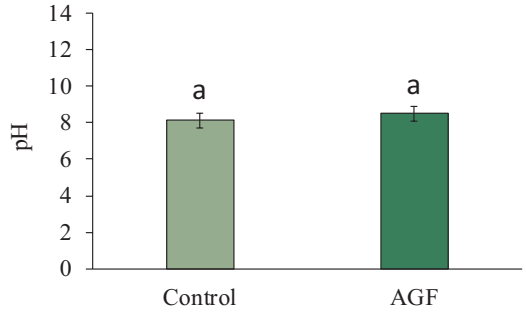

FIGURE 1. Levels of pH in amended and control soils following poultry feather ash (AGF) assisted phytostabilization. Lowercase letters show statistically significant differences among control and AGF treatments for a given metal ($p < 0.05$)

Source: own elaboration.

Both mobilities, as well as the availability of heavy metals in soils, depend on their total concentration as well as exchangeable forms. The content of the analyzed heavy metals in the soil at the end of the experiment was significantly dependent on AGF as a soil amendment (Fig. 2). Linked with the control, the treatment with AGF reduced the exchangeable form of Zn, Cu, Cd, and Pb by 25%, 23%, 20%, and 12%, respectively. This reduction can be attributed to the sorptive properties of AGF, which effectively bind heavy metals in the soil, thereby decreasing their solubility and availability for leaching (Moon, 2019). The sorption process involves multiple mechanisms, including adsorption, precipitation, and complexation, facilitated by AGF's high adsorption capacity owing to its porous structure and extensive surface area (Table 1).

Heavy metals present in the soil solution can readily bind to the surface of AGF particles, leading to a decrease in their concentration in the soil water and mitigating their potential for leaching. Additionally, the alkaline nature of AGF promotes the precipitation of heavy metals as insoluble hydroxides or carbonates, further immobilizing them within the soil matrix (Fahimi et al., 2020). As a result, soil quality was improved; the lower availability of heavy metals reduces their risk of leaching into

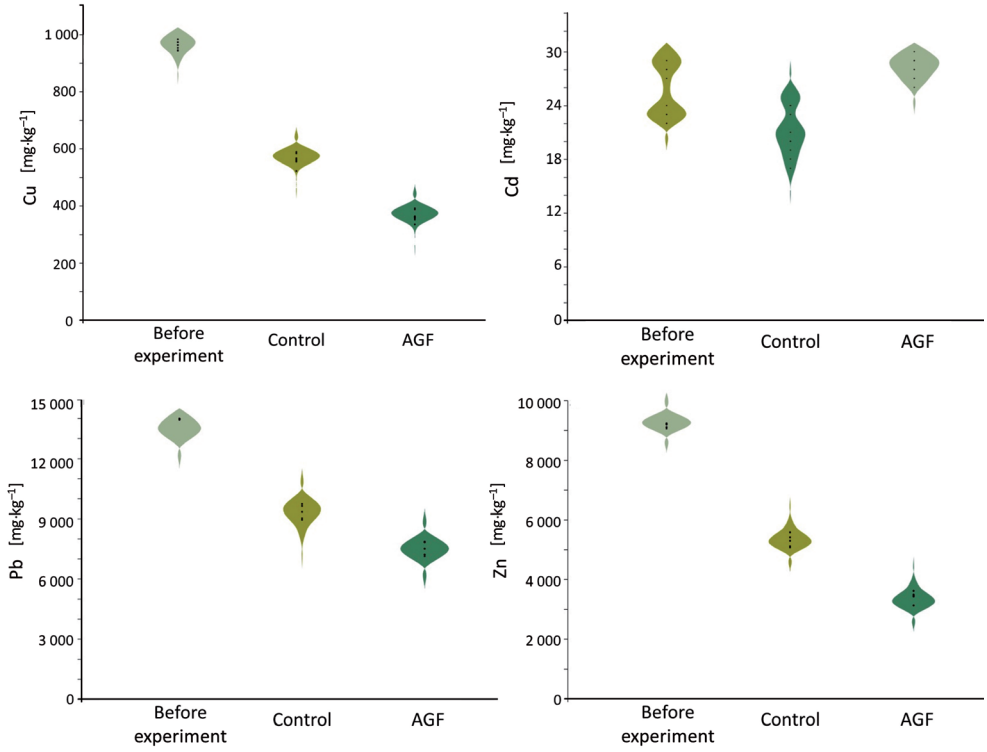

FIGURE 2. Content of heavy metals in soils
Source: own elaboration.

the groundwater and surface waters (Mohamed et al., 2023; Shahrokh et al., 2023). The reduction of complete forms of Cu and Zn, on the other hand, was decreased in both cases by 35%, with Pb and Cd by 20% and 17%, respectively, when likened to the control series. The obtained results clearly indicate that the addition of AGF can effectively decrease the mobility of Cd, Cu, Pb, and Zn in the soil. These findings are consistent with previous studies that showcased the remarkable efficacy of waste chicken feather-derived hydrolysates initiated by malic acid (Solcova et al., 2024). Authors demonstrated notable extraction efficiencies for various heavy metals from industrial soil, including 100% for As, 34.4% for Cr, 0.6% for Cu, 29.5% for Fe, 9.5% for Mn, 19.8% for Ni, and 19.8% for Zn. The parallels between our findings and those of Solcova et al. (2024) highlight the potential of utilizing agricultural waste-derived solutions for both extraction and immobilization purposes, offering a comprehensive approach to addressing heavy metal contamination in soils from industrial settings.

Klik, B., Jachimowicz, P., Liniauskiene, E., Gusiatin, M., Radzevičius, A., Brtnický, M., Šadzevičius, R., Bęś, A., Mazur, Z., Dapkienė, M., Radziemska, M. (2024). Ash from gasification of poultry feathers for heavy metal immobilization under assisted phytostabilization in soils. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 131–143. DOI 10.22630/srees.9761

Dactylis glomerata L. biomass and chemical composition

Maintaining an adequate vegetation layer in areas exposed to long-term pollution with heavy metals is one of the key reasons why treatments taking advantage of aided phytostabilization have been gaining so much popularity. According to Beddows (1959), *Dactylis glomerata* L. exhibits satisfactory growth at pH levels between 6.0 and 7.0, but also tolerates values as high as 8.5. This dependency held in results connected to the plant yield upon completion of the experiment. It was shown that the plant field of *Dactylis glomerata* L. is significantly dependent on the Cu, Cd, Pb, and Zn contents in the soil, as well as the addition of AGF (Fig. 3).

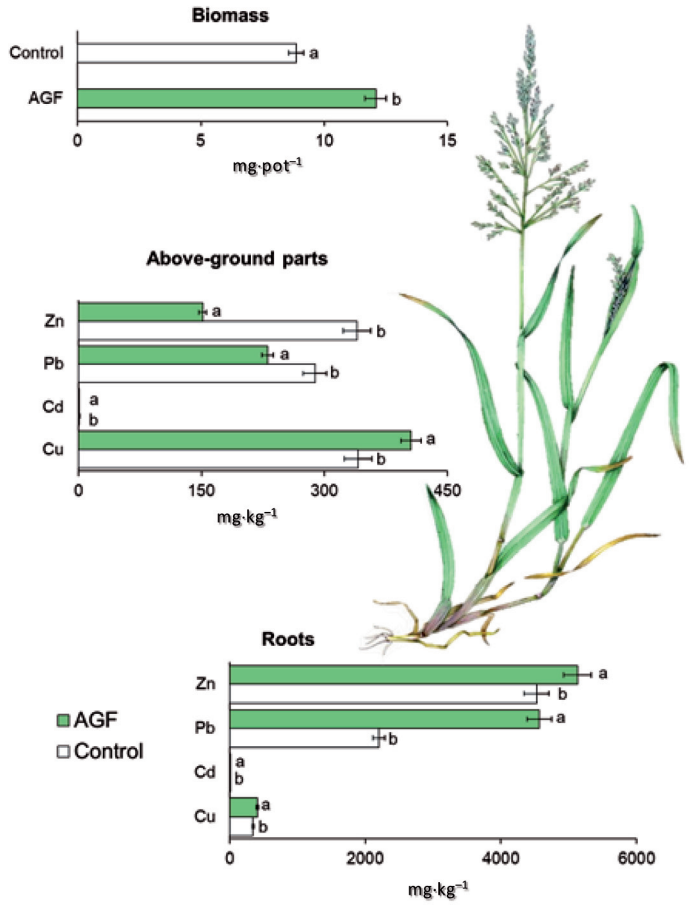

FIGURE 3. Plant biomass after phytostabilization with poultry feather ash (AGF) and metals concentration in shoots and roots of *Dactylis glomerata* L. Lowercase letters show statistically significant differences between control and AGF treatments for a given metal ($p < 0.05$)

Source: own elaboration.

The use of the analyzed soil amendment had a positive influence on the yield of the tested plant, which was 31% higher in this case when compared to the control series. This observation was similar to that reported by Radziemska et al. (2021), where the positive impact of AGF on *Lupinus luteus* L. growth was also observed. In the case of the mentioned studies, the test plant yield was 28% higher than in the control series. Similarly, Adekiya et al. (2019) demonstrated the beneficial effects of poultry feathers on soil characteristics, growth, and yield of tomato plants. The observed increase in plant yield following the AGF application was attributed to improvements in soil physical and chemical properties, enhanced nutrient availability, and the promotion of beneficial microbial activity. The combination of these factors creates a favorable environment for plant growth and development, ultimately leading to higher yields. One of the main advantages of applying various types of soil amendments to contaminated soils is stabilizing or restricting the mobility of heavy metals in the rhizosphere (Shackira & Puthur, 2019). In the carried out experiment, the roots of *Dactylis glomerata* L. were characterized by significantly higher contents of Cu, Cd, Pb and Zn, both in the control series as well as upon adding AGF to the soil. This dependency has been confirmed in the studies of other authors, in case of which the tested plants revealed higher heavy metal contents in their roots than in the shoots (Ivanov et al., 2003; Franco-Hernández et al. 2010; Khanthom et al., 2021). The higher accumulation of heavy metals in the roots of *Dactylis glomerata* L. can be attributed to two main factors: rhizosphere acidification and chelation processes, as well as the high cation-exchange capacity of cell walls (Sumiahadi & Acar, 2018; Shrivastava et al., 2019). Rhizosphere acidification and chelation processes involve plants releasing protons into the soil through plasma membrane-localized proton pumps, which lowers the pH of the rhizosphere. This acidification increases the solubility of metal ions, making them more available for root uptake (Sumiahadi & Acar, 2018). Additionally, plants exude low-molecular-weight compounds, such as organic acids and phytochelators, into the rhizosphere. These compounds form stable complexes with metal ions, enhancing metal uptake by plant roots (Rasci & Navari-Izzo, 2011). Furthermore, the high cation-exchange capacity of cell walls in root tissues plays a crucial role in limiting the translocation of heavy metals to shoots (Cui et al., 2021). Cell walls contain negatively charged sites that attract and bind positively charged metal ions, effectively immobilizing them within the root tissues. This restricts the movement of heavy metals to shoots and leaves, leading to their preferential accumulation in the roots (Shrivastava et al., 2019). Upon applying AGF as an additive aiding phytostabilization, the higher concentration of heavy metals in the roots of *Dactylis glomerata* L. was most apparent for Cu, Cd, Pb, and Zn. In this case, the contents of individual metals were higher by 16%, 37%, more than twice as high, and 12% when compared to the control series.

Conclusions

The application of AGF had a positive influence on the *Dactylis glomerata* L. plant yield. The plant biomass was 31% higher in pots to which AGF had been applied, as compared to the control series. The roots in the series with AGF were characterized by higher values of the analyzed heavy metals in relation to the shoots, which was noticeable in the case of Pb (over twice higher) and Cd – 37%. AGF influenced an increase in the pH values of soil (by 0.4 units) and to the highest degree limited exchangeable forms of Zn (25%), Cu (23%), Cd (20%), and Pb (12%) as well as total forms of Cu (35%), Zn (35%), Pb (20%) and Cd (17%) in the soil as compared to the control series. To sum up, the application of this type of waste material can be an important element of studies on the technologies of managing and reusing waste products in environmentally friendly solutions. What is more, the introduction of AGF as a soil amendment is an advancement in terms of environmental engineering activities in the scope of soil protection, facilitating the usefulness of the method of assisted phytostabilization, both in terms of the effectiveness of immobilizing heavy metals as well as the development of plant biomass in the contaminated area.

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Summary

Ash from gasification of poultry feathers for heavy metal immobilization under assisted phytostabilization in soils. The carried-out experiment aimed to assess the influence of ash derived from the thermochemical conversion of feathers (AGF) as a soil amendment, and *Dactylis glomerata* L. as a test plant in aided phytostabilization of soil strongly contaminated by Cu, Cd, Pb and Zn. The influence of AHG on the chemical properties of soil (pH as well as total and $CaCl_2$-extracted heavy metals) as well as the plant yield and concentration of heavy metals in the roots and shoots. The applied soil amendment influenced an increase in the pH values of soil (by 0.4 units) and a reduction in $CaCl_2$-extractable forms of Zn (25%), Cu (23%), Cd (20%) and Pb (12%), as well as total forms of Cu (35%), Zn (35%), Pb (20%) and Cd (17%) in the soil. The plant yield of the shoots of *Dactylis glomerata* L. following the application of AGF was 31% higher when compared to the control series. The roots of the tested plant in the AGF series contained higher values of the analyzed heavy metals in relation to the shoots, which was especially visible in the case of Pb (more than twice as high) and Cd (37%).

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Study of the influence of commercial activities on waste formation in Ukraine in the context of sustainable development

Keywords: sustainable development, environmental safety, waste formation, utilization and recycling, information support, multiple regression econometric model

Introduction

The issue of waste accumulation and management in Ukraine is a pressing concern and takes precedence among other environmental problems. The concentration of solid waste, household waste, and hazardous waste substances is a factor contributing to ecological instability and the occurrence of emergencies.

Flammini et al. (2022) emphasize the quantitative assessment of greenhouse gas emissions resulting from the combustion of fossil fuels for energy use in agriculture, forestry, and fisheries. Samojlik (2014) also emphasized the regional aspects of the necessity for waste utilization. At the same time, the author underlined the need for

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a comprehensive assessment of the waste management efficiency in the region based on balancing the economic, environmental, social, and technological criteria in this field. Within the framework of the topic, Kryvenko (2015) proves that waste management in regions is characterized by a significant impact on the environment due to waste utilization processes, lack of available land for waste disposal, and low efficiency of the waste management system overall. Viedienina et al. (2020) also assert that the disposal of solid household waste is a necessary foundation for sustainable economic development.

Pryshliak et al. (2021) justified the prerequisites and organizational-economic mechanism for the formation and implementation of waste management strategies in agricultural enterprises.

Electronic waste is of particular significance in modern times, being just as harmful as waste from agrarian activities. It contains not only hazardous substances but also precious metals such as gold, silver, copper, and platinum. For example, in 2016, approximately 0.44 million t of mobile phones were discarded worldwide, with a raw material value of 9.4 billion EUR (Honcharenko, 2021). Skorik (2017) summarized issues related to electronic waste and proposed an economic mechanism for managing electronic waste in Ukraine.

Kovalenko et al. (2022) focused on the problems of Ukraine's municipal solid waste and ways to address them.

Flammini (2022) also conducted research on key waste generation trends at global, regional, and national levels. Expanding on this research, Brohi et al. (2023) studied waste at the regional level, specifically solid municipal waste in Dadu, Sindh, Pakistan.

The state of waste management in countries is a significant concern and poses a threat to the ecological safety of a nation, necessitating the immediate implementation of a comprehensive set of legislative, organizational, and research measures aimed at the practical realization of the concept of sustainable development. UN member countries have identified waste management as one of the important requirements for achieving sustainable development goals (Government Portal of Ukraine, 2023) by incorporating Goal 12 (Responsible Consumption and Production), which emphasizes the need to reduce ecological impact by changing production and consumption patterns, and Goal 13 (Climate Action), which focuses on reducing greenhouse gas emissions, saving lives and helping communities (Government Portal of Ukraine, 2023). It is worth noting that the concept of sustainable development takes into consideration not only the environment, but also the economic and social dimensions (Kalemkerian et al., 2023). Adhering to sustainable development requirements is advocated by Škrinjarić (2020).

The information about the state of the environment, allowing for the identification of threats to nature and species and the development of strategies for their preservation, is the basis for deciding on a waste management mechanism. In addition, Dovga (2011) points out the necessity of implementing modern recycling technologies for solid household waste. Simultaneously, such an approach will ensure improvements in the quality of the environment and the quality of life for the population in the context of sustainable development goals (Masyk et al., 2023).The state of environment has a direct impact on human health. Air, water, and soil pollution can lead to illnesses, and information about these risks helps take preventive measures. Moreover, the quantity of waste and its management are crucial for agriculture and the level of food security, as demonstrated by Dziurakh et al. (2022). Furthermore, the increase in waste disposal expenses stimulates overall eco-expenditures within the region (Shpak et al., 2021b). Additionally, it is essential not to overlook the presence of qualified personnel capable of conducting such disposal effectively, as the COVID-19 pandemic and the war in Ukraine have led to a decrease in the population and resulted in a problem with the quality of personnel in Ukraine (Podolchak et al., 2021). Thus, the state of the environment is determined by a combination of information regarding its pollution and waste management (Lotrecchiano et al., 2022).

Martynovych et al. (2023) have prepared recommendations for the development of territories subject to restoration. They proposed a concept of territory conversion and justified the need to distribute territories based on the added value and the quality of life of the population.

However, currently there is insufficient research related to the influence of various factors on waste generation within specific territories. In particular, this study proposes to investigate the influence of agricultural, forestry, and fishery activities, mining and processing industries, construction, electricity, gas, steam, and conditioned air supply, and other economic activities in Ukraine on waste generation. This research will build upon previous waste management issues in European countries (Papagiannis et al., 2021) and in Ukraine. The increase in the volume of waste in Ukraine is facilitated by the increased use of packaged goods. Therefore, Krykavskyi et al. (2018) emphasize the importance of promoting ecological awareness and behavior among Ukrainians in this direction, promoting this idea at the state level, and engaging manufacturers and intermediaries in its implementation. Ishchenko et al. (2021) have also continued research in this direction. Research in this direction was also conducted by Shults et al. (2021), revealing the level of influence of stimulating and destimulating factors on consumer capacity. Simultaneously, Shpak et al. (2021a) indicate the need to formulate a develop-

ment strategy for each industry, taking into account the influence of various factors on its development. Bochko et al. (2022), on the other hand, point out the level of competitiveness of the development of each industry separately and the country as a whole, considering the necessity to apply the digital economy. However, the studies of these authors are relatively general and present the problem in a generalized manner.

Significant volumes of waste in Ukraine pose a substantial obstacle to its sustainable development. They require further processing and disposal, necessitating the provision of dedicated facilities for these purposes and the allocation of land for their accumulation. Simultaneously, waste has a negative impact on the state of the environment, the occurrence of emergencies, and people's health. Therefore, every country faces the issue of waste accumulation and the analysis of sources of their formation. In the pre-war period, various sectors of the economy primarily generated a significant portion of Ukraine's waste. In the conditions of the post-war state, their functioning will also negatively affect Ukraine's environment. Therefore, the aim of this article is to analyze the impact of various economic sectors in Ukraine on the formation of the total amount of waste in Ukraine based on statistical data.

Research into the impact of economic activity on waste generation in Ukraine in the context of sustainable development entails studying the influence of economic activities on the quantity and composition of waste generated in Ukraine. This research aims to develop strategies and practices for reducing the negative impact of various economic sectors on the environment. It is worth noting that an increase in the production and consumption of goods and services often leads to an increase in waste. There is a strong correlation between the increase in waste and an increase in energy consumption. The overall impact of economic activity on waste levels depends on various factors, including the industry, region, technologies, and stakeholders' awareness in the process. Effective waste management and the development of a sustainable economy can contribute to reducing the negative impact of economic activities on the environment.

In the current circumstances, during the wartime situation in Ukraine, the waste problem has taken unprecedented proportions, especially after the explosion of the Kakhovska Hydroelectric Station (Kyiv School of Economics, 2023). In general, waste volumes in Ukraine will continue to increase with the ongoing war initiated by the Russians (Kolesnichenko, 2023). The state can influence waste reduction through the regulation of various economic sectors that pollute the environment and the formation of ecological behavior among the population.

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Material and methods

To determine the quantitative assessment of the impact of various sectors of the economy on waste generation in Ukraine, it is advisable to use a multiple regression econometric model that allows for a quantitative evaluation of the influence of various factors on a specific economic process or phenomenon. In general, such a model takes the form of (Nakonechnyi et al., 2004):

$$y = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_m x_m + u. \tag{1}$$

To determine the structure of a multifactor linear model, a correlation matrix $\boldsymbol{R_y}$ is utilized, which includes both the factors and the indicator.

$$\boldsymbol{R_y} = \begin{pmatrix} r_{x_1x_1} & r_{x_1x_2} & \ldots & r_{x_1x_m} & r_{x_1y} \\ r_{x_2x_1} & r_{x_2x_2} & \ldots & r_{x_1x_1} & r_{x_2y} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ r_{x_mx_1} & r_{x_mx_2} & \ldots & r_{x_mx_m} & r_{x_my} \\ r_{yx_1} & r_{yx_2} & \ldots & r_{yx_m} & r_{yy} \end{pmatrix}, \tag{2}$$

where: $$r_{x_ix_j} = \frac{\frac{1}{n}\sum_{k=1}^{n}\left(x_{ik} - \overline{x}_i\right)\left(x_{jk} - \overline{x}_j\right)}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x}_i)^2 \sum_{j=1}^{n}(x_j - \overline{x}_j)^2}}. \tag{3}$$

The model should include factors that correlate with the indicator and not correlate with each other.

For multiple regression econometric models, it is important to investigate whether there are interrelationships between the factors, which is referred to as multicollinearity, as it negatively affects the quantitative characteristics of the econometric model.

Investigating multicollinearity can be done using the Farrar–Glaube's algorithm, which employs three types of statistical criteria (Nakonechnyi et al., 2004) to check for multicollinearity: multicollinearity in the entire array of factors (χ^2); multicollinearity of each factor with all other factors (*F*-criterion); multicollinearity between each pair of factors (*t*-criterion):

$$\chi_p^2 = -\left(n-1-\frac{2m+5}{6}\right)\ln\left(\det R\right), \tag{4}$$

where n is the number of observed data; m is the number of factors; $\det R$ is the determinant of the correlation matrix:

$$\boldsymbol{R} = \begin{pmatrix} r_{x_1x_1} & r_{x_1x_2} & \ldots & r_{x_1x_n} \\ r_{x_2x_1} & r_{x_2x_2} & \ldots & r_{x_2x_n} \\ \ldots & \ldots & \ldots & \ldots \\ r_{x_mx_1} & r_{x_mx_2} & \ldots & r_{x_mx_n} \end{pmatrix}, \tag{5}$$

$$F_j = \left(z_{jj}-1\right)\frac{n-m-1}{m}, \tag{6}$$

in which z_{jj} represents the elements of the matrix inverted from the correlation matrix.

To determine the structure of a multifactor linear model, a correlation matrix $\boldsymbol{R_y}$ is utilized, which includes both the factors and the indicator:

$$t_{ij} = \frac{r_{ij,1,2,\ldots,m}\sqrt{n-m-1}}{\sqrt{1-r^2_{ij,1,2,\ldots,m}}}, \tag{7}$$

where $r_{ij,1,2,\ldots,m}$ represents the partial correlation coefficients determined by following formula:

$$r_{ij,1,2,\ldots,m} = \frac{z_{ij}}{\sqrt{z_{ii}z_{jj}}}. \tag{8}$$

In the case of detecting multicollinearity, it is necessary to eliminate the factors that cause it. To determine the model parameters a_0, a_1, a_2, a_3, …, a_m, the method of least squares can be used (Nakonechnyi et al., 2004):

$$\vec{A} = \left(X^T X\right)^{-1}\left(X^T \vec{Y}\right), \tag{9}$$

where $\vec{Y}$ is the data vector of the indicator; X represents the data matrix of factors; $\vec{A}$ is the vector of model parameters.

To check the adequacy of the constructed multiple regression model, coefficients of determination (R^2), the F-statistic (F), the Neyman's criterion (Q), and the Student's t-test (t) can be used.

Coefficient of determination is calculated as follows:

$$R^2 = \frac{\sum(\hat{y}_i - \overline{y})^2}{\sum(y_i - \overline{y})^2}, \tag{10}$$

where $\hat{y}_i$ is the theoretical values; $\overline{y}$ is the mean value; y_i is the actual values.

The F value is calculated as follows:

$$F = \frac{\frac{R^2}{m}}{\frac{\left(1 - R^2\right)}{\left(n - m - 1\right)}} \tag{11}$$

The Q value is calculated as follows:

$$Q = \frac{\frac{\sum_{i=2}^{n}(u_i - u_{i-1})^2}{n-1}}{\frac{\sum_{i=1}^{n} u_i^2}{n}}, \tag{12}$$

where u_i represents the random deviations (residuals).

To determine the structure of a multifactor linear model, a correlation matrix $\boldsymbol{R_y}$ is utilized, which includes both the factors and the indicator.

$$t_{a_i} = \frac{|a_i|}{\sigma_{a_i}}, \tag{13}$$

where σ_{a_i} is the standard error of the parameter estimate.

The partial coefficient of elasticity for x_i factor is calculated using following formula:

$$E_{x_i} = \frac{\partial y}{\partial x_i}\frac{x_i}{y}. \tag{14}$$

The partial coefficient of elasticity indicates how the indicator y changes if the factor changes by 1% while keeping the values of other factors constant. To determine the quantitative assessment of the impact of various factors on waste generation in Ukraine across different directions, the authors proposed utilizing a multifactor econometric linear model.

To determine the quantitative assessment of the impact of various factors on waste generation in Ukraine across different directions, the authors proposed utilizing a multifactor econometric linear model:

$$\hat{y} = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6, \tag{15}$$

where $\hat{y}$ – total waste generated; x_1 – agriculture, forestry, and fisheries; x_2 – extractive industry and quarrying; x_3 – extractive industry and quarrying processing industry; x_4 – supply of electricity, gas, steam, and conditioned air; x_5 – construction; x_6 – other types of economic activities.

The indices of waste generation dynamics were determined as individual chain indices:

$$I_{w_{i,j}} = \frac{x_{i,j}}{x_{i,j-1}}, y = a_0 = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6, \tag{16}$$

where the value of the *i*-th type of waste in the *j*-th time period.

The research is based on statistical data regarding the dynamics of waste generation in Ukraine by sources for the years 2010–2022.

Bochko, O., Kosar, N., Kuzo, N., Fihun, N., Kliuvak, O. (2024). Study of the influence of commercial activities on waste formation in Ukraine in the context of sustainable development. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 144–162. DOI 10.22630/srees.6142

Results and discussion

Analysis of existing waste in Ukraine

The question of reforming the waste management system and reducing waste is a crucial component of Ukraine's national environmental security. Even before the full-scale invasion by Russia, Ukraine had accumulated approximately 54 million m^3 of waste. However, only 6% of the total municipal waste was subject to recycling, with the rest ending up in landfills, many of which have long exceeded their capacity. Over the past 10 years, solid municipal waste in our country has increased by nearly 50% per capita, averaging to 300–400 kg per capita annually (Rokhova, 2019). The increasing volume of waste poses a significant problem for the environment and society as a whole. Among the key factors contributing to the growth of waste during the pre-war period were population growth, rising consumer incomes, increased use of disposable goods and excessive packaging, technological development, the shift from production to a consumption-based economy, inefficient resource utilization, the need for recycling, and consumerism.

If these factors are not addressed, they will remain relevant for Ukraine in the post-war period. A graphical representation of the causes and consequences of waste generation in Ukraine is presented in Figure 1.

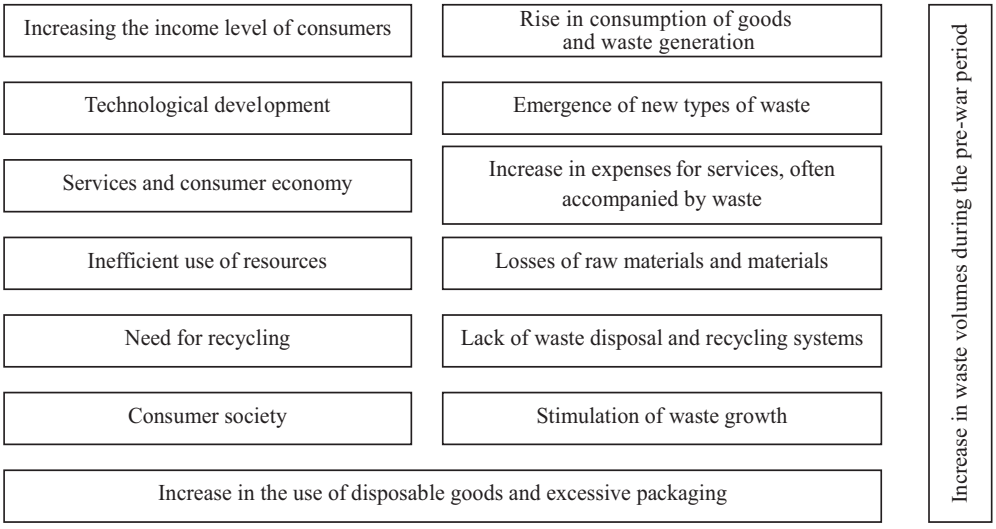

FIGURE 1. Main factors and consequences of waste generation in the pre-war period
Source: own elaboration.

Kolodiichuk (2022) identifies other factors influencing the level of waste generation in Ukraine. Notably, organizational and economic factors that determine the volume and structure of waste generation and disposal are mentioned. These factors encompass the country's macroeconomic situation, business activities of enterprises, waste logistics, economic and environmental incentives, and production constraints. The author also highlights a group of innovation and technological factors that affect the formation of waste management systems. These factors include the technological level of production and disposal facilities, investment activity, and access to credit resources.

To quantitatively assess the impact of various factors on waste generation in Ukraine from different sources, data from Table 1 were used. Figure 2 shows the dynamics of waste generation indices by sources for the years 2011–2020.

Analyzing Figure 2, we can observe that there are no clear trends in waste generation by sources. Therefore, to determine the impact of individual factors on the level of waste generation in Ukraine, it is advisable to use econometric modeling.

TABLE 1. Dynamics of waste generation by sources in 2010–2020

Year	Agriculture, forestry, and fisheries [kt]	Extractive industry and quarrying [kt]	Extractive Industry and quarrying processing industry [kt]	Supply of electricity, gas, steam, and conditioned air [kt]	Construction [kt]	Other types of economic activities [kt]	Total waste generate [kt]
	x_1	x_2	x_3	x_4	x_5	x_6	y
2010	8 304.5	347 442.3	47 676.5	8 636.4	326.7	3 795.8	422 549.9
2011	12 201.2	357 863.6	48 920.4	9 895.6	677.9	9 524.4	443 795.5
2012	10 030.4	364 964.1	48 709.9	9 805.5	609.4	5 059.7	446 716.9
2013	10 080.6	373 042.6	40 738.5	9 339.2	737.3	2 914.3	445 262.1
2014	8 451.4	297 290.0	34 796.7	5 972.7	306.4	1 868.9	355 000.4
2015	8 736.8	257 861.9	31 000.5	6 597.5	376.2	1 641.4	312 267.6
2016	8 715.5	237 461.4	34 093.0	7 511.5	300.2	1 442.0	295 870.1
2017	6 188.2	313 738.2	32 176.7	6 191.7	493.8	1 407.4	366 054.0
2018	5 968.1	301 448.9	31 523.2	6 322.7	378.8	1 148.7	352 333.9
2019	6 750.5	390 563.8	30 751.8	5 959.2	188.7	1 405.8	441 516.5
2020	5 315.4	391 077.9	52 311.0	5 333.7	14.5	2 371.3	462 373.5

Source: State Statistics Service of Ukraine (2021).

Bochko, O., Kosar, N., Kuzo, N., Fihun, N., Kliuvak, O. (2024). Study of the influence of commercial activities on waste formation in Ukraine in the context of sustainable development. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 144–162. DOI 10.22630/srees.6142

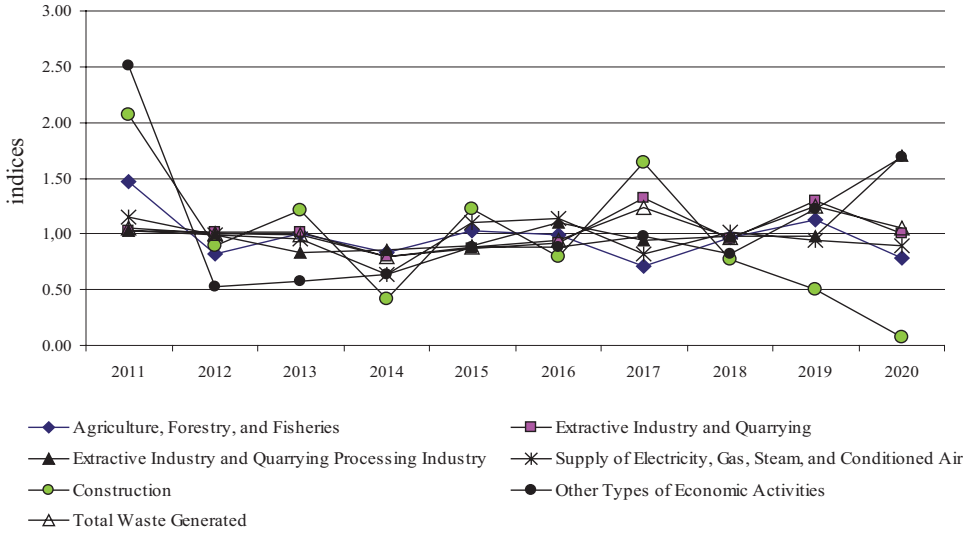

FIGURE 2. Dynamics of waste generation index by sources for the years 2011–2020
Source: compiled based on data from State Statistics Service of Ukraine (2021).

Studying the impact of individual factors on waste generation in Ukraine

To determine the significance of the influence of individual factors (different sectors of the economy) on the level of waste generation in Ukraine, a correlation matrix $\boldsymbol{R}_y$ was used:

$$\boldsymbol{R}_y = \begin{pmatrix} 1.000 & -0.004 & 0.327 & 0.859 & 0.743 & 0.765 & 0.140 \\ -0.004 & 1.000 & 0.594 & 0.213 & 0.045 & 0.374 & 0.982 \\ 0.327 & 0.594 & 1.000 & 0.516 & 0.106 & 0.682 & 0.717 \\ 0.859 & 0.213 & 0.516 & 1.000 & 0.796 & 0.758 & 0.357 \\ 0.743 & 0.045 & 0.106 & 0.796 & 1.000 & 0.546 & 0.134 \\ 0.765 & 0.374 & 0.682 & 0.758 & 0.546 & 1.000 & 0.511 \\ 0.140 & 0.982 & 0.717 & 0.357 & 0.134 & 0.511 & 1.000 \end{pmatrix}.$$

According to the matrix $\boldsymbol{R}_y$, waste generation in Ukraine is significantly influenced by the extractive industry and quarrying (x_2), the processing industry (x_3), and other types of economic activities (x_6).

In the construction of a multifactor econometric model, it's essential to ascertain whether the condition of independence between the selected factors is met, in other words, to verify the absence of multicollinearity. The Farrar–Glauber's method was employed to investigate the phenomenon of multicollinearity.

To perform further calculations, it is necessary to determine the correlation matrix (***R***):

$$\boldsymbol{R} = \begin{pmatrix} 1.000 & 0.594 & 0.374 \\ 0.594 & 1.000 & 0.682 \\ 0.374 & 0.682 & 1.000 \end{pmatrix}.$$

To determine multicollinearity in the entire set of factors, the criterion $\chi^2_p = 6.745$ was calculated, which needs to be compared with $\chi^2_k = 7.8$ with a reliability of 0.95 and degrees of freedom 3. The obtained value indicates the absence of general multicollinearity:

$$\boldsymbol{X} = \begin{pmatrix} 1.0 & 347{,}442.3 & 47{,}676.5 & 3{,}795.8 \\ 1.0 & 357{,}863.6 & 48{,}920.4 & 9{,}524.4 \\ 1.0 & 364{,}964.1 & 48{,}709.9 & 5{,}059.7 \\ 1.0 & 373{,}042.6 & 40{,}738.5 & 2{,}914.3 \\ 1.0 & 297{,}290.0 & 34{,}796.7 & 1{,}868.9 \\ 1.0 & 257{,}861.9 & 31{,}000.5 & 1{,}641.4 \\ 1.0 & 237{,}461.4 & 34{,}093.0 & 1{,}442.0 \\ 1.0 & 313{,}738.2 & 32{,}176.7 & 1{,}407.4 \\ 1.0 & 301{,}448.9 & 31{,}523.2 & 1{,}148.7 \\ 1.0 & 390{,}563.8 & 30{,}751.8 & 1{,}405.8 \\ 1.0 & 391{,}077.9 & 52{,}311.0 & 2{,}371.3 \end{pmatrix}, \quad \boldsymbol{Y} = \begin{pmatrix} 422{,}549.9 \\ 443{,}795.5 \\ 446{,}716.9 \\ 445{,}262.1 \\ 355{,}000.4 \\ 312{,}267.6 \\ 295{,}870.1 \\ 366{,}054.0 \\ 352{,}333.9 \\ 441{,}516.5 \\ 462{,}373.5 \end{pmatrix}.$$

To apply the least squares method, a matrix of factor values *X* and a vector of indicator values *Y* were formed.

As a result of the calculations, the parameters of the multifactor model were obtained:

$$\vec{A} = \begin{pmatrix} 22{,}587.404 \\ 0.989 \\ 0.995 \\ 2.227 \end{pmatrix}.$$

Therefore, the model will have the form of $\hat{y} = 22,587 + 0.989x_2 + 0.995x_3 + 2.227x_6$.

The obtained model was checked for adequacy with a reliability of 0.95 (Table 2).

TABLE 2. Results of the adequacy study of the multifactor model for the impact of identified factors on waste generation in Ukraine

Indicator	Value	Critical value	Result
Coefficient of determination	0.997	–	There is a strong correlation between the identified factors and the generation of waste in Ukraine.
F-criterion	883.522	4.35	The model is adequate to the general population data.
Neuman's criterion	1.390	1.18 3.61	No autocorrelation of residuals is present.
Student's criterion (ta_1)	44.548	2.365	The parameter a_1 is statistically significant.
Student's criterion (ta_2)	7.270		The parameter a_2 is statistically significant.
Student's criterion (ta_3)	4.762		The parameter a_3 is statistically significant.

Source: own elaboration.

Considering that the constructed multifactor econometric model is adequate to the static data of the general population, it can be used for further analysis of the waste generation process in Ukraine.

Assessing the significance of the impact of changes in waste generation in the researched economic sectors on waste generation in Ukraine

To determine the influence of the identified factors on waste generation in Ukraine, partial elasticity coefficients play a crucial role. They indicate the percentage change in the indicator when one of the factors changes by one percent while keeping the values of other factors constant. Partial elasticity coefficients are presented in Table 3.

TABLE 3. Impact of changes in the identified factors on waste generation in Ukraine

Elasticity coefficients	Value	Result
Ex_2	0.829	When waste from mining and quarrying industries increases by 1%, waste generation in Ukraine will increase by 0.829%, assuming that waste from the processing industry and other economic activities remains unchanged.
Ex_3	0.112	When waste from the processing industry increases by 1%, waste generation in Ukraine will increase by 0.112%, assuming that waste from mining and quarrying industries and other economic activities remains unchanged.
Ex_6	0.011	When waste from other economic activities increases by 1%, waste generation in Ukraine will increase by 0.011%, assuming that waste from mining and quarrying industries, as well as the processing industry, remains unchanged

Source: own elaboration.

Therefore, the key factors influencing waste generation in Ukraine are waste from mining and quarrying industries and the processing industry. A 1% increase in these factors can result in a 0.829% and 0.112% increase, respectively, in waste generation in Ukraine. Polyanska et al. (2022) pointed out that given the low rate of waste utilization and the increasing industrial production index, developing waste management skills within industries is crucial.

Conclusions

To quantify the impact of various factors on waste generation in Ukraine, statistical data was used to build a multi-factor econometric linear model. Information on waste generation from 2010 to 2020 was collected and analyzed, considering various economic sectors, such as agriculture, forestry, and fisheries, mining and quarrying industries, the processing industry, energy supply, construction, and other economic activities. The multi-factor econometric linear model and calculated partial elasticity coefficients indicated that the key factors influencing waste generation in Ukraine during the pre-war period were waste from mining and the quarrying industries, as well as the processing industry. A 1% increase in these factors could result in a 0.829% and 0.112% increase in waste generation in Ukraine, respectively. Therefore, it is essential to organize waste reduction and utilization in these economic sectors.

The war in Ukraine has had a negative impact on all aspects of people's lives, the economy, and the environment. From February 24, 2022 to May 2023, nearly 1.2 million t of pollutants were released into the atmosphere due to combat activities. This included 0.43 million t of carbon oxide, 0.7 million t of dust, and 0.04 million t of non-methane volatile organic compounds. The levels of heavy metals and other harmful substances in the atmosphere have also increased significantly due to the fighting. Forest and grassland fires were the primary sources of these emissions. Additionally, hundreds of thousands of tons of waste were generated as a result of the conflict, including significant construction waste due to the destruction and ruin of numerous buildings and structures, some of which contain toxic substances, polluting the environment. Currently, there are three main methods of handling construction waste: burial, disposal, and recycling. In the current Ukrainian context, the first two methods are primarily used. According to secondary marketing information provided by the Ministry of Ecology, the approximate environmental damage in Ukraine from land pollution amounts to over 900 billion UAH. However, significantly reducing the negative impact on the environment of waste generated in conditions of war is impossible. Today, due to the danger of hostilities, it is even difficult to

determine the quantity of such waste. A significant amount of waste is formed by metallic fragments from shells containing sulfur and copper. These substances, as a result of migration to groundwater, can enter food products and adversely affect the health of humans and animals. A crucial task for the post-war period is to develop an effective environmental monitoring system in Ukraine, including monitoring the quantity and analyzing the structure of waste, and developing measures for their disposal. This requires involvement not only of the legislative body, the Verkhovna Rada, and the Ministry of Environmental Protection and Natural Resources of Ukraine but also of the broader public.

Our research focuses on identifying the level of influence of key determinants on waste generation in Ukraine during the pre-war period and forming directions for their reduction, both at the state level and at the enterprise level.

To reduce waste generation, the following recommendations are proposed at the national level:

– Analyze and identify the types of waste generated in the mining and processing industries and study how they should be utilized or processed.
– Improve existing environmental standards and legislation, ensure their enforcement, and make waste disposal mandatory.
– Investigate the possibilities of reducing the impact of mining and processing industries on waste generation and based on this, develop measures for their disposal and processing.
– Develop conditions for and implement cooperation between the government and the public, as this can lead to the development and implementation of effective waste utilization and recycling strategies.
– Introduce environmental taxes and high environmental standards to incentivize companies to reduce emissions and waste.

To reduce waste generation, the following recommendations are proposed at the enterprise level:

– Enable on-site waste disposal, for example, by using technologies to reduce the amount of waste sent to landfills.
– Seek partners for joint waste disposal, as other companies or organizations may use this waste as raw materials in their production processes.
– Enable the secondary processing of waste to obtain new products or materials, as secondary processing can be economically advantageous and reduce waste.
– Implement innovative technologies that promote waste reduction and improved waste disposal.

– Involve staff and employees of enterprises as much as possible in addressing waste utilization and recycling, which can promote a more responsible approach in this area.

Promoting recycling and material reuse can help reduce waste and minimize the environmental impact of economic activities. Waste management will only develop if there is access to high-quality secondary raw materials on the domestic market. Currently, there is a deficit of secondary raw materials on Ukraine's internal market, accounting for about 30% of the industry's total needs due to poor quality sorting (Matveichuk, 2021). Ensuring waste disposal and recycling in mining and processing industries requires a comprehensive approach and collaboration from all parties. To achieve this goal, it is important to combine technological innovations, enhance environmental awareness among employees, and implement relevant legislative initiatives.

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Summary

Study of the influence of commercial activities on waste formation in Ukraine in the context of sustainable development. It has been determined that resolving waste reduction and disposal issues plays a crucial role in implementing the concept of sustainable development in individual countries. However, developing a waste management mechanism requires adequate information. The influence of various types of economic activities in Ukraine on waste formation is investigated in the pre-war period. It is assumed that these factors will remain relevant for Ukraine in the post-war period. To quantify the impact of various factors on waste generation in Ukraine, statistical data were used, and a multiple regression econometric model with partial elasticity coefficients was constructed. The calculations helped us establish that the determining factors influencing waste generation in Ukraine in the pre-war period were waste from the mining industry and quarry development and the processing industry. Ensuring waste reduction, disposal, and recycling in these sectors requires a comprehensive approach and cooperation from all parties. To achieve this goal, it is essential to combine technological innovations, environmental awareness among workers, and appropriate legislative initiatives. Recommended measures have been developed to reduce waste levels in various sectors of the economy at both the national and enterprise levels.

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Investigation on strength and ductility of confined geopolymer concrete subjected to axial loads

Keywords: geopolymer, strength, ductility, confinement, analytical expression

Introduction

Background

Geopolymer concrete is a relatively new material, which has been extensively researched in the last two decades. The research carried out aims to develop concrete and more environmentally friendly materials. This is based on the fact that every production of 1 t of ordinary portland cement (OPC) will emit 1 t of CO_2 gas into the atmosphere (Bouzoubaâ et al., 1999). As a result, a greenhouse effect arises in the atmosphere and the temperature on the Earth's surface increases, it gets hotter, thus leading to an environmental problem. Therefore, reducing the use of portland cement must be a priority in the world of construction, also among practitioners. One way to do this is to develop and manufacture geopolymer concrete that

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does not use 100% portland cement (Ekaputri & Triwulan, 2011; Owaid et al., 2021). Fly ash, which is obtained from burning coal and is pozzolanic and also cementitious according to ACI ACI 232 2R-96 standard (American Concrete Institution [ACI], 2002), is used to replace portland cement.

The mechanical characteristics of geopolymer concrete are not considerably different from the characteristics of concrete that uses OPC (OPC concrete), such as: compressive strength, tensile strength, modulus of elasticity, modulus of rupture, and other mechanical quantities (Hardjito et al., 2004; Diaz-Loya et al., 2011). The treatment effect in the process of making geopolymer concrete has a significant influence on increasing compressive strength and tensile strength (Triwulan et al., 2017). The mechanical properties of geopolymer concrete are also not significantly different from the mechanical properties of OPC concrete, even though the alkaline activator used is low, namely 4% (Romadhon et al., 2022). This material is also identified to have good resistance to chloride penetration and abrasion (Nagajothi et al., 2022; Wong, 2022).

In stress–strain behavior, geopolymer concrete also has a similar curve shape to normal concrete, especially in the behavior before peaking. However, geopolymer concrete has a different post-peak behavior from the post-peak behavior of normal concrete. In the post--peak curve behavior, the geopolymer concrete curve has a sharper shape and has sudden failure properties compared to the similar behavior in OPC concrete (Noushini et al., 2016). This indicates that geopolymer concrete has properties that are more brittle than normal concrete containing OPC. Substantially, Wang et al. (2023) revealed that the addition of fiber in the geopolymer concrete mixture can increase compressive strength, flexural strength and toughness.

Structural research on geopolymer concrete carried out by Annamalai et al. (2017) concerned beam structures with an underenforced reinforcement system made from geopolymer concrete. It was revealed that the flexural strength of beams made of geopolymer concrete was higher than the flexural strength of OPC concrete beams.

Haider et al. (2014) carried out triaxial tests on geopolymer concrete with a compressive strength of 25 MPa and high-strength concrete with a compressive strength of 85 MPa. The test results revealed that to achieve adequate ductility, normal-strength geopolymer concrete requires a tightness level that is not excessively high (confinement ratio < 0.4). However, high-strength geopolymer concrete requires a higher level of confinement, namely around 0.53, to achieve adequate ductility. The results are indications that the ductility properties of geopolymer concrete are like the ductility properties of OPC concrete: the higher the compressive strength of the concrete, the lower the strength and ductility so that a higher level of confinement is required. The consequence of this is that in its application to column structures, it requires confining reinforcement with a volumetric ratio; that is increasingly higher if the compressive strength of the concrete used is higher.

Meanwhile, the behavior of geopolymer concrete against triaxial loads studied by Wang et al. (2020) found that the increase in the strength of confined concrete (*K*) of geopolymer concrete was not considerably different from the increase in the strength of confined concrete in OPC concrete. In fact, the proposed *K*-value equation adopts the equation used in OPC concrete because the experimental results indicate similarities with the existing equation.

The behavior of geopolymer concrete towards passive confinement that has been carried out can be found in Lokuge and Karunasena (2016), Alzeebaree et al. (2020) and Abadel (2023). The passive confinement used is fiber-reinforced polymer (FRP), which is wrapped around the surface of the geopolymer concrete cylinder. The results of the tests carried out revealed that there was an increase in the strength and ductility of geopolymer concrete confined with the FRP confinement. Meanwhile, Ajmal et al. (2023) revealed that geopolymer concrete confined masonry is higher in initial stiffness and ultimate seismic capacity (around 45% and 4%) compared OPC concrete.

Based on the published data, research on the behavior of geopolymer concrete confined by transverse reinforcement for square cross-sections was carried out by, among others Lokuge et al. (2015), Du et al. (2022), Herwani et al. (2022), and Sudha et al. (2022). The results of the research state that because of confinement by transverse reinforcement installed in square cross-section specimens, the characteristics of transverse reinforcement, like volumetric ratio, spacing, and reinforcement configuration play a significant role in influencing the strength and ductility of confined concrete. Meanwhile, Ganesan et al. (2014) and Muslikh et al. (2018) tested round-section geopolymer concrete cylinders confined by hoops. The test results revealed the ductility of confined geopolymer concrete was lower than the ductility of confined OPC concrete.

Testing of geopolymer concrete confined by transverse reinforcement is still open to further research by reviewing more specific transverse reinforcement design parameters, such as spacing, volumetric ratio, and yield stress. Based on the description above, it raises the hypothesis that the installation of transverse reinforcement in column structures will play a significant role in determining the strength and ductility of geopolymer concrete columns.

Research significance and objective

An investigation of the behavior of confined geopolymer concrete will be extremely useful as a reference to describe the strength and ductility properties of confined geopolymer concrete as a whole. Confinement by transverse reinforcement in geopolymer concrete is absolutely vital because of the brittle nature of geopolymer concrete. The design equations resulting from research on geopolymer concrete confined by transverse reinforcement are extremely useful for more recent application in column structures. A review of existing confined models is absolutely necessary to determine the extent of their accuracy in predicting

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experimental results for confined geopolymer concrete. This research aims to explore more thoroughly the stress–strain behavior of geopolymer concrete confined by transverse reinforcement, especially its strength and ductility behavior. The tests carried out are still limited to confined on round cross-sections. Analytical expressions will be derived from the results of this research based on test results.

Experimental program

This research was experimentally carried out by producing a number of specimens and testing them in the laboratory. Twelve geopolymer concrete cylinders were then installed with confining reinforcement in the form of hoops designed by varying the characteristics of the hoop reinforcement, namely spacing, volumetric ratio, and yield stress. Apart from that, three geopolymer concrete cylindrical specimens were also made, which had the same dimensions as the confined concrete specimens, but without confining reinforcement. This specimen is a control for confined concrete specimens.

Materials

The fine aggregate and coarse aggregate used were from the local area. The aggregate test results are as follows: the coarse aggregate has a bulk density of 1,607 $kg \cdot m^{-3}$ and a fineness modulus of 6.6. Meanwhile for fine aggregate, the weight of the contents is 1,235 $kg \cdot m^{-3}$ and the fineness modulus is 2.68. The fly ash comes from waste from electric steam power plant (PLTU) Tanjung Jati, Central Java, Indonesia. The fly ash used weighs 561.6 $kg \cdot m^{-3}$.

The test results analyzed the chemical composition of fly ash using SEM-EDS to determine the shape, size, and elemental composition contained in the fly ash (Fig. 1). The fly ash used is type F. Based on the data in Table 1, CaO content is 5.89% (< 10%), SO_3 content is 1.13% (< 5%), and sum of SiO_2, Al_2O_3 and Fe_2O_3 equals 83.28% (> 70%). This value complies with the requirements of ASTM C 618-05 standard (American Society for Testing and Materials [ASTM], 2005) for type F fly ash. In this research, the alkali activator solution used was eight-molar sodium hydroxide (NaOH) and a 58% concentration of sodium silicate (Na_2SiO_3) with a ratio of one NaOH to two Na_2SiO_3.

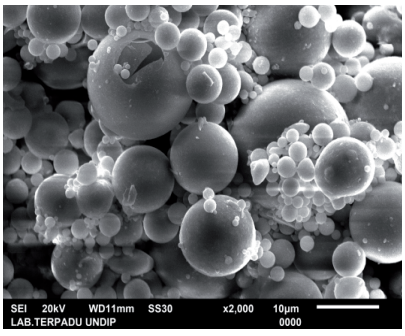

FIGURE 1. Scanning electron microscopy test of coal ash material

Source: own work.

TABLE 1. Chemical composition of Tanjung Jati fly ash (type F)

Composition [%]									
Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	T_iO_2	CuO
1.59	2.86	24.95	46.52	1.13	2.77	5.89	11.81	1.36	1.12

Source: own work.

Mix design of geopolymer concrete

The compressive strength of the designed concrete represents normal strength. The composition of the geopolymer concrete mixture is presented in Table 2. The treatment used the ambient temperature. The process of making geopolymer concrete from mixing to curing is shown in Figure 2.

TABLE 2. Mix design

Material	Composition [kg·m^{-3}]
Coarse aggregate	1 209.6
Sand	806.4
Fly ash	561.6
NaOH (eight-molar)	100.8
Natrium silicate	201.6

Source: own work.

a b c

FIGURE 2. Process for making geopolymer concrete: a – mixing process of geopolymer concrete; b – geopolymer concrete mold with transverse reinforcement; c – treatment process using wet sacks

Source: own work.

Specimen of confined concrete

The confining reinforcement is in the form of a plain round hoop with a diameter between 5.5 mm and 6 mm. Each reinforcement is tensile tested to determine the yield stress, strain hardening behavior, and ultimate stress. The tensile test result curve is shown in Figure 3. The design parameters studied are spacing, volumetric ratio, and yield stress of transverse reinforcement.

The specimens are cylindrical, 100 × 200 mm in size. All specimens come without a concrete cover. To maintain the stability of the confining reinforcement, both during

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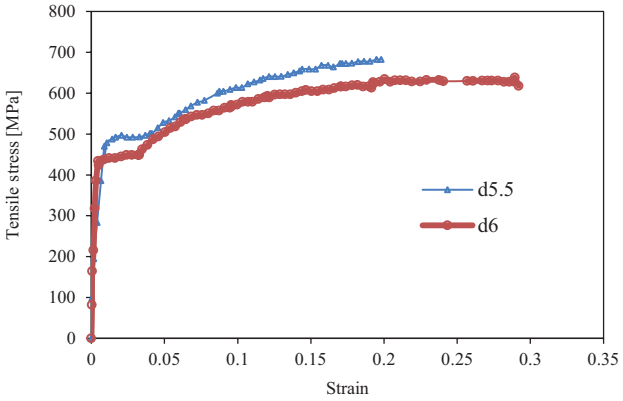

FIGURE 3. Stress–strain curves of hoops

Source: own work.

casting and during testing, four wires were installed in the longitudinal direction as hoop ties. The diameter of the longitudinal wire is extremely small that its influence in the calculation of confined concrete stresses can be neglected. A strain gage of type FLA-6-11 is installed in the confining reinforcement.

Testing and data acquisition

Figure 4 illustrates a test scheme for unconfined and confined geopolymer concrete using the universal testing machine (UTM). It has an effective capacity of 1,800 kN and a displacement control system. On the right and left of the specimen, an LVDT is installed to record the displacement in the axial direction, which is then processed into axial strain data. Cables from the LVDT, load cell and strain gauge are then connected to the Data Logger to record data (including load increments) until the specimen failures. Confined concrete stress is obtained from the load received by the specimen divided by the cross-sectional area of the specimen.

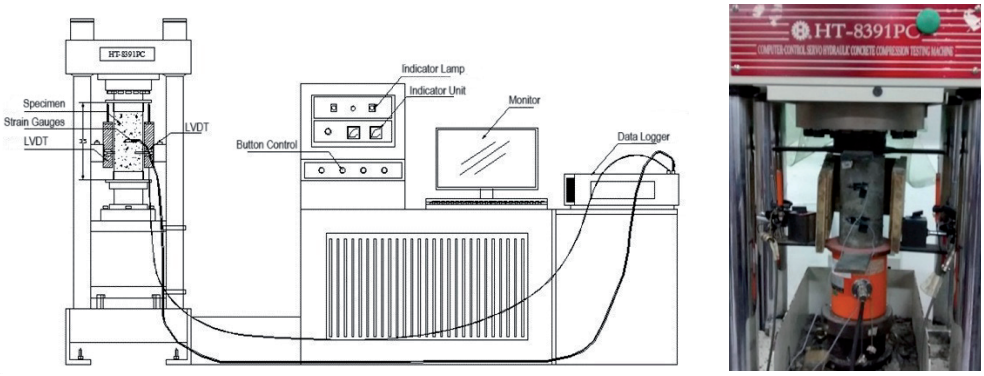

FIGURE 4. Unconfined and confined geopolymer concrete test: a – scheme of testing; b – specimen samples and test preparation

Source: own work.

The test results are then processed into a stress–strain curve. The parameters of the unconfined concrete test results reviewed include peak stress (f_{co}'), peak strain (ε_{co}'), and strain when the stress drops 15% of the peak stress (ε_{85}). Furthermore, the parameters for confined concrete displayed consist of peak stress (f_{cc}'), peak strain (ε_{cc}'), and strain when the stress drops 15% of the peak stress (ε_{85c}). The ductility of confined concrete (μ) is defined as the ratio of the value ε_{85c} to the value ε_{85c} (see Fig. 5).

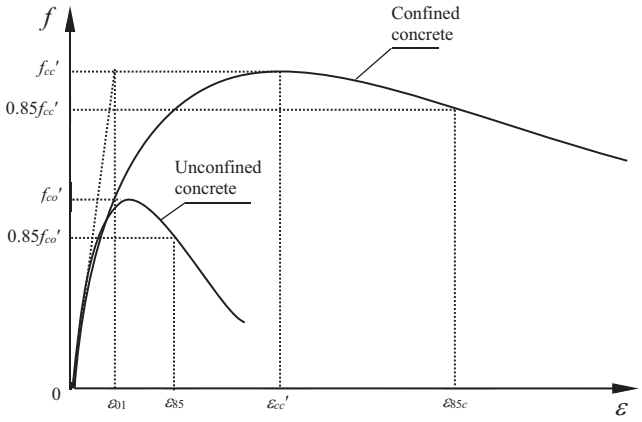

FIGURE 5. Parameter design of unconfined and confined geopolymer concrete
Source: own work.

Results and discussion

In this experiment, all specimens were tested on the same day (including unconfined concrete). So that the comparison results between the confined (CGP) and unconfined geopolymer concrete (UGP) test results could be measured with certainty. From the material testing results, the average Poisson's ratio value for geopolymer concrete was obtained at 0.25, and the average modulus of elasticity was 26.986 MPa. The results for the unconfined concrete obtained the average value of three specimens, namely $\varepsilon_{co}' = 0.0026$, $\varepsilon_{85} = 0.0034$ and $f_{co}' = 36.28$ MPa. The ε_{co}' value is above the value usually assumed for normal concrete (0.002–0.0022). Figure 6 shows the failure modes of unconfined geopolymer concrete (UGP) specimens. Similar to the results of other research on the behavior of geopolymer concrete, the results of this research also indicate the process of failure of unconfined and brittle geopolymer concrete.

Confined geopolymer concrete specimens installed with hoops with tighter spacing (s = 60 mm) showed a relatively ductile failure mode (Fig. 7a). Lateral expansion due to

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uniaxial compressive loads can be inhibited or controlled by hoop reinforcement so that the concrete core is completely undamaged. For the present, specimens installed with hoops with wider spacing (s = 100) had a faster failure mode (Fig. 7b).

FIGURE 6. Failure pattern of unconfined geopolymer concrete (UGP)
Source: own work.

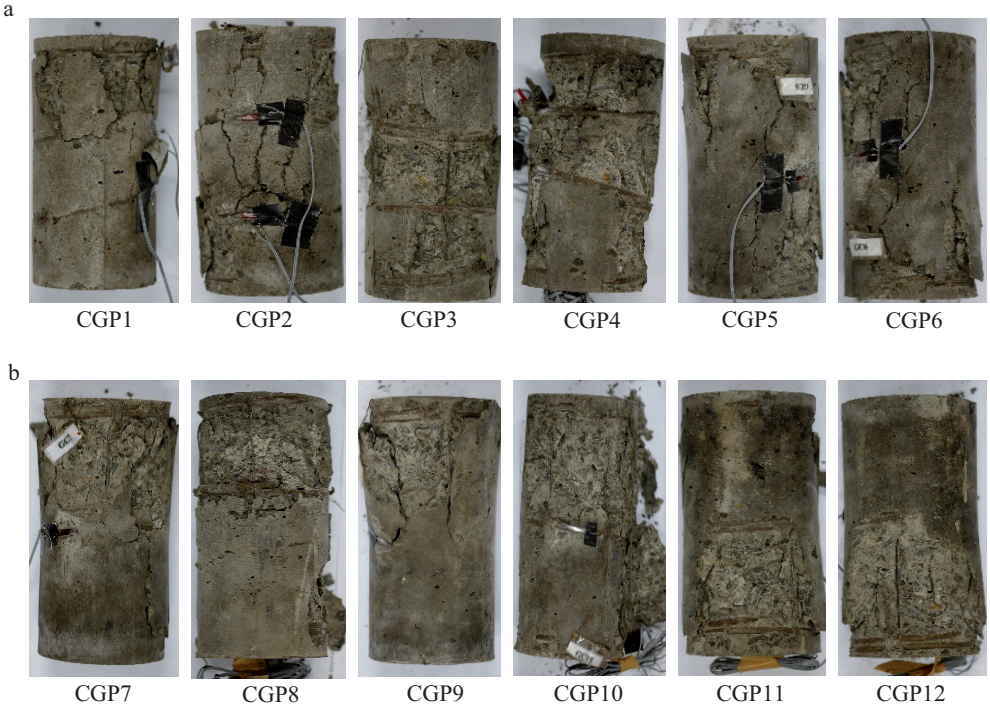

FIGURE 7. Failure pattern of confined geopolymer concrete: a – CGP specimen, hoop spacing 60 mm; b – CGP specimen, hoop spacing 100 mm
Source: own work.

As explained in the experimental program above in Table 3, there are four confined groups, each consisting of three specimens with the same confining reinforcement installation characteristics like: diameter, spacing, and yield stress. Table 3 explained in Figure 8, shows that the K value will be optimal if the confining reinforcement has an increased volumetric ratio, but the yield stress is lower (f_y = 466 MPa). This can be seen from the comparison between CGP1, CGP2, and CGP3 (average K of 1.44) specimens and CGP4, CGP5, and CGP6 specimens, which have a higher average K value of 1.53. The K value is also optimal in comparison between CGP7, CGP8, and CGP9 specimens (average K = 1.22) and specimens CGP10, CGP11 and CGP12 (average K = 1.26).

TABLE 3. Experimental results

Specimen	Confining reinforcement			f_{cc}' [MPa]	ε_{cc}'	ε_{85c}	$K = \frac{f_{cc}'}{f_{co}'}$	K_{avg}	μ	μ_{avg}
	ϕ–s [mm]	ρ_h	f_y [MPa]							
CGP1	5.5–60	0.0168	514	52.30	0.0095	0.0321	1.44	1.44	17.89	17.65
CGP2	5.5–60	0.0168	514	52.30	0.0069	0.0240	1.44		20.00	
CGP3	5.5–60	0.0168	514	52.78	0.0084	0.0286	1.45		15.05	
CGP4	6–60	0.0200	466	55.42	0.0075	0.0266	1.53	1.53	13.64	14.50
CGP5	6–60	0.0200	466	55.43	0.0058	0.0311	1.53		17.28	
CGP6	6–60	0.0200	466	56.03	0.0066	0.0176	1.54		12.57	
CGP7	5.5–100	0.0101	514	40.17	0.0039	0.0091	1.24	1.22	5.93	5.94
CGP8	5.5–100	0.0101	514	38.89	0.0035	0.0080	1.22		6.58	
CGP9	5.5–100	0.0101	514	40.33	0.0043	0.0097	1.21		5.31	
CGP10	6–100	0.0120	466	38.82	0.0049	0.0080	1.27	1.26	5.93	5.76
CGP11	6–100	0.0120	466	40.46	0.0043	0.0080	1.22		5.71	
CGP12	6–100	0.0120	466	41.06	0.0047	0.0079	1.29		5.64	

Source: own work.

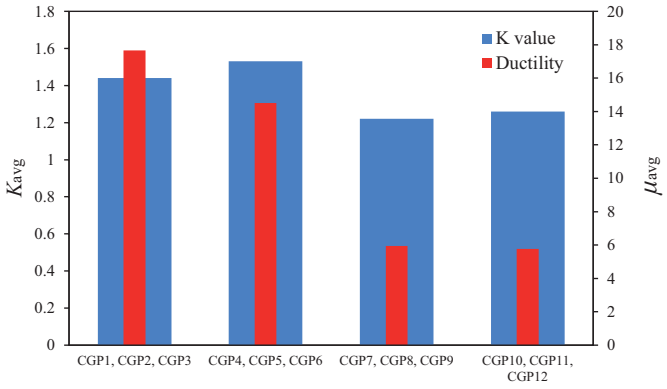

FIGURE 8. Comparison of average K and ductility (μ_{avg}) values

Source: own work.

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However, the opposite occurs in the magnitude of the ductility value of confined concrete where the optimum μ value occurs if the specimen is installed with confining reinforcement with a lower volumetric ratio but the yield stress is higher. The average ductility value of CGP1, CGP2, and CGP3 specimens is 17.65, which is higher than the average ductility of CGP4, CGP5, and CGP6 specimens (μ =14.50). Likewise, the average ductility of CGP7, CGP8, and CGP9 specimens is 5.94, which is still higher than the average ductility of CGP10, CGP11, and CGP12 specimens of 5.76.

Another phenomenon is that even though the spacing of the confining reinforcement installed is the same as the diameter of the specimen (CGP7, CGP8, CGP9, CGP10, CGP11, CGP12). There is still an increase in the strength of the confined concrete, although it is not significant (K > 1.2). Similarly, the ductility of confined concrete is still above 5. This phenomenon is not the same as what occurs in confined OPC concrete which states that there is no increase in the K value (or the same as in unconfined concrete); if the spacing of the confining reinforcement is the same as the cross-sectional diameter (Antonius et al., 2017).

Stress–strain behavior

Figures 9 and 10 show that in general, three specimens in one group that have the same confining reinforcement characteristics (for example, CGP1, CGP2, CGP3, and other specimen groups) have stress–strain curve shapes that almost coincide with each other.

As mentioned above, the ε_{co}' value which is greater than the ε_{co}' value usually assumed for normal concrete (OPC concrete). However, the post-peak behavior of unconfined concrete (UGP) is very brittle; where after the peak there is an extremely rapid decline in the

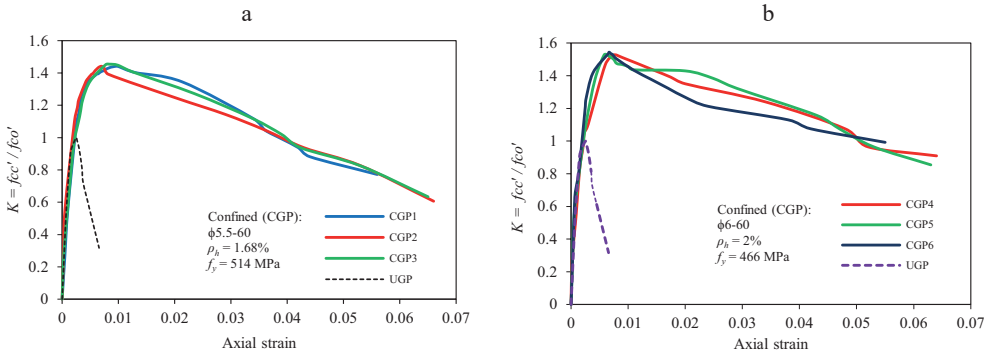

FIGURE 9. Behavior of confined versus unconfined geopolymer concrete (hoop spacing 60 mm): a – specimen CGP1, CGP2 and CGP3 versus UGP; b – specimen CGP4, CGP5 and CGP6 versus UGP
Source: own work.

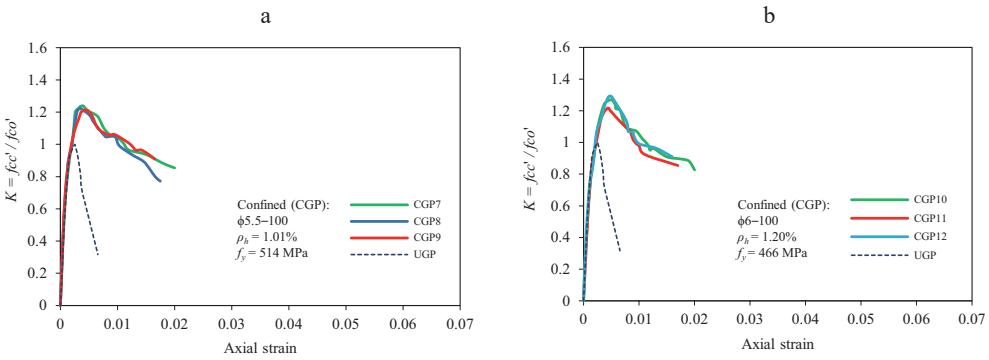

FIGURE 10. Behavior of confined versus unconfined geopolymer concrete (hoop spacing 100 mm): a – specimen CGP7, CGP7, CGP9 versus UGP; b – specimen CGP10, CGP11 and CGP12 versus UGP

Source: own work.

curve. This is in line with the results of several studies on the mechanical properties of geopolymer concrete, which state that geopolymer concrete is very brittle (Noushini et al., 2016; Muslikh et al., 2018). Therefore, installing confining reinforcement is a necessity to improve the extremely low ductility of geopolymer concrete.

In line with the results shown in Table 3, installing tighter hoop spacing has an extremely beneficial confining effect and can increase the *K* value and ductility of confined geopolymer concrete. As shown in Figure 11, the post-peak curve is relatively flat. The phenomenon of changes in *K* values and ductility due to the influence of transverse reinforcement spacing; is the same as the results of confined geopolymer concrete tests carried out by Herwani et al. (2022), but the specimen used represent a square cross-section.

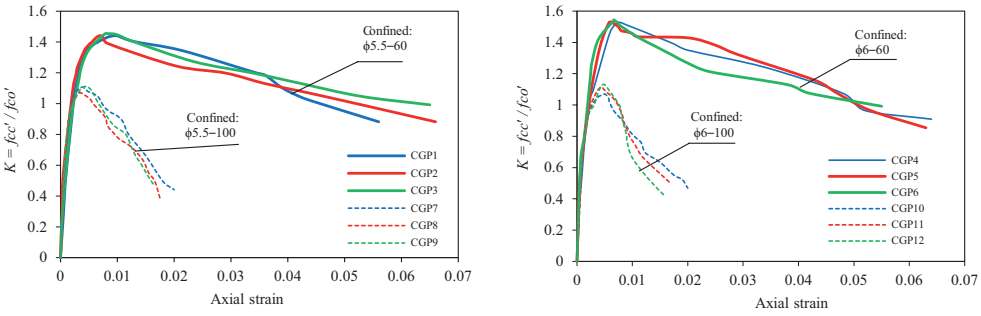

FIGURE 11. Effect of confining reinforcement spacing

Source: own work.

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Evaluation of confinement models

Confinement models are necessary to determine and ensure the level of structural safety. Until now, geopolymer concrete confinement models were based on passive confinement test results, namely concrete confined by transverse reinforcement. The recorded publication states that the confinement models derived from the results of passive confined testing are the model proposed by Ganesan et al. (2014) for round-section specimens, and the model proposed by Lokuge et al. (2015) for square-section columns. Confinement models resulting from triaxial tests, where the level of confinement can be regulated and its size determined with certainty include the model proposed by Haider et al. (2014) and the model by Wang et al. (2020). Further, we will evaluate both Mander's proposed confinement model and Ganesan's proposed model as well as Wang's proposed model to consider these models are applicable to the cross-section used in this research.

Model by Mander et al. (1988)

Mander's confinement model is widely known and is often used as a reference for confined concrete research. The model is basically derived from the test results of normal concrete (OPC concrete) columns. Mander's model can be applied to confined concrete of round cross-section and square cross-section. Mander et al. (1988) uses one equation to describe the stress–strain curve of confined concrete, namely:

$$f_c = \frac{f_{cc}' \frac{\varepsilon_c}{\varepsilon_{cc}} r}{r - 1 + \left(\frac{\varepsilon_c}{\varepsilon_{cc}'} \right)^r}, \tag{1}$$

where:

$$\frac{\varepsilon_{cc}'}{\varepsilon_{co}'} = 1 + 5\left(\frac{f_{cc}'}{f_{co}'} - 1 \right), \tag{2}$$

$$r = \frac{E_c}{E_c - E_{\text{sec}}}, \tag{3}$$

$$E_c = 5{,}000\sqrt{f_{co}'}\,\text{MPa}. \tag{4}$$

E_{sec} is the secant modulus, i.e.:

$$E_{sec} = \frac{f_{cc}'}{\varepsilon_{cc}'}. \tag{5}$$

Mander uses the Willam–Warnke failure criterion (five parameters) to derive the peak-stress equation for confined concrete. The proposed equation is:

$$K = \frac{f_{cc}'}{f_{co}'} = -1.254 + 2.254\sqrt{1 + \frac{7.94 f_l'}{f_{co}'}} - 2\frac{f_l'}{f_{co}'}, \tag{6}$$

where f_l' is the effective lateral stress.

Model by Ganesan et al. (2014)

The geopolymer concrete confinement model proposed by Ganesan et al. (2014) basically uses most of the equations from Mander mentioned in previous section, where the stress–strain equation uses Eq. (1). However, Ganesan carried out the necessary modifications after testing 24 specimens of confined geopolymer concrete cylinders and normal confined concrete. The modifications made by Ganesan were to the values:

$$r = \frac{E_c}{\frac{E_c}{1.62} + 8{,}888k}, \tag{7}$$

and

$$E_c = 6{,}965\sqrt{f_{ck}}, \tag{8}$$

where f_{ck} is the compressive strength of the concrete, and k is the confinement index namely:

$$k = \frac{\rho f_y}{f_c'}. \tag{9}$$

Lateral stress is calculated as follows:

$$f_l = \frac{\rho f_y}{2}. \tag{10}$$

Based on Eq. (10), Ganesan assumes that the confining reinforcement yields when the concrete peak response is confined.

Antonius, Han, A. L., Muslikh, Anggraini, N. K. (2024). Investigation on strength and ductility of confined geopolymer concrete subjected to axial loads. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 163–184. DOI 10.22630/srees.9212

Model by Wang et al. (2020)

Wang et al. (2020) carried out triaxial tests on a number of cylindrical geopolymer concrete specimens that possessed compressive strengths of 15 MPa and 85 MPa. Lateral stress is provided by fluid pressure, with pressures ranging from 0 MPa to 35 MPa. Wang proposed the peak stress of confined concrete (f_{cc}) as follows:

$$f_{cc} = f_c + 5.2 f_c^{0.91} \left(\frac{\sigma_l}{f_c} \right)^a, \tag{11}$$

where f_c is the unconfined compressive strength of concrete, and α:

$$\alpha = f_c^{-0.006}. \tag{12}$$

The peak strain of confined concrete (ε_{cc}) is derived from the results of non-linear regression using data from experiments carried out and produces:

$$\varepsilon_{cc} = \varepsilon_0 \left[1 + 13.446 \left(\frac{\sigma_l}{f_c} \right)^{1.2299} \right], \tag{13}$$

where σ_l is the lateral stress and ε_0 is the unconfined peak strain of concrete which is taken as 0.00225. The confined geopolymer concrete stress–strain curve refers to Mander's equation, namely Eq. (1), but the r equation is modified to:

$$r = \frac{k_r E_c}{E_c - E_{\text{sec}}} = \frac{k_r E_c}{E_c \dfrac{f_{cc}}{\varepsilon_{cc}}}. \tag{14}$$

The k_r value is:

$$k_r = \sqrt{\frac{f_c}{30}}. \tag{15}$$

Comparison of confinement models with experimental results

The above-mentioned confinement models were further validated with experimental results from this research. As seen in Figures 12 and 13, the confinement model by Mander, Ganesan, and Wang has a non-linear and concave post-peak curve. This behavior is differ-

ent from the experimental results of this research, where the post-peak behavior tends to be convex. The difference in the curve's shape is because the confined models assume that confined geopolymer concrete loses post-peak strength more quickly; compared to the post-peak strength loss from the test results.

In general, the peak stress of confined concrete (f_{cc}') based on confined models is not considerably different from the f_{cc}' value from experimental results. However, the existing confinement models underestimate the post-peak behavior of the experimental results if the confinement reinforcement spacing is 60 mm (Fig. 10). Furthermore, Figure 11 explains that except for Wang's proposed model, other confinement models are absolutely accurate in predicting: the f_{cc}' value from experimental results if the specimen is installed with confining reinforcement with larger spacing (s = 100 mm). However, the post-peak behavior of all confinement models overestimates the post-peak behavior of the experimental results.

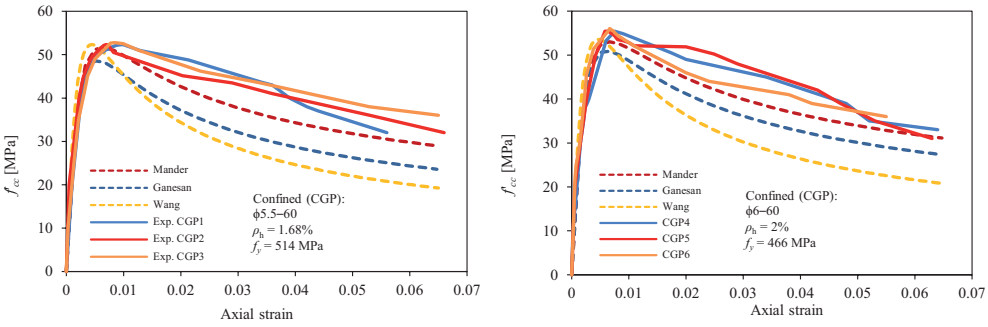

FIGURE 12. Confinement models vs experimental specimens with hoop spacing of 60 mm
Source: own work.

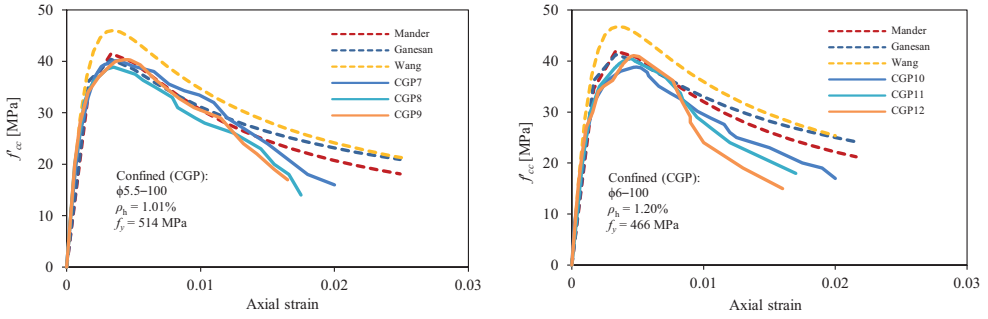

FIGURE 13. Confinement models vs experimental specimens with hoop spacing of 100 mm
Source: own work.

Antonius, Han, A. L., Muslikh, Anggraini, N. K. (2024). Investigation on strength and ductility of confined geopolymer concrete subjected to axial loads. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 163–184. DOI 10.22630/srees.9212

Analytical expression of confined geopolymer concrete

The results of the comparison between the confined models and the experimental results above show that the peak stress value of confined concrete is not considerably different from the experimental results: except for Wang's proposed model if wider stirrups are installed on the specimen (in this case, the hoop spacing is the same as the core diameter of the concrete cross section.). In addition, predictions of post-peak behavior also differ from experimental results. Based on this fact, there was an attempt to develop an analytical expression of the stress–strain behavior of confined geopolymer concrete from the experimental results above. Analytical expression is carried out by modifying the existing confinement model as necessary. Strength enhancement of confined geopolymer concrete (K) has a very significant role in determining the volumetric ratio of the minimum confining reinforcement that must be installed in the column structure. The K-value equation uses the equation proposed by Haider et al., which was derived based on the test results of geopolymer concrete with active confined, namely:

$$K = \frac{f_{cc}'}{f_{co}'} = 1 + 3.3\left(\frac{f_2}{f_{co}'}\right)^{0.8}, \tag{16}$$

where f_2 represents the lateral stress. The f_2 value uses Eq. (10). The lateral stress is corrected by the effectiveness of the confinement, which uses the proposal of Mander et al., that is:

$$k_e = \frac{\left(1 - \frac{s'}{2d_c}\right)}{\left(1 - \rho_{cc}\right)}. \tag{17}$$

In Eq. (17), s' is the clear spacing of confining reinforcement, d_c is the core diameter of the concrete section, and ρ_{cc} represents the ratio of longitudinal reinforcement to the core area of the section. The peak strain of confined concrete compared to the peak strain of unconfined concrete represents a function of the K value, and the results of non-linear regression from experimental data produce the equation (Fig. 14):

$$\frac{\varepsilon_{cc}'}{\varepsilon_{co}'} = 1 + 4.9845\left(K - 1\right)^{1.3716}. \tag{18}$$

The unconfined concrete peak strain (ε_{co}') is assumed to be 0.002.

The confined concrete stress–strain curve is divided into two parts, namely the ascending branch curve, which uses Eq. (1). The *r* and *k* values use the formulation by Ganesan values, namely Eqs (7) and (9). The modulus of elasticity uses the equation proposed by Romadhon et al. (2022), which is:

$$E_c = 2{,}673 f_c^{0.65} \tag{19}$$

Furthermore, the post-peak confined geopolymer concrete curve, or the one that represents the ductility behavior of the structure is assumed to be linear. The curve equation is:

$$f_c = f_{cc}' - \left(\varepsilon_c - \varepsilon_{cc}'\right)\frac{0.15 f_{cc}'}{\left(\varepsilon_{85c} - \varepsilon_{cc}'\right)}. \tag{20}$$

Similar to the derivation of the peak-strain equation for confined concrete above, the ductility of confined concrete is also derived based on experimental data using non-linear regression as follows (Fig. 15):

$$\frac{\varepsilon_{85c}}{\varepsilon_{85}} = 1 + 23.71\left(K - 1\right)^{1.9226}. \tag{21}$$

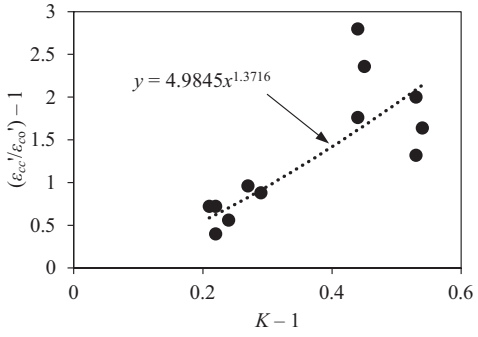

FIGURE 14. Regression of ε_{cc}' values
Source: own work.

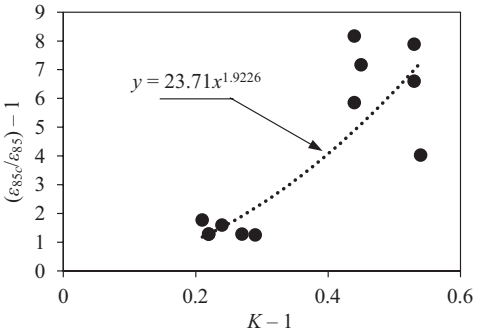

FIGURE 15. Regression of ε_{85c} values
Source: own work.

Antonius, Han, A. L., Muslikh, Anggraini, N. K. (2024). Investigation on strength and ductility of confined geopolymer concrete subjected to axial loads. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 163–184. DOI 10.22630/srees.9212

Comparison of analytical expressions with experimental results

Figures 16 and 17 are a comparison of the stress–stress behavior of confined geopolymer concrete with experimental results. Based on these Figures, the developed analytical expressions are able to predict the stress behavior of the pre-peak confined geopolymer concrete very well. Furthermore, the analytical expression on the post-peak curve has a line shape that is in line with and very close to the post-peak behavior of the experimental results.

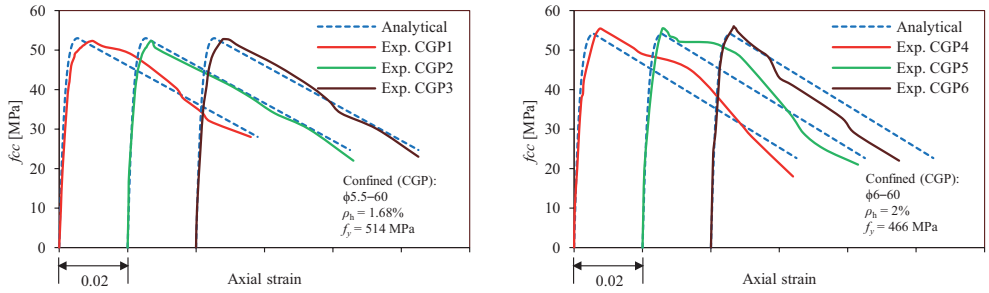

FIGURE 16. Analytical expression versus experimental results for specimens with confining reinforcement spacing of 60 mm

Source: own work.

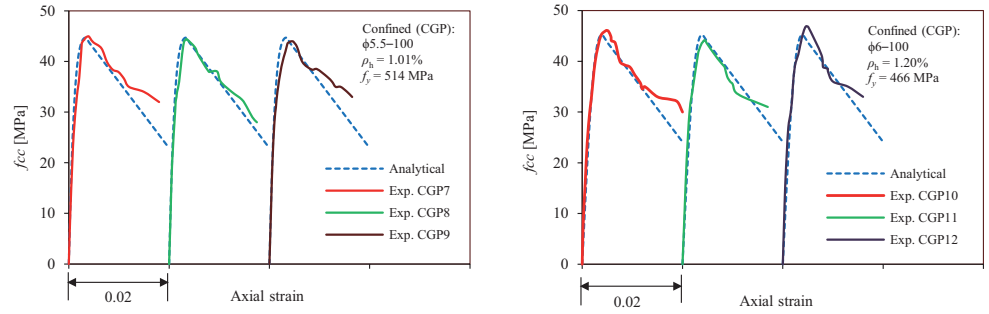

FIGURE 17. Analytical expression versus experimental results for specimens with confining reinforcement spacing of 100 mm

Source: own work.

Conclusions

The investigation of the behavior of confined geopolymer concrete has been carried out by conducting experimental tests. Some of the conclusions obtained are as follows:

1. Geopolymer concrete has a very brittle behavior, which can be seen in the behavior of unconfined geopolymer concrete. However, by installing confining reinforcement with a relatively high volumetric ratio and tighter spacing, the behavior of geopolymer concrete changes to become very ductile.
2. In general, the strength of confined geopolymer concrete increases along with the installation of tighter confining reinforcement. This increase in strength is also in line with the increase in ductility of confined concrete.
3. Based on experimental results, the *K* value will be optimal if geopolymer concrete is installed with confining reinforcement with an increased volumetric ratio but decreased yield stress. However, on the contrary, the optimum ductility value will occur if the confining reinforcement has a volumetric ratio that tends to be lower but the yield stress increases.
4. Even though the spacing of the confining reinforcement installed is the same as the cross-sectional diameter of the concrete core, the confined geopolymer concrete still has a fairly good *K* value (average *K* value above 1.2).
5. Except for Wang's proposed model, the existing confinement models made of OPC concrete and geopolymer concrete are generally not completely different in predicting the peak stress value from experimental results.
6. The ductility behavior of confined concrete based on existing confined models is still significantly different from the ductility behavior of experimental results.
7. The analytical expression for confined geopolymer concrete, which was developed based on modification of the existing confined model and the derivation of several equations from experimental data, is able to predict: the *K* value, pre-peak and post-peak behavior very well.

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Summary

Investigation on strength and ductility of confined geopolymer concrete subjected to axial loads. This paper presents the results of an investigation into geopolymer concrete confined by hoop reinforcement. The investigation focused on the strength and ductility of confined geopolymer concrete subjected to axial loads. The main objective of this research is to evaluate the strength and ductility behavior of confined concrete: by varying several confining reinforcement design parameters, like volumetric ratio, spacing, and yield stress. A total of 15 unconfined and confined geopolymer concrete specimens was produced and tested against axial loads. The test is carried out until the specimen collapses. Experimental results show that unconfined geopolymer concrete is highly brittle, characterized by very sharp post-peak behavior. The volumetric ratio, spacing, and yield stress of reinforcement play a significant role in determining the strength and ductility of confined geopolymer concrete. The comparison between the existing restraint models reviewed in the research was able to predict behavior before the peak of the experimental results very well. However, the existing confinement model has significantly different ductility behavior from the ductility behavior of the experimental results. In this research, an analytical expression of stress–strain for confined geopolymer concrete is developed by modifying the existing confinement model. The validation of confined concrete stress–strain between analytical expressions and experimental results is relatively close.

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The effect of pre-vulcanized latex usage on Marshall characteristics and stiffness modulus in hot mix asphalt wearing course (AC-WC) mixtures

Keywords: pre-vulcanized latex, AC-WC, modified asphalt binder, Marshall characteristics, stiffness modulus

Introduction

Asphalt pavement is the most widely used type of flexible pavement globally. Flexible pavements are composed of aggregates and asphalt mixed at high temperatures, commonly referred to as hot mix asphalt (HMA). Hot mix asphalt pavements typically consist of 93–96% aggregate and 4–7% asphalt by weight. However, factors such as increased traffic volume, harsh climate and environmental conditions, as well as inappropriate material usage can negatively impact the quality of HMA pavements, leading to issues like fatigue cracking and rutting (Özel et al., 2023). To address these concerns, it's essential to enhance the

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quality of the existing asphalt materials. Various additives have been used to improve the behavior and performance of asphalt in different settings (Shaffie et al., 2016; Hasaninia & Haddadi, 2017; Wu, 2018). By incorporating these additives, it's possible to increase the durability and lifespan of asphalt pavements, ultimately reducing maintenance costs and promoting sustainable infrastructure development. Engineers and material scientists have been trying to modify the properties of binders using various modifiers, such as fillers, fibers, extenders, plastics, anti-stripping agents, oxidizers, antioxidants, recycled rubber, polymers, and non-materials in an effort to solve or reduce these problems (Behnood & Gharehveran, 2019; Dai & Jia, 2022; Nguyen et al., 2022; Tamele Jr. et al., 2022; Jimmyanto et al., 2023; Ramadhani et al., 2023). Asphalt binders are typically modified to enhance one or more basic characteristics of asphalt, such as stiffness, elasticity, brittleness, storage stability and durability, and resistance to cumulative damage. Engineers can select the best modifier to achieve desired qualities by analyzing how the modifier affects the performance of an asphalt binder (Behnood & Gharehveran, 2019).

Rubber is one of the ways polymers are used to enhance the characteristics of asphalt mixtures at high temperatures. Used tires, natural rubber, and synthetic rubber have all been used in previous studies, but there is currently only limited data on the use of natural rubber in research (Prastanto et al., 2019; Guo et al., 2020; Irfan et al., 2022). Natural rubber latex is a sustainable and renewable resource. Natural rubber latex can be easily obtained by tapping rubber trees. Natural rubber can be utilized as a thermoplastic elastomer form to create modified polymer bitumen. The thermoplastic elastomer known as natural rubber, commonly referred to as latex, helps improve the stiffness and elasticity of asphalt while reducing its sensitivity to temperature fluctuations (Daniel et al., 2019; Poovaneshvaran et al., 2020; Jamaris et al., 2021). Natural rubber is available in liquid and solid forms. Latex refers to natural rubber in a liquid form, while cup lump refers to natural rubber in a solid form. The thick sap extracted from tapped trees is known as latex (Putri & Sari, 2021).

Previous studies on the use of pre-vulcanized latex as a material in HMA have been conducted by Irfan et al. (2021) and Prastanto et al. (2019). These studies utilized pre-vulcanized latex at levels ranging from 3% to 7% as an additive in asphalt mixtures. Prastanto et al. (2019) focused on asphalt concrete-wearing course (AC-WC) mixtures, while Irfan et al. (2022) investigated asphalt concrete--binder course (AC-BC). The results obtained by Prastanto et al. (2019) indicated

that the use of pre-vulcanized latex at levels of 5–7% in AC-WC asphalt mixtures can enhance physical characteristics and Marshall parameters with stability ranging from 1,046 to 1,103 kg. Irfan et al. (2021), on the other hand, stated that the addition of pre-vulcanized latex at levels of 3–7% reduces the penetration value while increasing viscosity and softening point. Moreover, the incorporation of this pre-vulcanized latex can significantly improve Marshall stability up to 1,618–1,771 kg. Wan et al. (2023) revealed that Marshall is a commonly used indicator for evaluating the performance of asphalt mixtures. The Marshall method allows for selecting appropriate aggregate sizes based on desired design criteria. This method can determine the optimum asphalt binder content in an asphalt mixture measured by stability, flow, and air void parameters. Previous studies have discussed the influence of rubber concentration with asphalt binder content, such as Siswanto (2019), although they focused on latex rubber.

Liquid latex has been widely used in asphalt mixed applications, according to the literature currently in publication. Pre-vulcanized latex is a liquid latex modified to blend easily with asphalt mixtures and made by Indonesian natural rubber products. Prior studies only included pre-vulcanized latex as an additional material in asphalt mixtures. Nevertheless, there is a study gap because no data about the impacts of utilizing pre-vulcanized latex as a substitute for asphalt binder has been discovered. This substitution aims to reduce the use of asphalt binder in the HMA mixture, thereby saving costs and energy associated with the asphalt binder production process (Bindu et al., 2020). This paper uses the AC-WC mixture design in HMA mixtures to test the impact of pre-vulcanization latex content as an asphalt binder substitute. Laboratory testing methods include physical and rheological characterization tests for asphalt binder materials and Marshall and stiffness modulus tests for HMA mixtures.

Material and methods

Materials

In this paper, asphalt binder with a penetration of 60/70 is used. The rubber used comes from the Indonesian Rubber Institute Bogor, with the type of pre-vulcanized latex. Table 1 shows the testing characteristics of pre-vulcanized latex, where the total solid content is 55.73%, pH is 11.48, and polymer content is 87.28%.

TABLE 1. Testing the characteristics of pre-vulcanized latex

Test type	Result	Test method
Total solid content [%]	55.73	ASTM D 1076 (ASTM International [ASTM], 2023)
Mechanical stability time [s]	> 1 800	ASTM D 1076
pH	11.48	ASTM D 1076
Chloroform number	4	ASTM D 6370-99 (ASTM, 2019)
Acetone extract [%]	9.23	ASTM D 297 (ASTM, 2021)
Polymer content [%]	87.28	ASTM D 6370-99

Source: own elaboration.

The materials used as ingredients in the asphalt mixture consist of coarse aggregates [a combination of Split A (max 9.5 mm), Split B (max 4.75 mm), and Split C (max 2.36 mm)]. Fine aggregates are made using Musi River sand, and filler material uses stone dust that passes through a sieve size of 0.075 mm. Each of these aggregates undergoes characteristic testing referring to SNI 1969:2016 (Badan Standardisasi Nasional [BSN], 2016) and SNI 1970:2008 (BSN, 2008b). Table 2 shows the results of aggregate and filler characteristic testing, where each aggregate has a specific gravity ranging from 2.49 to 2.75 and water absorption ranging from 1.10% to 3.50%. For coarse aggregate abrasion testing, it follows SNI 2417:2008 (BSN, 2008a), and the obtained results meet the specification which is less than 40%.

TABLE 2. Test results for aggregate and filler characteristics

Test type	Split A	Split B	Split C	Musi River sand	Stone dust filler	Spec.	Method
Particles passing the 0.075-millimeter sieve [%]	1.70	0.20	2.79	5.60	100	max. 2	SNI 03-4142:1996 (BSN, 1996)
Abrasion with Los Angeles engine 500 rotation [%]	14.48	12.19	–	–	–	max. 40	ASTM C 131-76 (ASTM, 1976)
Bulk specific gravity	2.64	2.75	2.49	2.52	2.73	–	ASTM C 127-84 (ASTM, 1984) ASTM D 854-02 (ASTM, 2002)
Apparent specific gravity	2.72	2.84	2.73	2.67	2.73	–	
Water absorption [%]	1.10	1.10	3.50	2.04	–	–	

Source: own elaboration.

Preparation of modified asphalt binder

Latex pre-vulcanization, as seen in Figure 1a, is used as a partial substitute for asphalt binder where the content should not be too high. According to a study by Wititanapanit et al. (2021), using a rubber content of up to 6% in asphalt binder can improve its performance and stability at high temperatures.

a b

FIGURE 1. Preparation of modified asphalt: a – pre-vulcanized latex; b – design of asphalt binder mixing equipment

Source: own elaboration.

However, Jitsangiam et al. (2021) suggest that the rubber content should not exceed 12% as it may result in poorer performance. Therefore, this study uses latex pre-vulcanization content of 7% (LP 7%) and 9% (LP 9%) by weight of asphalt binder as substitutes (Table 3). The mixing of asphalt binder and latex pre-vulcanization is done using a mixer with specifications of 800 rpm and 750 W. The mixing is carried out in a container equipped with a thermometer and gas stove to maintain the mixing temperature (Fig. 1b).

TABLE 3. Testing the characteristics of pre-vulcanized latex

Code samples of modified asphalt binder	Asphalt binder penetration 60/70 content [%]	Latex pre-vulcanization content [%]
Aspen or LP 0%	100	0
LP 7%	93	7
LP 9%	91	9

Source: own elaboration.

The temperature and mixing time for the modified asphalt binder used in this paper refer to previous researchers (Ramadhani et al., 2023), where liquid form latex pre-vulcanization is easier to mix with asphalt binder due to their phase similarity.

The design mix formula (DMF) and job mix formula (JMF) for AC-WC mixture

The design mix formula (DMF) is a proposed asphalt binder content design (Pb) that can be determined using an approach based on the percentage of aggregate retained on sieve 8 (2.36 mm) and passing through sieve 200 (0.075 mm). The AC-WC is the asphalt mixture used in this study (asphalt concrete – wearing course), referring to the Bina Marga Specification Year 2018 (Revision 2) in Indonesia. Figure 2 shows the proposed job mix formula (JMF) for AC-WC used in this research. Based on the matrix analysis from sieve analysis testing for each aggregate and filler, the composition of AC-WC obtained is Split A at 32.24%, Split B at 26.62%, Split C at 25.56%, river sand at 10.37% and filler at 5.21%. In determining

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the optimum asphalt binder content (KAO) with Marshall testing, a range of asphalt binder contents are used: 5.0%; 5.5%; 6.0%; 6.5% and 7.0% with three specimens tested for each mixture proportion.

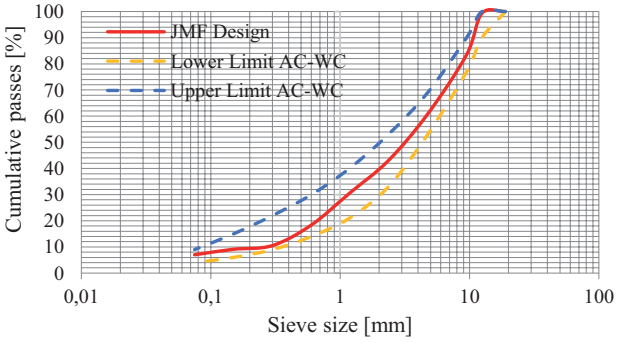

FIGURE 2. AC-WC mixed plan gradation
Source: own elaboration.

Testing of modified asphalt binder characteristics

To determine the characteristics of the asphalt binder used, penetration testing, softening point testing, viscosity testing, specific gravity testing, and rheology testing are conducted. Penetration testing (ASTM D 5 – ASTM, 2020), softening point testing (ASTM D 36 – ASTM, 2010), viscosity testing (ASTM D 4402 – ASTM, 2012), and specific gravity (ASTM D 70-03 – ASTM, 2003) testing are intended to analyze the physical characteristics of the asphalt. Rheology testing using a dynamic shear rheometer (DSR) is performed to determine the complex modulus of the asphalt binder based on AASHTO T315-10 (American Association of State Highway and Transportation Officers [AASHTO], 2010).

Testing characteristics of asphalt mixtures

The asphalt mixture samples made can be seen in Table 4, which includes three variations. The first variation consists of a control sample using 60/70 asphalt binder, the second variation consists of a sample using 7% LP modified asphalt binder, and the third variation consists of a sample using 9% LP modified asphalt binder. Each variation was used to make 15 Marshall test specimens to determine the optimum asphalt binder content (OAC) for each variation. Table 5 shows the number of Mar-

shall test specimens made using OAC, where each variation is made with six units. The characteristics of the asphalt mixture are tested using the Marshall test apparatus and stiffness modulus test. The Marshall testing follows the ASTM D 1559-89 standard (ASTM, 1989), while the stiffness modulus testing follows BS DD 213-1993 (British Standards Institution [BSI], 1993) using a universal testing machine (UTM) 30 with a pulse width of loading of 250 ms and a pulse repetition period of 3,000 ms. Stiffness modulus testing is conducted at temperatures of 25°C and 40°C, with the number of samples indicated in Table 6.

TABLE 4. Samples for making Marshall test specimens using the planned asphalt content binder

Variation	Sample	Asphalt binder used	Amount (unit)	Plan asphalt binder content
1	M-ASP	Aspen (0% LP)	15	5%; 5.5%; 6%; 6.5%; 7%
2	M-LP 7%	7% LP	15	
3	M-LP 9%	9% LP	15	
×	×	Total	45	×

Source: own elaboration.

TABLE 5. Marshall test object samples with KAO

Variation	Sample	Asphalt binder used	Amount (unit)
1	KAO-M-ASP	Aspen (0% LP)	6
2	KAO-M-LP 7%	7% LP	6
3	KAO-M-LP 9%	9% LP	6
×	×	Total	18

Source: own elaboration.

TABLE 6. Samples of stiffness modulus testing specimens

Sample	Asphalt binder used	Testing temperature (T) [°C]	Asphalt binder content	Total
Mod-ASP-25	Aspen (0% LP)	25	KAO M-ASP	2
Mod-ASP-40	Aspen (0% LP)	40	KAO M-ASP	2
Mod-LP7%-25	7% LP	25	KAO-M-L 7%	2
Mod-LP7%-40	7% LP	40	KAO-M-L 7%	2
Mod-LP9%-25	9% LP	25	KAO-M-L 9%	2
Mod-LP9%-40	9% LP	40	KAO-M-L 9%	2

Source: own elaboration.

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Results and discussion

Asphalt binder physical characteristics test results

The results of the penetration testing can be seen in Table 7, where the addition of 7% LP reduces asphalt binder penetration, while the addition of 9% LP increases it. This is because at 9% LP, asphalt binder becomes more elastic as the asphaltene particles absorb more rubber. On the other hand, for 7% LP with lower penetration, it can provide advantages in terms of intermediate temperature resistance characteristics and also improve durability in asphalt mixtures (Al-Mansob et al., 2014; Abdelmagid & Feng, 2019; Al-Sabaeei et al., 2020).

The results of the softening point testing of modified asphalt binder using pre-vulcanized latex can be seen in Table 7. The results show an increase in the softening point when the LP content is increased, indicating that the use of LP can increase both the value of asphalt's softening point and its penetration. As a result, resistance to permanent deformation increases due to this higher softening point. Therefore, the use of LP can improve rutting performance due to an increase in the softening point.

TABLE 7. Basic characteristics of the modified asphalt binders

Basic characteristics of the binders	Sample of modified asphalt binder					
	Aspen (0% LP)		7% LP		9% LP	
	result	*SD*	result	*SD*	result	*SD*
Penetration testing (0.1 mm)	60.4	1.3	45.3	2.5	68.1	1.5
Softening point test R&B [°C]	54	0.0	56.5	1.4	65.5	1.4
Viscosity at 0.2 Pa·s for mixing temperature [°C]	151	–	168	–	166	–
Viscosity at 0.4 Pa·s or compaction temperature [°C]	137	–	157	–	160	–

Source: own elaboration.

The calculation of the penetration index (*PI*) is intended to indicate the susceptibility of modified asphalt binder to temperature. The range of *PI* values is between –3 (high-temperature susceptible asphalt binder) and 7 (low-temperature susceptible asphalt binder). The results of the penetration index, where for asphalt binder without LP, a *PI* value of 0.218 was obtained, for asphalt binder with 7% LP it was 0.065, and for asphalt binder with 9% LP it was 2.926. This means that asphalt binder mixed with 7% LP is more susceptible to high temperatures, while asphalt binder with 9% LP is more susceptible to low temperatures. Asphalt binder with 7% LP has a stiffer nature compared to asphalt binder with 9% LP, which has elastic properties, so when influenced by temperature changes,

the viscosity of asphalt binder with 9% LP changes faster. The rotational viscometer is used to measure viscosity in modified asphalt binders at different levels. The test results reveal that increasing amounts of pre-vulcanized latex have an impact on the viscosity properties of the asphalt binder. In particular, when comparing samples with 0% and 7% LP content, they display similar characteristics in terms of their viscosity gradient lines; however, there is an observed difference in temperature between these two samples. According to the Superpave specification, the viscosity value at a temperature of 135°C should not exceed 3.0 Pa·s because high viscosity can lead to difficulties related to workability. The results of the viscosity testing at a temperature of 135°C show that the test values are not higher than 3.0 Pa·s, indicating that the addition of pre-vulcanized latex still falls within acceptable workability limits. The results of viscosity testing can also determine the mixing temperature and compaction temperature limits in making Marshall samples. The viscosity limit for mixing temperature is 0.2 Pa·s and the viscosity limit for compaction temperature is 0.4 Pa·s. Based on Table 7, it can be determined that the mixing temperature for the 0% LP, 7% LP and 9% LP samples respectively is 151°C, 168°C and 166°C, while the compaction temperature for the 0% LP, 7% LP and 9% LP samples respectively is equal to 137°C, 157°C and 160°C.

Asphalt binder rheology test results

When modifying materials such as pre-vulcanized latex (LP) are added, changes in the viscoelastic properties of the asphalt binder are thought to be a significant factor because of the strong interaction between elastic modulus and rutting resistance at high temperatures. In this study, the viscoelastic properties of asphalt binder are characterized by the complex modulus (G^*) and phase angle (δ). The time lag between the applied shear stress and the shear strain is known as the phase angle. Perfectly elastic materials have a phase angle value of zero, while viscous materials have a phase angle value of nearly 90°. Thus, in order to examine the rheological properties of modified asphalt, DSR testing was done (Fig. 3; Rahman & Zega, 2018; Bethary & Subagio, 2020).

The DSR test result (Fig. 3) shows that the complex modulus value decreases as the test temperature increases. The complex modulus (G^*) value decreases with each addition of LP between 52 and 70°C, with 7% LP having the highest complex modulus value. The Aspen (0% LP) sample failed at 76°C, indicating that the addition of pre-vulcanization latex increased resistance to high temperatures (Wen et al., 2017; Poovaneshvaran et al., 2020). A 1.0 kPa criterion limit for unaged

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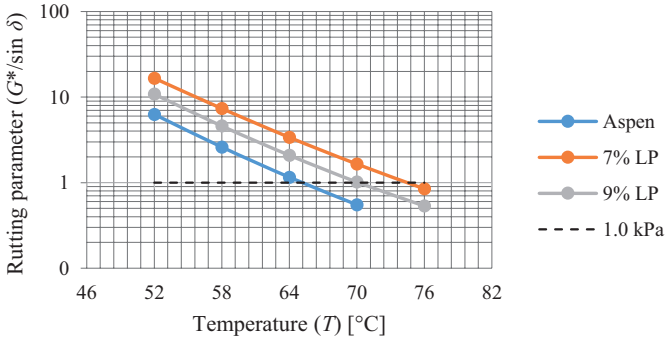

FIGURE 3. Effect of pre-vulcanization latex (LP) on $G^*/\sin\delta$ and temperature
Source: own elaboration.

asphalt binder, or a $G^*/\sin\delta$ limit value of 1.0 kPa, is stated by Superpave (Superior PERforming asphalt PAVEment). This allows for the determination of the asphalt binder classification, which is PG 64 for Aspen, PG 70 for 7% LP, and 9% LP based on performance grade (PG).

Testing asphalt mixture characteristics

Marshall testing is done in order to examine the properties of asphalt mixtures that contain pre-vulcanized latex. The results of the Marshall test for the M-ASP, M-LP 7%, and M-LP 9% samples are illustrated in Table 8 for the asphalt binder content range of 5% to 7%. Five parameters have specifications based on the Indonesian rubber asphalt recommendations. For every sample, the test findings for the sta-

TABLE 8. Marshall test results for the asphalt binder content range of 5–7%

Parameter	Spec.	M-ASP		M-LP 7%		M-LP 9%	
		result	*SD*	result	*SD*	result	*SD*
Type of asphalt binder used	–	Aspen (0% LP)	–	7% LP	–	9% LP	–
VMA [%]	min. 15	15–17	0.8	15–18	0.7	15–17	0.9
VIM [%]	3–5	2–8	2.4	3–8	1.6	1–7	2.1
VFA [%]	min. 65	52–88	13.8	53–84	10.1	59–90	12.7
Stability [kN]	min. 8.83	8.47–14.16	1.62	10–18	2.19	9–16	1.85
Flow [mm]	2–5	4–7	1.1	4–7	1.0	3–8	1.4
Marshall quotient (MQ) [kN·mm^{-1}]	–	1.65–3.04	0.45	1.49–3.94	0.82	1.24–3.22	0.65

Source: own elaboration.

bility and VMA criteria met the required standards. The Marshall test is performed with a compression machine, in which the sample is put in and gradually compressed to the maximum load.

The outcome of creating Marshall samples from M-LP 7% and M-LP 9% for each intended asphalt binder content is shown in Figure 4. To determine the sample's density, its dry weight, submerged water weight, and dry surface weight are all measured.

FIGURE 4. Results of making Marshall samples
Source: own elaboration.

The asphalt binder percentage limit known as the optimal asphalt binder content, or KAO, can produce high stability values while satisfying the criteria for flow, VIM, VMA, and VFA. As seen in Table 9, the KAO results from samples M-ASP, M-LP 7%, and M-LP 9% differ in value. This is because the viscosity and density of the asphalt mixture are impacted when pre-vulcanized latex is used. It can be observed that the KAO value of the M-ASP sample is higher than the KAO values of the M-LP 7% and M-LP 9% samples, indicating that the use of pre-vulcanized latex can minimize the amount of asphalt binder in the mixture.

Six Marshall samples were made for KAO, three of which were soaked for 30 min at 60°C and the other three of which were soaked for 24 h at 60°C, in order to learn more about the properties of the asphalt mixture. This is to examine the asphalt mixture's ability to withstand the effects of being immersed in water for a full day, a condition known as Marshall residual stability.

The results of the Marshall test, which uses KAO and has seven parameters with specifications, are displayed in Table 9. KAO-M-ASP has the highest VMA value of 15.94%, while the KAO-M-LP sample has the lowest VMA value of 7%.

TABLE 9. Marshall test results for KAO samples

Parameter	Spec.	KAO-M-ASP		KAO-M-LP 7%		KAO-M-LP 9%	
		result (AVG)	*SD*	result (AVG)	*SD*	result (AVG)	*SD*
KAO [%]	–	6.00	–	5.90	–	5.65	–
VMA [%]	min. 15	16	1.8	15	2.4	16	0.5
VIM [%]	3–5	4	2.0	4	2.7	5	0.5
VFA [%]	min. 65	73	9.7	73	12.7	70	2.5
Stability, 30-minute immersion [kN]	min. 8.83	11.68	1.20	11.63	1.15	10.69	2.77
Stability, 24-hour immersion [kN]	min. 8.83	11.09	0.67	10.84	0.39	9.85	1.92
Flow [mm]	2–5	4	0.3	4	1.5	4	0.4
Marshall quotient (MQ) [kN·mm^{-1}]	–	2.72	0.16	2.81	1.10	2.84	0.61
Residual Marshall stability after 24-hour immersion [%]	min. 90	94.9	–	93.2	–	92.1	–

Source: own elaboration.

This results from the asphalt being absorbed on the aggregate surface, where the VIM value is also impacted by the KAO-M-ASP sample filling more aggregate pores than the KAO-M-LP 7% and KAO-M-LP 9% samples. Despite getting the highest VIM value of 9%, the KAO-M-LP sample still meets the requirements. The behavior of the 9% LP asphalt filled the aggregate pores more than the air spaces in the mixture is what is causing this large VIM value. This 9% pre-vulcanized latex content might be stickier and thicker, which would make covering the aggregate's surface easier than just inserting it in air spaces. When compared to the stability specification value of 8.83 kN, the Marshall stability value using pre-vulcanized latex had a positive effect, increasing by 32.28% for a grade of 7% and 21.06% for a grade of 9%.

When comparing pre-vulcanized latex samples to the control sample (KAO-M-ASP), Table 9 additionally shows a decrease in the Marshall stability; nevertheless, the resulting Marshall stability still satisfies specification requirements. In addition, the application of pre-vulcanized latex can lower the amount of asphalt binder needed in the AC-WC mixture; the control sample needs 6% of asphalt binder, whereas the pre-vulcanized latex sample needs 5.9% and 5.65% of asphalt binder. This demonstrates that utilizing pre-vulcanized latex in asphalt mixtures has the major benefit of allowing for a reduction in the quantity of asphalt binder used. The sample using pre-vulcanized latex has a lower Marshall stability than the control sample, but it is still within the acceptable ranges. The pre-vulcanized latex samples showed a decrease in flow parameter results from 4.30 mm to 4.13 mm, or 3.95%, for the 7%

content, and from 4.30 mm to 3.77 mm, or 12.33%, for the 9% content. The mixture utilizing pre-vulcanized latex tends to be stiffer than the control sample, as shown by the resulting decrease in flow values.

To find the remaining Marshall stability, each KAO sample was immersed in water at 60°C for 30 min and then for 24 h. The sample using modified asphalt binder with pre-vulcanized latex has a smaller residual Marshall stability than the control sample, where the smallest residual stability value is at KAO-M-LP 9%, according to the results of the residual Marshall stability test, which are depicted in Table 9. This is also consistent with a study by Jitsangiam et al. (2021) that suggests the quantity of pre-vulcanized latex that can be used in asphalt binder has a limit. The storage stability of asphalt binder can be affected using excessive amounts of pre-vulcanized latex.

Table 10 presents a comparative analysis between the findings of previous research and the current study. Prastanto et al. (2019) and Irfan et al. (2022) looked at the impact of applying pre-vulcanized latex to asphalt mixtures with a rubber content of 3–7% for AC-WC and AC-BC. When compared to the specification value of 8.83 kN, the use of pre-vulcanized latex has the ability to increase Marshall stability, as demonstrated by the comparison of previous research results in Table 10. In the current study, pre-vulcanized latex was substituted for asphalt binder at weights of 7% and 9%. Previous research had used it as an additive to asphalt binder. In contrast to the research findings of Prastanto et al. (2019), there is a decrease of 8.22% in the flow value and an increase in Marshall stability from 10.32 kN to 11.63 kN, or 12.69%. This shows that the substitution effect of pre-vulcanized latex in asphalt binder has a better impact than as an additional in asphalt binder. In addition, this substitution has the benefit of absorbing natural rubber's usage as a hot asphalt mixture material while using less asphalt binder overall.

TABLE 10. Comparison of Marshall test results with previous researchers

Parameter	Current study		Prastanto et al. (2019)		Irfan et al. (2022)
	substitution pre-vulcanized latex		addition pre-vulcanized latex		
Rubber content	7%	9%	5%	7%	3%
Mixed gradation type	AC-WC	AC-WC	AC-WC	AC-WC	AC-BC
KAO [%]	5.90	5.65	6.00	6.08	5.58
Stability, 30-minute immersion [kN]	11.63	10.69	10.82	10.32	–
Flow [mm]	4.1	3.8	4.4	4.5	–
Marshall quotient (MQ) [kN·mm^{-1}]	2.81	2.84	2.46	2.29	–

Source: own elaboration.

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Stiffness modulus of asphalt mixture (S_{mix})

According to Irfan et al. (2022), the stiffness modulus, which is determined by dividing the load size by the recoverable stress, indicates the asphalt mixture's capacity to withstand loading without losing its elastic properties.

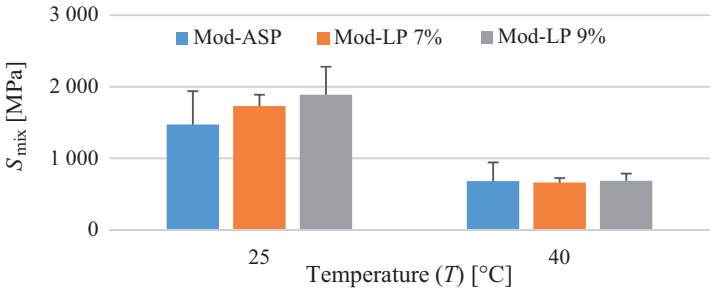

FIGURE 5. Stiffness modulus of asphalt mixture test results with the UTM tool
Source: own elaboration.

This test is performed using the UTM instrument depicted. A mathematical model presented by Brown and Brunton (1984), and Read and Whiteoak (2003) can be used to calculate the stiffness modulus prediction (Rahman & Zega, 2018). According to Rahman and Zega (2018), and Bethary and Subagio (2020), the magnitude of the asphalt stiffness modulus (S_{bit}) acquired from DSR testing affects each of these mathematical models. The results of the stiffness modulus testing with the UTM tool and the stiffness modulus results from calculations using a mathematical model were compared in this study.

The S_{mix} test results for samples with 0% LP, 7% LP, and 9% LP asphalt are shown in Figure 5. The average value of the test results carried out three times on one specimen was used to determine the S_{mix} test results at 25°C and 40°C. When the asphalt mixture reaches a temperature of 25°C, it is considered to be in normal condition; in Indonesia, however, the pavement temperature is 40°C (Irfan et al., 2021). It demonstrates that at 25°C, the sample with 9% LP has the largest S_{mix} value (1,888 MPa), followed by the Mod-LP7% sample (1,729 MPa). The Mod-LP7% sample and the Mod-LP9% sample both observed increases in S_{mix} of 17.46% and 28.26%, respectively, in comparison to the control sample (Mod-ASP). The Mod-LP9% sample had the largest S_{mix} at 685 MPa, followed by Mod-LP7% at 661 MPa, with an increase of 8.21% and 4.42%. The results of the S_{mix} test at 40°C revealed the same trend as at 25°C.

Stiffness modulus prediction model for asphalt mixtures

Predictive stiffness modulus models for asphalt mixtures are currently available solely for petroleum asphalt binder; however, no progress has been made in the area of modified asphalt binder utilizing pre-vulcanized latex. Ramadhani et al. (2023) have studied the prediction model for asphalt binder stiffness (S_{bit}) using pre-vulcanized latex; however, their research is restricted to asphalt binder.

TABLE 11. Results of making a prediction model for stiffness modulus of asphalt mixture S_{mix} containing pre-vulcanized latex

Model	Model type	Equation	R^2
1	linear	$S_{mix} = -2\,064.813 + 24.382 \cdot LP + 111.465 \cdot VMA + 616.839 \cdot VIM + 45.603 \cdot S_{bit} - 50.006 \cdot T$	0.8441
2	nonlinear	$S_{mix} = e^{(5.591 + 0.007 \cdot LP + 0.012 \cdot VMA + 0.548 \cdot VIM + 0.039 \cdot S_{bit} - 0.048 \cdot T)}$	0.8519
3	nonlinear	$S_{mix} = 10^{(2.428 + 0.003 \cdot LP + 0.005 \cdot VMA + 0.238 \cdot VIM + 0.017 \cdot S_{bit} - 0.021 \cdot T)}$	0.8519

By gathering test results from the laboratory, this stiffness modulus prediction model for asphalt mixtures can be developed. The dependent variable (y) in the model created is S_{mix}, while the independent variable (x) is the percentage of pre-vulcanization latex content in asphalt binder (LP), *VMA* value, *VIM* value, S_{bit} value and temperature (T). To create this model, a multiple linear regression model was used, creating linear and non-linear models. The proposed model's regression analysis is depicted in Table 11, which shows the results for three different model types – linear and nonlinear. Model 2 and Model 3 have an R^2 value of 0.8519, indicating that the model in Table 11 is closer to the laboratory results, as indicated by a larger R^2 value.

Conclusions

The behavior of pre-vulcanized latex AC-WC mixtures has been thoroughly studied. The impact of pre-vulcanization latex on the physical properties and rheology of asphalt binder and asphalt mixtures offers positive effects, according to the procedure and test objects used. Many inferences can be made from the test results that have been conducted:

1) Pre-vulcanized latex may decrease penetration and raise the softening point, which is beneficial for modified asphalt binder. In comparison to 9% pre-vulcanized latex, 7% pre-vulcanized latex performs better in terms of resistance to high temperatures, according to the penetration index computation results.
2) Based on Marshall test results, the AC-WC mixture using pre-vulcanized latex achieved Marshall stability of 11.63 kN or increased by 32.28% at 7% content, while at 9%, it resulted in Marshall stability of 10.69 kN or increased by 21.06%, compared with the specification limit which is 8.83 kN.
3) The stiffness modulus value of the asphalt mixture increases in tandem with an increase in the pre-vulcanization latex content, according to the results of the stiffness modulus test conducted using the UTM tool at 25°C and 40°C. Using pre-vulcanized latex, the stiffness modulus prediction model for asphalt mixtures is obtained as a nonlinear model with ln and log functions, and its R^2 value is 0.8519.

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Summary

The effect of pre-vulcanized latex usage on Marshall characteristics and stiffness modulus in hot mix asphalt wearing course (AC-WC) mixtures. Flexible pavement itself uses asphalt binder as a binding material between aggregates, but with the increasing number of vehicle loads, the ability of flexible pavement needs to be improved. A rubber is a natural polymer material that can be used to improve the performance of asphalt mixtures. This paper aims to analyze the effect of using pre-vulcanized latex on characteristics in hot mix asphalt wearing course mixtures. Pre-vulcanized latex is used as a substitute material for

asphalt binder at levels of 7% and 9% by weight. Based on Marshall test results, the AC-WC mixture using pre-vulcanized latex achieved Marshall stability of 11.63 kN or increased by 32.28% at 7% content, while at 9%, it resulted in Marshall stability of 10.69 kN or increased by 21.06%, compared to the specification limit, which is 8.83 kN. The stiffness modulus test results of the asphalt mixture showed that at a temperature of 25°C, there was an increase of 17.46% and 28.26%, respectively, when using pre-vulcanized latex at levels of 7% and 9%. These findings indicate that the use of pre-vulcanized latex as a partial replacement for asphalt has a positive impact on temperature changes in the pavement material.

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Public-private partnerships scheme of pioneer train case study in South Sumatera area

Keywords: asset commercialization, life cycle cost, pioneer train, unbundling

Introduction

Transportation challenges for developing countries, such as Indonesia, include increasing travel demand, rising vehicle ownership (Rahman et al., 2012), safety issues, congestion (Obeng-Atuah et al., 2016), unreliable public transportation services, unreliable pedestrian facilities, and irregularities in traffic discipline (Adarkwa & Poku-Boansi, 2011). To overcome these challenges, the government began promoting an affordable and effective mass transportation system (Poku-Boansi & Marsden, 2018). The government chose rail transportation because it is the most suitable transportation, even better than road transportation and more environmentally friendly (Carpintero et al., 2010; Kulshreshtha et al., 2017). It can also reduce travel time and help save energy (Oliveira Cruz et al., 2015). This transportation is also being promoted in Indonesia by the government through

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the Regulation of the Minister of Transportation of the Republic of Indonesia No. 22 of 2020 concerning transportation rates for people by pioneer trains (Berita Negara Republik Indonesia Tahun 2020 Nomor 464). The pioneer train line was built in a new area. It has not been able to bring commercial benefits to its operators. Until now, there have been 6 pioneer railway lines in various cities, all of them funded by the Indonesian Government (Mulyono, 2023). No pioneer trains have yet been funded through the public-private partnerships (PPP) scheme yet. All pioneer trains in Indonesia are purely funded by the state through the state budget (APBN). One of the pioneer trains in Indonesia is the Kertalaya rail bus which was launched by the government on February 19, 2009. Kertalaya train was first produced in Indonesia using the concept of a combination of light buses and trains produced by PT. INKA. Kertalaya train service is a type of AC economy commuter. The purpose of its construction is to reduce the congestion of the highway on the Palembang-Prabumulih road. The rail bus on the Kertalaya train consists of three carriages. All of the funding of Kertalaya construction and operation is funded by the government. Similar trains are used in other countries which is carrying passengers from one place to another (Poku-Boansi & Marsden, 2018; Li & Love, 2020; Meng et al., 2022; Xiahou et al., 2022).

The costs of the construction, operation, and maintenance of Kertalaya trains are very large. The right funding scheme is needed to overcome these financing problems. Many financing schemes have been carried out to fund railway projects, including full funding by the government, tax subsidies (Noviarti et al., 2023), privatization (Tomikawa & Goto, 2022), and PPP. Public-private partnerships are considered as one of the right schemes for funding the project because business entities can effectively bridge the limited financial resources of the government (Christiansen, 2008; Chang, 2013; Rahman et al., 2019). This type of financing scheme has many risks and challenges (González-Medrano & Martín, 2021; Huang et al., 2022). Many studies have shown that PPP financing schemes have not been able to achieve the goal of obtaining decent financial results. At the end the operation and maintenance, these modes are taken over by the government (Bernardino et al., 2010). For examples: the UK Channel Tunnel, London Underground and Taiwan High Speed Rail (Gangwar & Raghuram, 2015). Based on the results of the study, the decline in railway operations is due to inadequate investment in infrastructure, poor service, lack of market orientation, and large numbers of staff/crews in railway operations. The success factor of the railway transportation are trains that have to be connected with commercial areas, housing, campuses, zoos, and have comfortable facilities (Carpintero et al., 2010; Liao, 2016). Regulatory reform is needed to create an environment which supports the private sector to participate in PPP scheme funding (Rock & Wu, 2020). Usually, one train problem in Indonesia is about the ticket fares. The passenger ticket fares determined by the government through the approval of the DPR (Xiahou et al., 2022).

This study aims to analyze the most effective unbundling scenario for the operation and maintenance of the Kertalaya pioneer train majoring in Indralaya – Tanjung Senai. The evaluation is carried out by calculating life cycle costs and sensitivity analysis in accordance with applicable regulations. The scenario created is based on the increase in ticket prices and support from the government for the Kertalaya train operation and maintenance plan by calculating the net present value (*NPV*) and internal rate of return (*IRR*) values. The novelty of this research is because so far there has been no pioneer train in Indonesia that is financed using PPP. For this reason, in this study we attempted to use the PPP scheme in preparing pioneer trains.

Material and methods

This research is located on the Kertalaya pioneer train line that connects Kertapati (Palembang) and Indralaya (Ogan Ilir). This train line is included in Regional Subdivision III of the South Sumatra area (Fig. 1).

There are four stages of research: Stage 1. Literature study and focusing on the problem; Stage 2. Field measurement; Stage 3. Preparation of the cost budget plan for Indralaya – Tanjung Senai railway line and calculation of life cycle cost (LCC) and Stage 4. Simulation of distribution of responsibilities in the PPP scheme.

Stage 1: The literature sources are taken from the Scopus reference. Secondary data were collected to support this research. They include: unit price analysis (AHS) of rail roads and railway bridges, evaluation report of operating the Perintis train Kertapati – Indralaya line which is owned by the Ministry of Transportation, and passenger data from PT. KAI Divre 3 South Sumatra. From the evaluation report of the Pioneer Train book, it was found that there was a government plan to build the Indralaya – Tanjung Senai rail line (Ogan Ilir Regency Government Center). Based on an unpublished report from PT. KAI, the number of passengers of the Palembang – Indralaya Kertalaya train can be seen in Table 1. After 2019, the Kertalaya train was no longer used because it was hampered by overhaul costs and COVID-19 conditions that caused Unsri students to study online.

TABLE 1. Number of Kertalaya train passengers for five years

Year	Number of passengers
2015	27 331
2016	28 941
2017	32 968
2018	23 835
2019	20 842

Source: own work.

Stage 2: Based on the secondary data, measurements were made to the field from Indralaya station to the station planned to be

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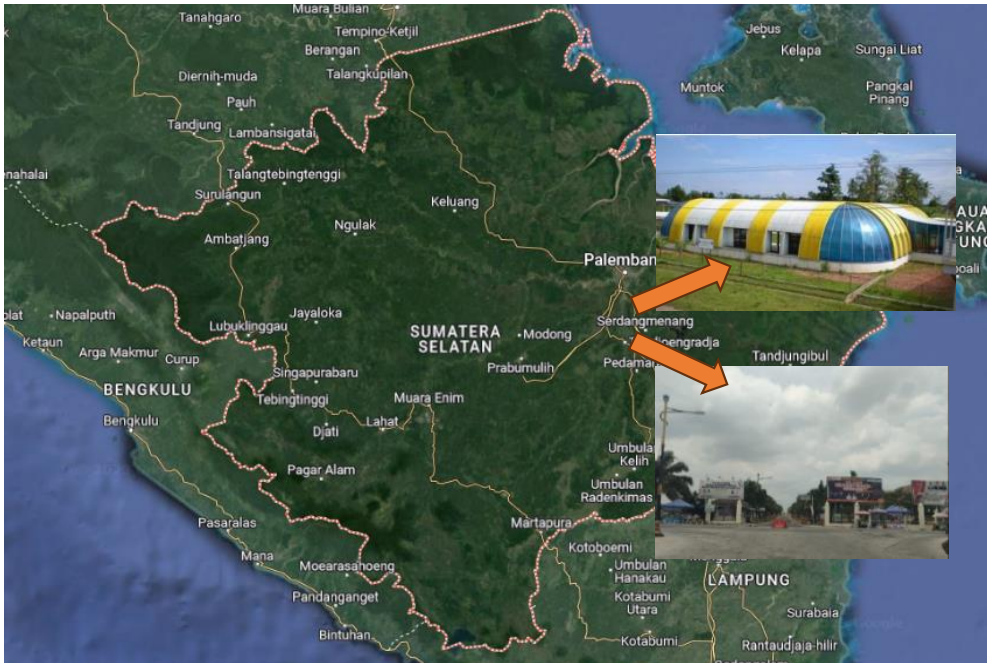

FIGURE 1. Research location of Indralaya Station and Tanjung Senai Integrated Office Complex (KPT)
Source: own work.

built in Tanjung Senai. Measurements were carried out in order to obtain accurate measurement data for the preparation of the RAB for the Indralaya – Tanjung Senai rail road plan.

Stage 3: Through this approach, the total cost of Capex and Opex for 40 years is calculated. In this study, the cost of rail line construction or capital expenditure (Capex), which is calculated, includes the construction costs (landfill, railway, crossing, signal, telecommunications, bridges, and stations), land acquisition costs, train revitalization costs, planning costs, licensing costs, and environmental impact analysis (AMDAL) costs. Operational and maintenance costs or operational expenditure (Opex) are taken into account include maintenance of railway lines, maintenance of carriage components, train operational costs, and wages/salaries of staff and operators. All Opex costs and revenue components are calculated over 40 years. The planned duration of the concession is 40 years. It took 40 years because the pioneer train project has a high level of risk for business entities. This pioneer train only has a limited target of passengers in the environment of Unsri students and employees at the Ogan Ilir Regional Government. So that the long

concession period will make the management business entity more interested in being involved in this project. The 40-year period is also taken from previous research which also discussed PPP railway projects.

Stage 4: In this stage, three scenarios were made for the distribution of responsibilities in the PPP scheme. This scheme was carried out to attract private investors to be involved in financing the pioneer Kertalaya train by showing positive *NPV* and significant *IRR* (Kim et al., 2022). Three scenarios were chosen because they could be the basis for several other scenarios to be created by raising and lowering the percentage.

In this study, there is an existing 26 km long Kertapati – Indralaya train line. It was assumed that this rail is still in good condition and can be used. The focus of this paper is on the distribution between government and private responsibilities on operations, maintenance and improvement of passenger railway facilities and infrastructure. Meanwhile, on the planned route between Indralaya and Tanjung Senai will be built a new rail unit along 5.2 km. Consideration is made by taking into account the value of *NPV* and *IRR*. *NPV* is done by taking into account the amount and forecast of discounted future cash flows at the current time. Formula used $NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$, which C_t is a net cash flow during the period, t is a period, C_o is the total initial investment, r is a discount rate [%].

Internal rate ratio is calculated by adding up the present value and future flow of funds minus the investment value. A calculation scenario will be carried out based on a combination of *NPV*, *IRR* and government support.

In this study, a discount rate of 15% was used because it was taken based on the risk of investment opportunities from the investor's point of view. In this case it is possible for investors to use several sources of capital. In addition, research on trains also uses the same value.

Results

Investment cost (Capex) on the Indralaya – Tanjung Senai rail road development plan

In this study, the is construction of a new 5.2 km long train line was assumed from the end point at Indralaya station to the Tanjung Senai Integrated Government Office (KPT). The investment cost of its railway project is fully borne by the government. Investment costs. The construction of new rail lines in this study consists of components that in detail can be seen in Table 2.

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TABLE 2. Investment cost of Indralaya rail road construction project – KPT Tanjung Senai

Category	Component	Cost [IDR]
Construction cost	Earthworks	9 556 500 000
	Railway single track	20 800 000 000
	Crossing road	2 250 000 000
	Signal	1 014 000 000
	Telecommunications	936 000 000
	Bridge	11 000 000 000
	Large Station	10 000 000 000
	Total	**55 556 500 000**
Others	Land Release	2 150 000 000
	Train revitalization	18 334 001 000
	Total	**18 334 001 000**
PM cost	VAT	
	Project management and consulting fee	227 781 650
	Licensing fees, AMDAL (0.5% from construction)	91 670 005
	Total	**319 451 655**

Source: own work.

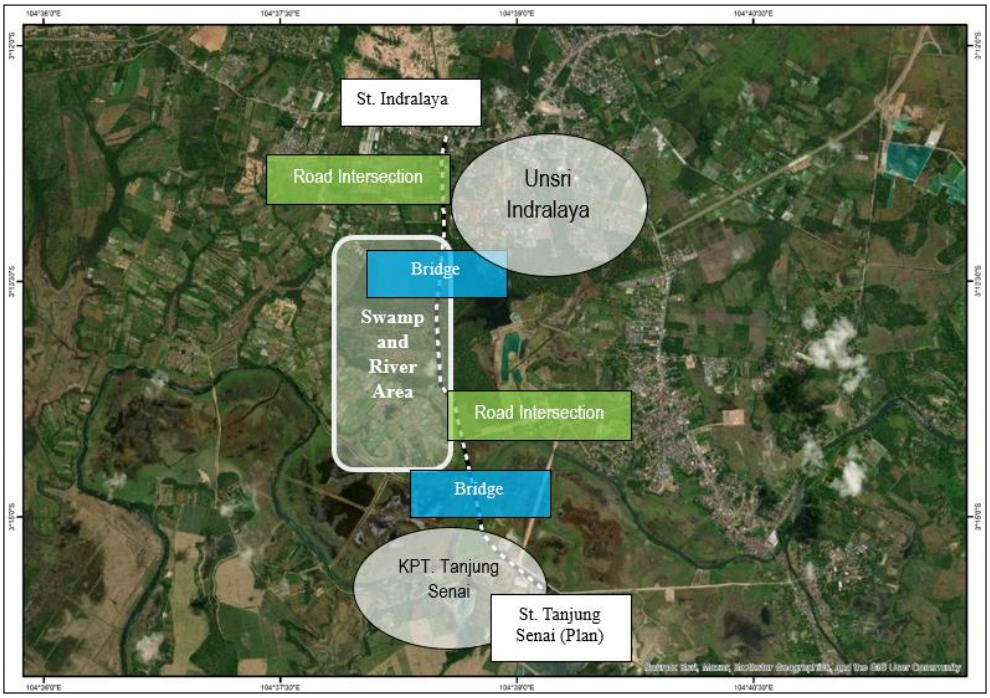

FIGURE 2. Indralaya Tanjung Senai pioneer train line plan

Source: own work.

Based on the "Study evaluating the usefulness of the Pioneer Train Lintas Kertapati – Indralaya" book, the railway line will be made from Indralaya Station – KPT Tanjung Senai can be seen in Figure 2. The planned train line will pass through some forests and swamps located on the edge of the Sriwijaya University.

Operational and maintenance costs on the Indralaya – Tanjung Senai rail road construction plan

In this study, operational and maintenance costs during the project life cycle (LCC) consist of railbus operational costs, infrastructure maintenance, operations and facility maintenance. Life cycle costs planned for 40 years consist of components that can be seen in Table 3.

If calculated manually between the cost of OM and the maximum number of passengers, then the minimum cost of passenger tickets is IDR 20,000 (rail road maintenance fee per year divided by the number of passengers per year).

TABLE 3. Components of rail road maintenance costs per year

Components	Annual cost [IDR]
Rail bus maintenance	366 680 020
Electrical costs	221 395 860
Personnel salaries	96 000 000
Track maintenance costs	1 406 080 000
Station maintenance	120 000 000
Total	2 210 155 880

Source: own work.

Refund/Revenue from ticket sales

Refunds on railway projects can come from passenger ticket payments, government subsidies, capital grants, and financing from private entities (Li & Love, 2020). The returns are only focused on profits resulting from passenger ticket sales. For passenger tickets, it is at IDR 3,000 per passenger. Based on the calculation results, the amount of revenue in the last five years of using Kertalaya trains can be seen in Table 4.

TABLE 4. Total revenue derived from passenger ticket sales for five years

Year	Number of passengers	Revenue IDR]
2015	27 343	82 029 000
2016	28 941	86 823 000
2017	32 968	98 904 000
2018	23 835	71 505 000
2019	20 842	62 526 000

Source: own work.

Based on Table 4 data, it can be concluded that it is not possible for the government to get a business entity that is willing to become a PPP partner in the development of the Kertalaya pioneer train project. Because the amount of income is smaller than the operational funds per year. Several Kertalaya train financing scenarios are needed, so that business entities become interested in investing in the development of the Kertalaya pioneer train project.

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As an illustration, if the maximum passenger assumed at 70% of the maximum capacity of the train is met, and the passenger ticket price is increased to IDR 5,000 per passenger, then an income of IDR 783 million per year will be obtained. The income from this assumption is insufficient for the operational and maintenance costs of the Kertalaya train. There will also be fewer passengers on holidays (Saturdays, Sundays and other public holidays and sabbaticals).

Public-private partnerships scheme

Based on the data obtained above, it can be seen that income from tickets cannot cover operational and maintenance costs (Opex) at all. Based on the data from the Dinas Perhubungan Sumatera Selatan, in one year the Kertalaya only gets IDR 900 million for operational and maintenance funds. A strategy is needed that can make business entities want to invest by sharing scenarios for the distribution of responsibility between the government and business entities so that the construction of this route does not become a burden on the state budget – APBN (Lee et al., 2022). Because this rail road was only built as part of the existing length, so the focus scenario in this study is only on operational and maintenance costs (Opex) and the plan to add the Indralaya – Tanjung Senai rail line along 5.2 km.

Scenario 1: The government bears all Capex costs, while the Opex costs are fully borne by the business entity. In this scenario, the business entity has the right to determine passenger fares and has the right to manage and earn revenue from commercial areas both inside and outside the station, through sales, restaurants, cafes, and advertisements.

Scenario 2: The government bears Capex and maintenance costs, while business entities bear the costs of train operations and maintenance of both stations because they are related to tenant rent. Here an unbundling system is applied or a breakdown of Opex costs. In this scenario the tariff is determined by the government, but the business entity has the right to manage and earn revenue from commercial areas both inside and outside the station, through sales, restaurants, cafes, and advertising. The government stipulates that business entities can only charge a ticket price of IDR 5,000 per passenger, both for students, the public, and weekends.

Scenario 3: The government bears the Capex costs except for train procurement/ /revitalization, while the business entity bears the Opex costs and the government subsidizes the ticket price of IDR 10,000 per passenger.

In addition, revenue must be by maximizing commercial areas both inside and outside the station, through sales, restaurants, cafes, and advertising (Table 5).

TABLE 5. Public-private partnerships scenarios for pioneer trains

Cost component	Scenario 1	Scenario 2	Scenario 3
Income	Passenger ticketing and asset commercialization	Passenger ticketing and asset commercialization	Passenger ticketing and asset commercialization
Ticketing	Non subsidy	Government determined	Subsidy IDR 10 000 per passenger
Government support	Capex	Capex dan maintenance	Capex except the procurement/revitalise railbus
Entities responsibilities	Opex	Opex except maintenance	procurement/revitalise railbus and Opex

Source: own work.

Sensitivity analysis

The sensitivity analysis will consider the number of passengers heading to the Unsri campus and the number of passengers reaching the final station at the Tanjung Senai Office, as well as ticket prices. According to calculations, if 70% of passengers are students and 30% of passengers are employees at the Tanjung Senai office with a difference in fares for students of IDR 5,000 and IDR 10,000 for public and IDR 15,000 for holidays. The rate is increased by IDR 5,000 per five years as can be seen in Figure 3. The tariff increase is taken into consideration based on the increase in inflation in Indonesia, which in a year can reach 3.5%.

Based on the calculation results of sensitivity analysis, the values of the Capex, Opex and revenue for 40 years of life cycle cost, the revenue obtained from the commercialization assets is assumed about IDR 21 million per station per month. Based on the calculation results, the *NPV*

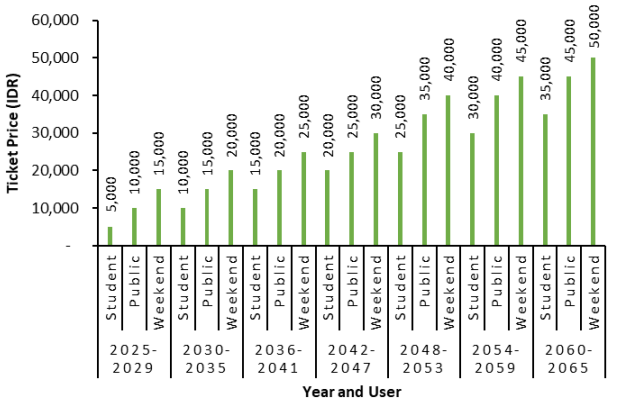

FIGURE 3. Planned ticket price increase
Source: own work.

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value in 40 years with a discount of rate 15% can be seen in Figures 4 and 5, namely for Scenario 1 of IDR 185 million, for Scenario 2 of IDR 4.64 million and negative value of IDR 1.37 million for Scenario 3 (Table 6).

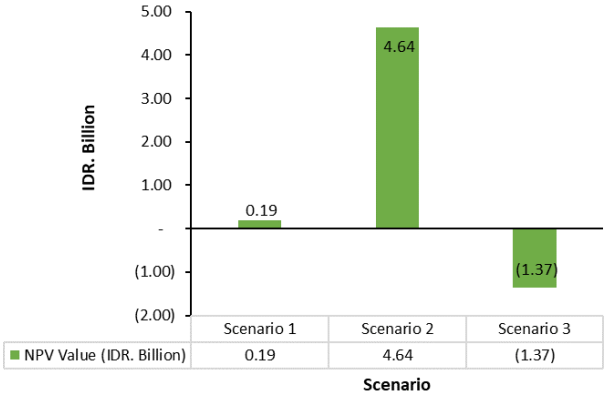

FIGURE 4. *NPV* values for all three scenarios

Source: own work.

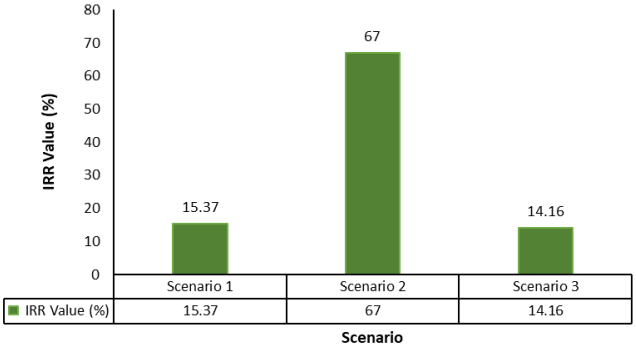

FIGURE 5. *IRR* values for all three scenarios

Source: own work.

TABLE 6. Recap of Capex, Opex and revenue values for 40 years from three scenarios

Variant	Capex	Opex	Revenue	Description
	million IDR			
Scenario 1	0	123 225.03	197 615.00	Capex borne by the government
Scenario 2	0	24 386.57	57 965.00	Capex and maintenance borne by the government
Scenario 3	8 847.00	123 225.03	308 275.00	The construction of rails is borne by the government

Source: own work.

Discussion

Existing conditions

The existing line of the Kertalaya pioneer train is 26 km long. If added again as planned to KPT Tanjung Senai, then 5.2 km will be added along. KPT Tanjung Senai is located in a less strategic position because it is not located on the edge of the main road. If you travel along the existing road, you must use a private vehicle, such as a motor such as motor rickshaw to go to KPT Tanjung Senai. The costs incurred are also high. In general, if one wants to visit KPT Tanjung Senai, people usually rent motor rickshaw, because these vehicles will also be used for people to exit again from the KPT Tanjung Senai Area. According to the preliminary survey conducted, it costs IDR 20,000–35,000 to rent a motor rickshaw to in and to out of KPT Indralaya. If someone departs from Kertapati to Indralaya by travel car, a fee of IDR 20,000 will be charged. Plus, the rental of a motor rickshaw of IDR 20,000 then an employee can spend money for travel costs of IDR 50,000–60,000 per day. Unsri students spend IDR 30,000 per day for a trip to the Indralaya campus. It is hoped that the Kertalaya train can reduce the travel costs of students and people going to KPT Tanjung Senai. Efficient use of capacity on railway infrastructure can result in cost savings for passengers (Ali et al., 2020). In addition, the use of trains is expected to reduce road congestion and road load Palembang – Indralaya and reduce traffic accident (Loo, 2019; Tao et al., 2021).

The condition of Kertalaya that has not been used for five years requires revitalization (Fig. 6). Revitalization here means improvement. The improvements to be implemented are also quite extensive. So, it requires special handling for repairs in order to operate optimally. Repairs can only be carried out at PT INKA Madiun, so the train must be sent back to its hometown.

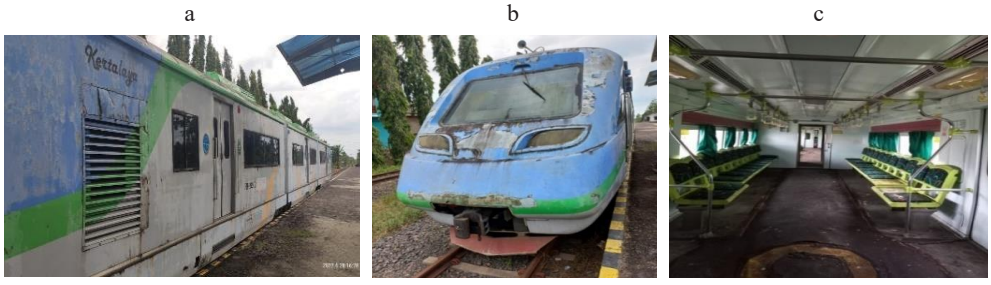

FIGURE 6. Interior (a and b) and exterior (c) damage to Kertalaya train
Source: own work.

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Beside the exterior and interior of the train, damage also occurred to the train engine, train bogies, generators and motor traction, electrical panels, braking systems and air supply. According to information from the Department of Transportation, the cost of revitalizing the train is about IDR 18.3 billion.

Line construction financing plan and Indralaya train revitalization – KPT Tanjung Senai

Based on the calculation results in Table 2, the total cost of making a new rail road along 5.2 km is IDR 55.5 billion. The cost includes the construction of two bridges, each of which is planned with a span length of about 20 m, because the rail line is planned to be built through swamps and rivers, as well as the cost of crossing with roads. There are two crossings, located on the Indralaya – Prabumulih arterial road and the local road in Tanjung Pering Village. The location of the development plan is also within a swamp area and part of Unsri's forest. So, there are a lot of piles.

Operational costs and maintenance of Kertalaya train facilities and infrastructure

Kertalaya train operational and maintenance costs consist of railbus maintenance costs, fuel costs, personal salaries, track maintenance costs, and station maintenance costs. There are two units of station operational and maintenance costs, namely Indralaya station and Tanjung Senai station. The budget allocated is IDR 5 million per month per station. Personal salary costs of IDR 96 million per year are calculated by two people, with UMR salary. Railbus maintenance costs are calculated at 2% per annum of the cost of making rail roads (Berawi et al., 2014). Track maintenance costs are IDR 1.4 billion per year. So that the total operational and maintenance cost budget is IDR 2.2 billion in the initial 5 years. For the following years this cost is calculated to increase by 10% (Rahman et al., 2016; Love et al., 2017; Rahman et al., 2019). In the next five years, it will increase again by 10%. The increase in operational costs will be adjusted to the price of passenger ticket prices for the future.

Kertalaya train revenue

In accordance with applicable regulations, ticket sales are at IDR 3,000 per passenger. The results of passenger ticket sales for five years only range from IDR 60-90 million per year. Revenue from tickets is very less to cover operational

and maintenance costs on Kertalaya trains. In this study, an attempt was made to try and change the ticket price by increasing it to IDR 5,000 per student passenger and IDR 10,000 per general passenger and passengers on Saturday–Sunday. For general passengers who get off at Indralaya station still pay IDR 5,000. Unless passengers get off at Tanjung Senai station, passengers must pay IDR 10,000. General passengers who board from Indralaya station to Tanjung Senai station must pay IDR 5,000. This ticket price is valid for five years, namely from 2024–2029. For the next five years, ticket prices will be increased by IDR 5,000 each. So, the minimum payment is IDR 10,000. Until the final limit of life cycle costs calculated in this study, which is 40 years (Rahman et al., 2018, 2019). Ticket prices become a maximum of IDR 35,000, up to IDR 50,000. Details can be seen in Figure 2. Ticket price increases are not the only way. There must be creative ideas to bring profit to this project.

Previous studies have proposed several accreditives to increase income from scratch. One of them is by using land around rail roads or commercializing assets (Martín et al., 2014). There are also those who use the tax system for private vehicles that create congestion (Crozet, 2014; Emmanuel & Crozet, 2014; Xuto et al., 2022). Train financing in some countries of the world is financed by governments (Lowe, 2013; Jillella & Newman, 2016; Dehornoy, 2018). To reduce the burden on the state, it would be good if the government started involving business entities in making rail roads, train operations, and maintaining railway supporting facilities and infrastructure.

Utilization of assets around the station or commonly called asset commercialization can take place in the form of (Martín et al., 2014):

1. Creating minimarkets, coffee shops, and restaurants in the station area, both Indralaya station and Tanjung Senai station.
2. Working with the local government of Ogan Ilir to create tourist attractions in the Tanjung Senai area, so that the train can still operate on national holidays.
3. Providing places for advertising for tenants located at the station.

It is hoped that the use of land around the station can bring benefits that can cover operational and maintenance costs.

This research plans for each station to get a profit of around IDR 21 million per month, which comes from the benefits of renting space for tenants and advertisements, all of which are managed by Business Entities that work with tenants of food and other local products. so it can be calculated that the profit from the use of the two assets owned by PT KAI reaches IDR 500 million per year which will be included in non-ticket income (Rahman et al., 2018). The creation of a commercial area around this station can also be an attraction for prospective passengers, both general passengers and students.

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Especially for student passengers, there are several other things that can be done so that they want to use the train: (1) the train departure time must adjust to the student's lecture schedule, (2) there must be a mode of transportation (feeder) from Indralaya station to the Unsri campus for free, because the distance is a bit far to get to the Unsri campus, which is about 1.4 km and stops the operation of student buses.

After several scenarios for tariffs were made, *NPV* and *IRR* values were calculated as a result of government support (Tao et al., 2011; Rahman et al., 2016, 2018, 2019).

Kertalaya train operational financing scenario

Many scenarios can be made in funding PPP schemes. The distribution of investment costs, as well as operational and maintenance costs is carried out in order to obtain the same expected goals (Berawi et al., 2018, 2019, 2021).

In this study, three financing scenarios with PPP schemes for pioneer trains were proposed. The aim is to divide responsibility to Business Entities (Ismail, 2013; Wibowo & Alfen, 2015; Sun et al., 2017). In order to continue Kertalaya train operational, the business entity must always take care of the Kertalaya train. For this reason, the focus of this research is on how business entities manage and maintain Kertalaya trains. The Kertalaya train had to be overhauled after 10,000 hours of use. If used every day for two hours, then for seven years it must be overhauled so that the engine continues to run properly. So far, the overhaul costs have been carried out by the South Sumatra Provincial government. Due to cost constraints, the overhaul was not carried out, so the engine was damaged and the railbus could not be run. The application of the unbundling system was carried out in this study with the aim that Business Entities can benefit (Gangwar & Raghuram, 2015).

In Scenario 1, the business entity bears all maintenance and operational costs of the Kertalaya train, and the business entity also has the right to determine the price of passenger tickets, but still under the approval of PT. KAI as the manager. Business entities set ticket prices of IDR 5,000 for students, and IDR 10,000 for the general public. As for Saturday–Sunday, the ticket price is IDR 10,000 also per passenger. In this scheme, a discount value of 15% is used, calculated life cycle cost for 40 years (Berawi et al., 2018; Rahman et al., 2018; Berawi et al., 2021). The calculation results from Scenario 1 obtained an *NPV* value of IDR 185 million and an *IRR* value of 15.37. That means that this scenario is feasible and can be profitable for business entities.

In Scenario 2, the ticket price is equal for all students and the public, which is IDR 5,000, but the government bears the maintenance costs of both train overhaul

and rail road maintenance. This cost is IDR 1.7 billion per year, while the cost borne by the private sector is IDR 437 billion per year. In Scenario 2, the highest *NPV* value was obtained at 4.61 billion. So, it will be very profitable for business entities. This second scenario can be further developed, for example by shortening the concession period for business entities or by asking business entities to give back some of their profits to the government.

In Scenario 3, the government handed over train revitalization to business entities worth IDR 18 billion. The government will also subsidize ticket prices of IDR 10,000 per passenger, but passengers still pay according to Scenario 1. In this scenario, a negative *NPV* value of IDR 1 .36 billion and an *IRR* value of 14.16 were obtained. This means that the company's maximum discount only reaches 14.16% per year. This will certainly be difficult for business entities (Ali et al., 2016; Belal et al., 2020).

Based on the results of the analysis and calculation, Scenario 2 is most likely to attract business entities to invest, where business entities only fund the operational costs of pioneer trains and on the other hand, people who use trains will find it very helpful because of affordable fares. All scenarios use a 15% discount rate.

All scenarios include the commercialization value of assets as non-ticket income. Commercialized assets are obtained from advertising and land use around the station by business entities (Jillella & Newman, 2016). In this study, the average profit value from asset commercialization is IDR 20 million per month per station. Of course, this value can increase because of advertising, renting, and sales of food and beverage tenants around the station. If without commercialization of assets, then for scenario get an *IRR* value of IDR 2 million (negative), Scenario 2 get an *IRR* value of IDR 2 million (positive) and IDR 23 million (negative) for Scenario 3.

Based on the findings of this study, it was found that for pioneer trains, the government still has to intervene a lot in financing, this is because ticket prices cannot be too high set by business entities. In addition, it is also very important to cooperate with Unsri and parties in Ogan Ilir Regency so that the utilization of the Kertalaya train can run optimally.

Conclusions

The results of this study calculate the feasibility of financing Kertalaya pioneer trains. Based on the calculation results, the *NPV* value in 40 years is obtained with a discount of 15% for Scenario 1 of IDR 185 billion, for Scenario 2 of IDR 4.64 billion and a negative value of IDR 1.37 billion for Scenario 3. From this

research, it can be concluded that the role of the government is still very necessary for the feasibility of the Kertalaya pioneer train project plan. Other things that can be taken into consideration are the commercialization of assets and the system of solving responsibility (unbundling) and increasing ticket prices in order to cover train operating costs. To attract the interest of Unsri students and employees in Tanjung Senai, cooperation between business entities and the government is needed. Cooperation with the Department of Transportation to provide a mode of transportation that can transport students from the station to the campus. Another collaboration could take place with the Ogan Ilir Regency government in order to make the Tanjung Senai area more alive by creating recreation or tourism centers so that on Sundays and other holidays the Kertalaya train can still operate. This study has not considered the risk problems that will be faced with the unbundling system in the PPP scheme. It is hoped that this research can be a recommendation for funding other pioneer trains through the PPP scheme. Compared to similar studies, this study has differences in the form of the application of the unbundling system in the management of railway operational costs in the provincial city center and district city center.

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Summary

Public-private partnerships scheme of pioneer train case study in South Sumatera area. Pioneer trains in Indonesia have been fully funded by the government. The construction needs a lot of funding that would burden the state budget. One of the alternatives is the public-private partnership scheme. This study aims to analyze the most effective unbundling scenario for financing and maintaining the Indralaya-Tanjung Senai train. The life cycle costs and conducting sensitivity analysis according to applicable regulations. The scenarios are based on ticket price increases and government support for the operation and maintenance (O&M) for this pioneer train route, calculated net present value (*NPV*) and internal rate of return (*IRR*) value. Scenario 1 assumes that tickets do not receive subsidies; private companies are responsible for O&M costs. Scenario 2 assumes that ticket prices are set by private companies; the government is responsible for procurement and maintenance costs. Scenario 3 assumes that the government provides subsidies of IDR 10,000 per passenger as well as railway infrastructure; private companies bear the cost of procuring railbuses and operational expenses. Based on calculations with Scenario 1 *NPV* is IDR 0.73 billion; with Scenario 2, it is IDR 4.64 billion and with Scenario 3, it is IDR (–)1.34 billion. The analysis shows that increasing passenger fares according to price raises and inflation rates, and subsidies from governments for maintenance costs will make this railroad project financially feasible.

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