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IDENTIFYING THE INFLUENCE OF ADDING PLASTIC AND PAPER WASTE ON STABILIZATION OF SUBGRADE FOR TOLL ROADS

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This paper discusses soil stability with high water content and low bearing capacity, which can damage the pavement and shorten the lifespan of the toll road. The problem is that high water content and low soil carrying capacity can trigger subgrade instability and decreased pavement performance. Experimental variations using plastic waste with a percentage of 7%, 10%, and 15%, paper waste with a percentage of 4%, 8%, and 10%into the original soil. The results showed that the addition of plastic and paper waste increases soil strength and CBR values significantly compared to conventional stabilizers. Plastic increases shear resistance and decreases development potential, while paper increases cohesion A combination of 10% plastic waste and 8% paper waste provides optimal results that meet the subgrade stabilization criteria, with a CBR value reaching 10.5% on the 11th day. Excessive use of these materials decreases soil density and CBR. This result is caused by a complementary mechanism, where plastic acts as a binder that reduces soil moisture content and plasticity, while paper fibers strengthen the soil matrix through increased cohesion. The synergy of two types of waste in the optimum proportion produces reliable, sustainable, and more economical stabilization performance than traditional alternatives such as cement or lime. Use is suitable for regions with unstable subgrade and high water content, with prerequisites for the availability of waste material, controlling proportions (± 10% plastic, ± 8% paper), homogeneous mixing, and compaction according to technical specifications. This approach offers practical, cost-effective and environmentally friendly solutions to improve road infrastructure

Keywords: plastic waste, paper waste, soil stabilization, California bearing ratio, toll roads, environmental sustainability, subgrade stabilization

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1. Introduction

The development of toll roads often faces challenges related to subgrade stability, especially on soil with high water content and low bearing capacity, which has the potential to cause instability and reduce the performance of the road pavement layers. Such soil is prone to deformation and loss of bearing capacity, which can damage the road pavement layers and shorten the lifespan of the toll road. This issue becomes increasingly relevant with climate change that increases rainfall and worsens soil conditions.

Scientific research on subgrade stability is important to find effective solutions in strengthening and improving such soil, thereby enhancing the bearing capacity and stability of toll roads. Innovations in soil improvement, such as the use of additives or geotextiles, can help address this problem. In addition, this research also contributes to the development of more efficient, environmentally friendly, and sustainable construction standards, which are essential for reducing maintenance costs as well as negative impacts on the environment and society.

The results of research on subgrade stability in toll road construction can provide significant contributions to field practices, particularly in the planning and implementation of more effective and efficient toll road development. One of the main benefits is the development of more appropriate soil improvement methods. This research can produce more innovative soil stabilization techniques, such as the use of additives or geotextiles, which can enhance the bearing capacity of poor subgrade soil. With the application of these techniques, toll road construction can be carried out more safely and durably, while reducing the potential for future damage.

Therefore, studies that are devoted a sustainable solution by using plastic and paper waste as soil stabilization materials for high water content soil are scientific relevance.

2. Literature review and problem statement

Subgrade stability is a critical factor in the construction of toll roads, as it directly influences the durability and functionality of the road in the long term. Previous studies have identified various issues related to the use of conventional stabilizers like lime and cement, particularly in soils with high heavy metal content, which hinder the hydration process and result in inconsistent strength development. For

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example, heavy metals such as copper and zinc can impede cement hydration, causing slow strength gain in tropical latent clay [1]. This issue is compounded by the fact that many regions, including the Probolinggo-Banyuwangi corridor, face challenges with contaminated soils that contain high levels of metals, which are not effectively stabilized by traditional methods. This study aims to address this problem by exploring the potential of using plastic and paper waste as stabilizing agents, which could overcome the limitations of conventional stabilizers affected by heavy metal content.

Research on the stabilization of clay soil with lime and cement shows that while lime offers long-term strengthening, cement provides faster initial strength. However, the hydration rate between the two materials can vary, affecting the final stabilization results [2]. In tropical regions, high humidity often exacerbates this issue, as the hydration process is slower, leading to reduced efficiency in stabilizing the soil. The aspect that has not been extensively explored is the influence of humidity on the hydration rate, which is difficult to measure due to local soil and climate factors, as well as methodological and mathematical difficulties in modeling that variability.

In addition, the stabilization of expansive soil using lime, cement, and fly ash has shown that controlling water content and curing time is very important to achieve effective stabilization. Improper hydration can lead to poor soil strength development [3, 4]. This is caused by methodological difficulties in controlling water content and curing in the field as well as limitations in mathematical modeling that can handle those variables.

The addition of tile waste to the lime mixture has been proven to increase soil strength, but similar to lime and cement, the slower pozzolanic reaction between lime and tile waste requires a longer curing time [5]. The challenge here is the availability and disposal of tile waste, especially in urbanized areas with increasingly complex waste management problems. In addition, methodological difficulties in measuring the direct impact of tile waste management on the environment as well as the longer curing process also become inhibiting factors for further research.

Plastic waste has been identified as a potential stabilizing agent, as studies show that it can increase the carrying capacity of subgrade soils by 50% in high-humped soils [6]. However, there are still several aspects of this issue that have not been explored in depth. One of them is the challenges related to plastic waste processing and high processing costs, which hinder the widespread adoption of plastic waste for soil stabilization. In addition, the management of plastic waste in areas with poor waste disposal infrastructure also becomes a significant environmental issue. The part that has not been extensively explored in this research is practical solutions to address the complexity of plastic waste processing and processing costs, as well as ways to improve waste disposal infrastructure in areas with infrastructure limitations. These constraints may be caused by methodological difficulties in accurately assessing the long-term impacts of using plastic waste in soil stabilization, as well as mathematical challenges in modeling the complex interactions between plastic waste and soil characteristics under various environmental conditions.

Research on biotechnology-based stabilization techniques, such as using microorganisms to alter soil structure, has shown promise in increasing soil carrying capacity by 25% [7]. However, part of the problem that has not been fully explored is the understanding of the complex interaction between microorganisms and soil stabilizing agents. This has not been studied in depth due to objective reasons, namely limitations in obtaining sufficient empirical data regarding the interaction mechanisms. In addition, methodological difficulties also become obstacles, because laboratory testing involving biological and chemical variables in varying field conditions is very complex and requires very specific tools and techniques. Moreover, the mathematical approach to modeling the interaction between microorganisms and soil stabilizing agents requires very detailed data processing and more accurate models, which are still in the development stage to date. Therefore, further research is very much needed to overcome these challenges.

Moreover, the combination of chemical stabilization techniques with mechanical processes has been shown to increase subgrade quality by up to 60% [8]. Nevertheless, the main challenge that has not yet been fully explored is the high cost and the time required for land management, which becomes a significant obstacle to the widespread application of this method. The aspect of the problem that has not been fully explored is how to optimize cost and time efficiency in the application of this stabilization technique without reducing the quality of the resulting subgrade. The reason why this aspect has not been extensively studied may be due to methodological difficulties in accurately evaluating the relationship between cost, time, and soil quality improvement. The use of more complex models and more careful measurements of these variables requires a deeper approach and more thorough analysis, which has not been widely applied in previous research.

While lime and cement have been widely used in subgrade stabilization, their effectiveness is limited in soils with high humidity, a common issue in tropical climates [2, 9]. Although lime and cement have been widely used for stabilization, their effectiveness is limited to certain types of soil, especially those with high moisture content. One aspect of the problem that has not been extensively explored is how to enhance the effectiveness of these materials in soils with high moisture content, which is more common in tropical climates. Some reasons why this aspect has not been extensively researched may be due to methodological difficulties in measuring and testing the effects of high moisture on the stabilization process, as well as mathematical challenges in modeling the complex interactions between stabilization materials and varying soil conditions. In addition, the highly variable tropical climate factors may also pose obstacles to conducting consistent research across various locations.

The problem studied in this research is the use of chemicals combined with organic materials to enhance soil strength, with calcium chloride as an example of the chemical and organic materials as an additive. Although this combination has been proven to increase soil strength by up to 70% [10, 11]. A part of the problem that has not been fully explored is the environmental impact of using those chemicals, particularly in terms of potential pollution caused. This part has not been fully studied, due to objective reasons related to research limitations that are more focused on the effectiveness of soil strengthening rather than its environmental impact. In addition, methodological difficulties in measuring long-term impacts on ecosystems and soil quality also pose challenges that need to be addressed. Therefore, although there is evidence of increased soil strength, further research is needed to balance the technical benefits with the potential environmental risks posed.

Geosynthetic materials have proven to enhance subgrade carrying capacity by up to 80%, but their high cost and the need for proper material selection based on field conditions present obstacles to their widespread application [12]. The problem that has not yet been fully explored is how to reduce the cost of geosynthetic materials and simplify the material selection process that suits specific subgrade conditions. Proper material selection requires complex field condition evaluations and in-depth analysis related to the physical and mechanical properties of the subgrade at various locations. This part has not been thoroughly studied, possibly due to methodological difficulties in integrating various highly variable field variables, as well as limitations in developing predictive models that can accurately account for those factors. In addition, mathematical difficulties in performing cost and material optimization also pose challenges, considering the complexity of interactions between geosynthetic materials and diverse soil characteristics.

The combination of mechanical and chemical stabilization techniques has been proven to increase subgrade quality by up to 65%, although the long-term effects on toll road structural resistance need further investigation [13]. One issue that has not been fully explored is the long-term impact of that stabilization on structural resilience, which requires further research to ensure its sustainability and effectiveness over time. The reason why this aspect has not been fully studied is due to the methodological and mathematical challenges associated with monitoring and analyzing the changes that occur in the long term. Accurate long-term predictive modeling requires more comprehensive data as well as more complex analysis methods, which have not been extensively developed or applied in previous research.

3. The aim and objectives of the study

This study aims is the determining the possibility of stabilizing the subgrade for toll roads adding of plastic and paper waste. The results are expected to provide an environmentally friendly and economic stabilization solution in toll road construction.

To achieve this aim, the following objectives were accomplished:

– evaluate the effect of adding plastic and paper waste on the plasticity and density of subgrade clay with low carrying capacity for toll road construction;

– evaluate the effect of adding plastic waste and paper waste on the carrying capacity of subgrade claws for toll road construction.

4. Materials and methods

The object of this study is the soil stability with high water content and low bearing capacity, which can damage the pavement and shorten the lifespan of the toll road.

The main hypothesis of this study is that the addition of plastic and paper waste to the subgrade soil can increase the strength and bearing capacity of the soil (CBR value) for the stabilization of toll road foundations, compared to subgrade soil that is not added with such waste.

The soil sampling location for the Probolinggo-Banyuwangi toll road at STA 16+800 includes clay soil that has a very high water content (36.5%), with grain size percentages as shown in Table 1.

Table 1

Grain size percentage

Description	Result	Percentage
Percentage passing Sieve No. 200 (75mm)	44.52	%
Percentage of sand fraction (No. 4 > D > No.200)	55.48	%
Percentage of gravel fraction (No. 4 < D)	0.00	%

Table 1 shows that the tested soil samples are dominated by fine sand, while the gravel fraction is very small or even absent altogether. This condition can affect the use of the material in the construction industry. The dominant fine sand in this sample makes it more suitable for use in concrete mixtures or other building materials that require materials with smaller grain sizes. However, the very small presence of the gravel fraction indicates that this soil is less suitable for applications that require large and strong aggregates.

The material used in this study consists of plastic waste (PET – Polyethylene Terephthalate) and paper waste (HVS paper). For testing the Atterberg limits using plastic waste that passes through sieve No. 40 or has a diameter of 0.425 mm, while for compaction and CBR testing using plastic waste that passes through sieve No. 4 or has a diameter of 4.750 mm. Plastic waste is cut through filter No. 4, while filtered until No. 40 for the Atterberg and CBR boundary test. Paper waste, first processed into paper porridge, dried and filtered using the same filter size. Fig. 1, 2 show PET plastic waste material and HVS paper waste.

Fig. 1. Size of plastic passing sieve no.4

Fig. 2. HVS paper waste

Experimental variations using plastic waste (WP) with a percentage of 7%, 10%, and 15%, paper waste (WK) with a percentage of 4%, 8%, and 10%into the original soil (OL), clay soil from STA.16+800 Probolinggo-Banyuwangi Toll Road. The location of Soil Sampling can be seen in Fig. 3.

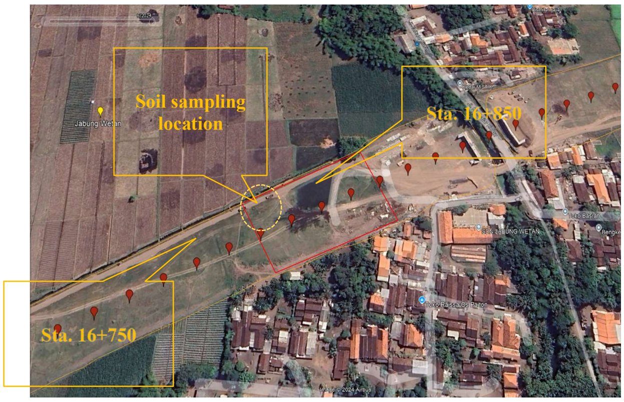

Fig. 3. Location of soil sampling in STA 16+800

Furthermore, the Atterberg limit test is used to assess soil quality for construction, The Atterberg limits test includes the liquid limit, plastic limit, and shrinkage limit. In the Atterberg limits test using the ASTM D 4318 testing standard. The Proctor test is used to determine the optimum moisture content (OMC) and maximum dry density (MDD). Table 2. shows the soil compaction testing method according to the ASTM D 1556 standard.

Table 2

Proctor test standard ASTM D 1556

Testing	Standard				Modified			
Method	A	B	C	D	A	B	C	D
Diameter (mm)	102	152	102	152	102	152	102	152
Mold height (mm)	116	116	116	116	116	116	116	116
Mold volume (cm^3)	943	2124	943	2124	943	2124	943	2124
Tamping rod weight (kg)	2.5	2.5	2.5	2.5	4.54	4.54	4.54	4.54
Drop height (cm)	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5
Number of layers	3	3	3	3	5	5	5	5
Number of tamps per layer	25	56	25	56	25	56	25	56
Material passing sieve (mm)	4.75	4.75	1.90	1.90	4.75	4.75	4.75	4.75

In this research, the modified compaction method A will be used, namely using a mold volume of 943, a tamper weight of 4.25 kg with a drop height of 30.5 cm, 5 layers with 25 blows per layer, and using test specimens that pass through No. 4 sieve. with a mold with a diameter of ±102 mm and height of ±116 mm. Then, compaction testing is carried out according to ASTM D 1556 standard. the California bearing ratio (CBR) test is used to measure the carrying capacity of the soil. This test aims to determine the ability of the soil or soil mixture to withstand traffic loads without experiencing excessive deformation. In testing the CBR value using the ASTM D 1883,1987 standard, the corrected load value for each test specimen at penetration of 2.54 mm (0.10 inches) and 5.08 mm (0.20 inches). Table 3. shows the standard load.

Table 3

Standard load

Penetration (mm)	2.5	5	7.5	10.00	12.50
Force (kN)	13.24	19.96	25.15	30.30	34.83
Stress (kN/m^2)	6,900	10,300	13,000	16,000	18,000

As for the equipment that must be prepared for the California bearing ratio (CBR) test, it includes a load frame machine equipped with a load ring and dial gauge, a mold with a diameter of approximately 5.2 cm and height of approximately 12.6 cm, including the connecting neck and base spacer as well as the separator disk, a ram with a weight of 4.54 kg and a drop height of 45.7 cm, a penetration piston/plunger with a diameter of 4.49 cm, a 4 kg load spacer, and a scale with 1 gram accuracy. The curing time for 1, 7, and 11 days is applied to analyze the effect of the hydration and binding process.

5. Results of adding plastic and paper waste as material for the stabilization of subgrade

5. 1. Atterberg limit testing results

To find out the nature of the plasticity of the clay soil, the Atterberg Limit test is carried out to assess the plasticity index and the plastic boundary value.

Plasticity index (IP) is the range of water content in which the soil is still in plastic conditions. Therefore, the plasticity index indicates the nature of the clastic soil. Mixed composition:

1) both blue, orange, gray (100% OL);

2) blue (93% OL + 7% WP), orange (96% OL + 4% WK), gray (89% OL + 7% WP + 4% WK);

3) blue (90% OL: 10% WP), orange (92% OL + 8% WK), gray (82% OL + 10% WP + 8% WK);

4) blue (85% OL: 15% WP), orange (90% OL + 10% WK), gray (75% OL + 15% WP + 10% WK).

Fig. 4 shows the results of research on the relationship between the liquid limit value and the addition of plastic waste and paper.

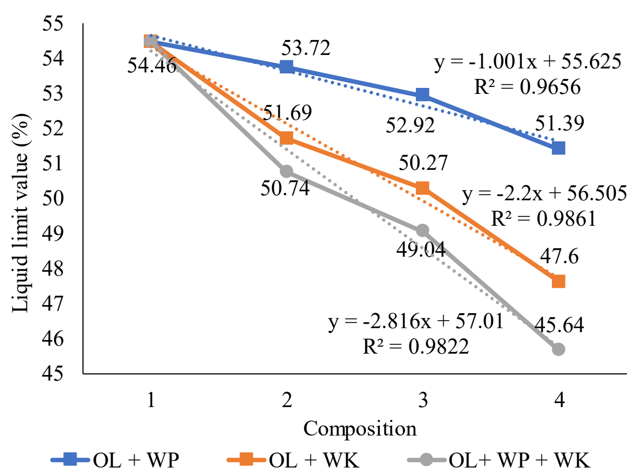

Fig. 4. Relationship of liquid limit value with add plastic waste and paper

The Fig. 4 show that the relationship between the liquid limit value and the composition of subgrade soil mixtures containing plastic waste (WP) and paper waste (WK). Based on the data presented, the liquid limit of the original subgrade soil (OL), initially around 54.46%, decreases as the proportion of plastic and paper waste increases. The mixture with plastic waste (OL + WP) shows a steady decline in liquid limit from 54.46% to 51.39% in the fourth composition, with the regression equation $y = -1.001x + 55.625$ and $R^2 = 0.9656$, indicating a good linear relationship between the plastic waste proportion and the decrease in liquid limit. On the other hand, the mixture with paper waste (OL + WK) exhibits a sharper decrease, starting at 53.72% in the first composition and reaching 47.6% in the fourth, with the regression equation $y = -2.2x + 56.505$ and $R^2 = 0.9861$, showing that paper waste is more effective in reducing the liquid limit compared to plastic waste. Additionally, the combination of plastic and paper waste (OL + WP + WK) leads to the most significant decrease in liquid limit, from 52.92% in the first composition to 45.64% in the fourth, with the regression equation $y = -2.816x + 57.01$ and $R^2 = 0.9822$, indicating a faster decline. This demonstrates the synergy between the two wastes in modifying the soil's physical properties. This phenomenon indicates that adding plastic and paper waste reduces soil plasticity, increases cohesion, and decreases moisture content, making the soil more stable and suitable for use in toll road construction, especially in soils with high water content and low load-bearing capacity.

Fig. 5 shows the results of the plastic limit testing plus stabilization material in the form of plastic waste and paper waste.

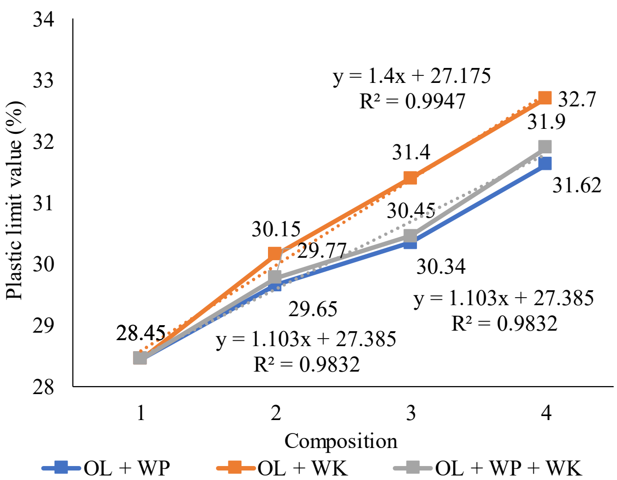

Fig. 5. Relationship of changes in plastic limit value with add plastic waste and paper

Fig. 5 shows the relationship between the plastic limit value and the composition of subgrade soil mixtures containing plastic waste (WP) and paper waste (WK). The plastic limit (PL) of the soil increases as the proportion of waste materials rises. For the OL + WP mixture, the PL starts at 28.45% in composition 1 and gradually increases to 30.34% in composition 4, following a positive linear trend with the regression equation ($y = 1.103x + 27.385$) and ($R^2 = 0.9832$). Similarly, the OL + WK mixture shows an increase from 29.65% to 31.4%, with a slightly stronger positive correlation, indicated by the regression equation ($y = 1.4x + 27.175$) and ($R^2 = 0.9947$). The OL + WP + WK combination results in the highest increase, starting at 29.77% and reaching 31.62% in composition 4, with the same regression equation as the plastic waste mixture, ($y = 1.103x + 27.385$), and ($R^2 = 0.9832$). These trends suggest that both plastic and paper waste enhance the plasticity of the soil, with paper waste having a slightly greater effect. The combination of both waste materials results in the highest plastic limit values, indicating that the addition of waste materials increases the soil's plasticity, potentially affecting its performance in road construction applications.

Fig. 6 shows a process test to determine the optimal water content (OMC) and the maximum dry density (MDD) of the soil, with a period of 1, 7, and 11 days.

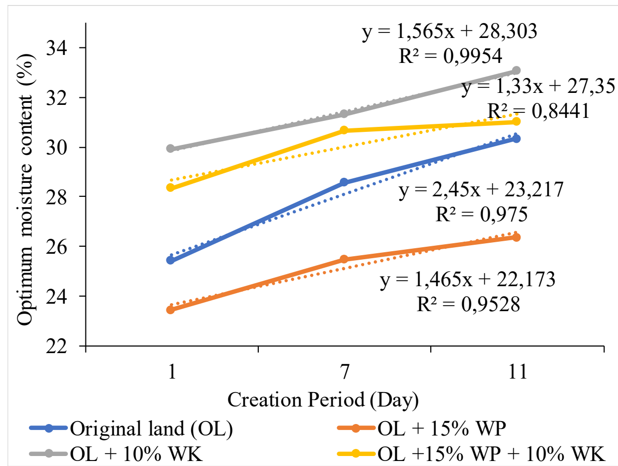

Fig. 6. Relationship of optimal moisture content (OMC) with add plastic waste and paper

Fig. 6 shows the relationship between optimum moisture content (OMC) and creation period for several variations of soil mixtures and additives, namely plastic waste (WP), paper waste (WK), and original soil (OL). Each curve on the graph represents a different combination, namely original soil (OL) added with WP and WK materials. All combinations show a trend of increasing OMC as the production period increases (1, 7, and 11 days). For original soil (OL), the increase in OMC follows the regression equation $y = 2.45x + 23.217$ with $R^2 = 0.975$, which indicates a very strong linear relationship between OMC and the production period. The combination OL + 15% plastic waste (WP) also shows an increase in OMC, but at a lower rate compared to OL, with the regression equation $y = 1.465x + 22.173$ and $R^2 = 0.9528$, which still indicates a strong linear correlation. For OL + 10% paper waste (WK), the increase in OMC is even lower, with the regression equation $y = 1.33x + 27.35$ and $R^2 = 0.8441$, which indicates a weaker linear relationship but still significant. The combination OL + 15% plastic waste + 10% paper waste (WP + WK) shows the lowest increase in OMC, although it has a very strong linear correlation, with $R^2 = 0.9954$, and the regression equation $y = 1.565x + 28.303$.

Fig. 7 shows the relationship between maximum dry density (MDD) and the Creation Period for variations of the original soil mixture with the addition of plastic waste and paper waste. All combinations show a decrease in MDD as the production period increases (1, 7, and 11 days), with a more significant downward trend in combinations containing plastic and paper waste.

In the original soil, the decrease in MDD occurs at a slower rate, with the regression equation $y = -0.0105x + 1.4293$ and $R^2 = 0.9643$, indicating a fairly strong negative linear relationship. The addition of 15% plastic waste accelerates the decrease in MDD, with the equation $y = -0.0191\ln(x) + 1.3899$ and $R^2 = 0.9462$, which describes a sharper negative logarithmic relationship. The addition of 10% paper waste further accelerates the decrease, with the equation $y = -0.0221\ln(x) + 1.3881$ and $R^2 = 0.9698$, showing a steeper decline in MDD compared to plastic waste. The combination of 15% plastic waste and 10% paper waste shows the most significant decrease in MDD, with the equation $y = -0.0231\ln(x) + 1.3832$ and $R^2 = 0.9801$, which indicates a very sharp decline over time.

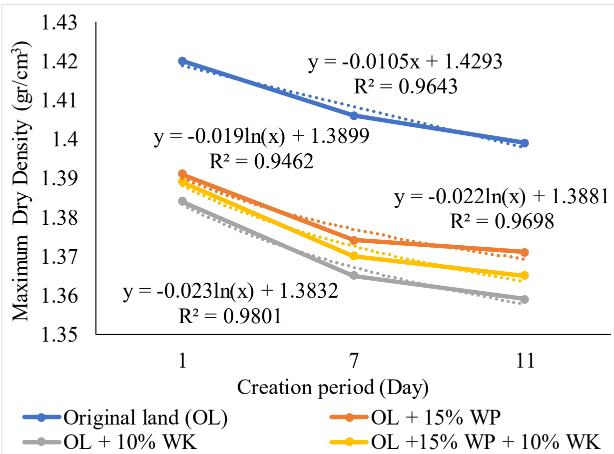

Fig. 7. Relationship of maximum dry density (MDD) with add plastic waste and paper

The phenomenon that occurs shows that the addition of plastic and paper waste causes a faster decrease in MDD compared to the original soil, especially in their combination. This is likely related to the water absorption properties of these waste materials, which make the material lighter and reduce its dry density. With increasing production periods, these materials absorb more water, leading to a greater decrease in MDD.

5. 2. California bearing ratio (CBR) test

To find out the carrying capacity of the soil, CBR testing is carried out in unsoaked and soaked conditions.

Fig. 8 shows the California bearing ratio (CBR) test results in unsoaked conditions, testing is carried out on several additional variations of plastic and paper waste.

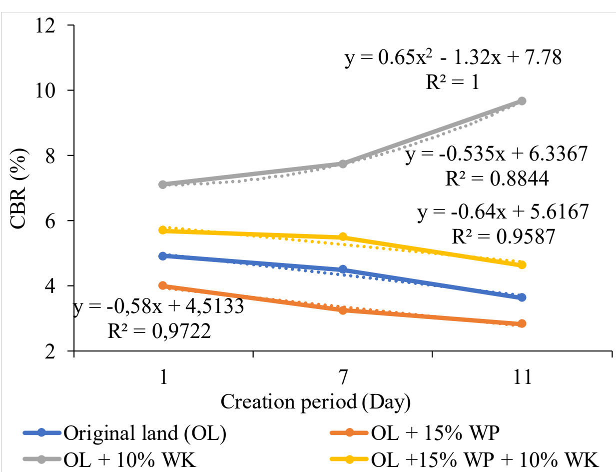

Fig. 8. California bearing ratio (CBR) test results in unsoaked conditions

Fig. 8 shows the results of the California bearing ratio (CBR) testing in unsoaked conditions for the original soil mixture with plastic waste and paper waste for three curing periods (1, 7, and 11 days). For original soil, the data shows a clear trend of increasing CBR as the curing period increases. The quadratic regression equation ($y = 0.65x^2 - 1.32x + 7.78$) with ($R^2 = 1$) indicates a very strong and perfect relationship, where the CBR value continues to increase with longer curing periods. This indicates that the original soil experiences an increase in strength after a certain time, which may be related to natural compaction processes or other changes in physical properties.

In contrast, for OL + 15% waste paper, the observed trend is a decrease in CBR as the curing period increases. In this graph, there are three distinct linear trends, each with increasingly steeper slopes. The regression equations generated for each trend are ($y = -0.535x + 6.3367$) with ($R^2 = 0.8844$), ($y = -0.64x + 5.0167$) with ($R^2 = 0.9587$), and ($y = -0.58x + 4.5133$) with ($R^2 = 0.9722$). These three equations show a strong linear relationship between the curing period and the decrease in CBR in soil added with 15% WP, with the CBR decline becoming steeper over time. These results indicate that adding 15% waste paper to the original soil changes the soil's strength behavior, which can lead to a reduction in the soil's bearing capacity (CBR) over time. The decrease in CBR in this mixture is likely caused by chemical interactions between waste paper and soil components that can affect the soil structure as well as the compaction process that occurs during the curing period. Further analysis is needed to understand the factors influencing this CBR decline and potential improvements or further modifications to the soil mixture with the addition of materials like waste paper.

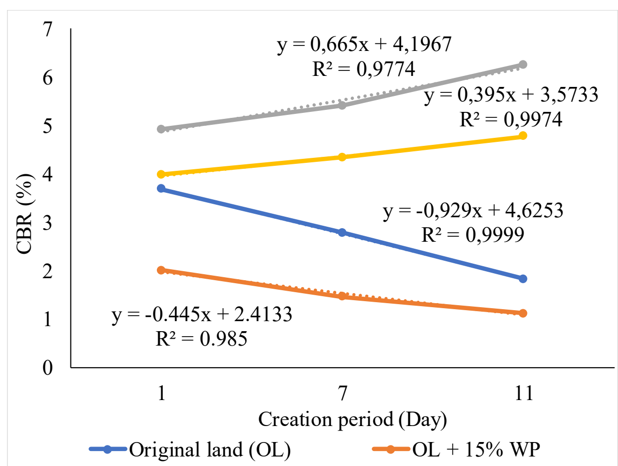

Fig. 9. California bearing ratio (CBR) test results in soaked conditions

Fig. 9 shows the results of CBR testing in soaked soil with various mixtures of ingredients and curing periods (1, 7, and 11 days). Data analysis shows different trends for each soil mixture. For original soil, the data shows a consistent increase in CBR as the curing period increases. With the regression equation $y = 0.665x + 4.1967$ and $R^2 = 0.9774$, a strong linear relationship is evident between the curing period and CBR increase, indicating an increase in soil bearing capacity over time. In contrast, OL + 15% WP shows a sharp decline in CBR with the regression equation $y = -0.929x + 4.6253$

and $R^2 = 0.9999$, which indicates a very strong linear relationship and suggests that adding 15% waste paper causes a reduction in soil bearing capacity over time. OL + 10% WP shows a similar trend, but with a milder rate of CBR decline. The regression equation $y = 0.395x + 3.5733$ and $R^2 = 0.9974$ indicates a still quite strong linear relationship, but with a decline not as rapid as the mixture with 15% WP. Finally, the OL + 15% WP + 10% WK mixture shows a sharper CBR decline compared to the other mixtures. The regression equation $y = -0.445x+2.4133$ with $R^2 = 0.985$ indicates a significant decline, which is likely caused by more complex interactions between waste paper and waste plastic, affecting the soil structure in a faster and more drastic way. Overall, these results indicate that adding additives such as waste paper and waste plastic can affect soil strength behavior in different ways, with mixtures containing more additives showing a faster CBR decline over time.

6. Discussion of utilization of plastic and paper waste for subgrade stabilization

Fig. 4 shows a significant change in the liquid limit (LL) along with the addition of plastic waste and paper waste in the soil mixture. This indicates the presence of synergy between the two types of waste in modifying the physical properties of the soil. This faster reduction can be explained by the interaction between plastic and paper that mutually reinforces their impact in reducing soil moisture and increasing soil cohesion. The combination of both creates a more stable and durable soil structure, where the physical properties of the soil are improved in a more efficient manner.

This phenomenon indicates that the addition of plastic and paper waste can reduce soil plasticity, which in turn increases cohesion and reduces soil water content. Thus, soil containing this waste mixture becomes more stable, making it more suitable for use in toll road construction, especially in soils with high water content and low bearing capacity [14]. This decrease in the liquid limit value indicates that the soil can have better strength and higher stability when plastic and paper waste is added, which is an attractive solution for improving the quality of base soil in large construction projects.

Fig. 5 shows that the addition of plastic waste and paper waste affects the plastic limit (PL) value in the soil mixture. The results of this research show that the plastic limit of the soil increases along with the addition of the proportion of waste material added. Based on the presented data, the OL + WP mixture shows an increase in PL value from 28.45% in the first composition to 30.34% in the fourth composition. This indicates a strong positive linear relationship, where the more plastic waste added, the greater the soil's plastic limit value. The addition of plastic to the soil appears to increase the soil's plasticity, meaning the soil becomes more susceptible to moisture changes and more easily deformed.

For the OL + WK mixture, there is a greater increase in the PL value, starting from 29.65% in the first composition and reaching 31.4% in the fourth composition. This indicates that paper waste has a greater influence in increasing the soil's plastic limit value. This is caused by the properties of paper waste that more easily absorbs moisture and enhances interactions between soil particles, thereby increasing its plasticity.

In the OL + WP + WK mixture, which combines both types of waste, the plastic limit experiences the greatest increase, starting from 29.77% and reaching 31.62% in the fourth composition, meaning there is a synergistic effect between plastic and paper, with the effect not much different compared to the plastic mixture alone. Nevertheless, the combination of both types of waste results in a higher plastic limit value, indicating that both materials contribute to increasing soil plasticity simultaneously. This is similar to research [15], which states that a decrease in soil density causes an increase in PL.

Fig. 6 shows the addition of plastic waste (WP) increases the OMC value, with a mixture of OL + 10% WP shows the highest OMC value of around 31%. This result shows that the addition of plastic and paper waste affects the soil's ability to absorb water, with plastic reducing the rate of OMC increase and paper slightly increasing water absorption, although not as effectively as the original soil [16]. The combination of both shows a more moderate increase, which indicates that both materials can modify soil moisture properties in a more controlled and stable manner.

Fig. 7 shows that MDD can be influenced by WP andWK. This is because This phenomenon can be explained by the water absorption capacity from plastic and paper waste. The longer the production period, the more water is absorbed by these materials, which causes the soil to become lighter (reduced MDD) because the materials add water volume to the mixture but do not contribute to a sufficiently significant increase in mass. As a result, the faster decrease in MDD in mixtures with plastic and paper is caused by a combination of the physical properties of these materials, namely their low capacity to increase soil density, even though they absorb moisture over time. Conversely, a decrease in MDD with a higher proportion of plastic waste is also a phenomenon that has been widely recorded in the study of the effect of plastic waste on soil density [17].This leads to lighter soil with lower dry density, which has implications for the strength and stability of the soil, especially in road construction or other infrastructure applications.

Fig. 8. shows that the physical properties of plastic waste and paper waste affect the California bearing ratio (CBR) of the soil. Results of California bearing ratio (CBR) testing under unsoaked conditions for a mixture of original soil with the addition of plastic waste and paper waste over three compaction periods (1, 7, and 11 days). The test results show that the original soil experiences an increase in CBR value as the compaction period increases, indicating a very strong and perfect relationship between the compaction period and the CBR increase. This indicates that the original soil experiences an increase in strength after a certain compaction period, which is likely related to the natural compaction process or other physical changes in the soil. This research aligns with previous studies which state that plastic waste has a small influence on CBR [18, 19], while paper waste has a greater impact on decreasing CBR.

Fig. 9 indicates that the addition of additives such as paper and plastic waste can affect soil strength behavior in different ways. Mixtures containing more additives, especially paper waste, show a faster CBR decline, caused by increased water absorption, chemical changes in the soil structure, and reduced soil compaction ability. This decline indicates that the use of additives like plastic and paper waste can reduce the soil's bearing capacity, which must be considered in construction applications where soil strength is crucial.

This study shows that WP can even increase the value of CBR by strengthening soil structure, which is consistent with previous research, which states that additional materials, such as WP, can increase soil cohesion and CBR [20]. This process takes time, so the CBR value continues to increase over time. Overall, this additional material increases the carrying capacity of the soil by reducing excessive humidity and improving bonds between soil particles.

This study has several limitations, so the scope of the study remains focused; this study does not include testing chemical elements in plastic and paper waste. The testing included soil testing (water content, Atterberg limit, and CBR soaked and unsoaked). In addition, the sample payment period for CBR testing was carried out for 1 day, 7 days, and 11 days.

One of the shortcomings of this research is the absence of long-term observation of soil mixture behavior in various environmental conditions, such as varied temperatures and humidity. Further research can include various types and proportions of waste material to provide a more comprehensive understanding of their interactions with the soil, so the results are more applicable in the real world.

In addition, methodological challenges such as difficulties in mixing consistent waste materials and variations in large-scale results need to be considered. The use of more complex modeling techniques, such as numerical simulations, can help predict the impact of waste mixtures on the nature of the soil more accurately in the future.

7. Conclusion

1. The addition of 10% plastic waste and 8% paper waste significantly increases the bearing capacity (CBR value) and strength of the subgrade soil, meeting the subgrade stabilization criteria. This combination reduces soil plasticity and increases cohesion, providing a more economical and environmentally friendly stabilization solution compared to conventional materials.

2. The combination of plastic and paper waste improves the stability of subgrade soil with an optimal CBR value of 10.5% on the 11th day. Although excessive use can reduce soil density, this combination still provides a more environmentally friendly, sustainable, and economical alternative.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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