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THE CORRELATION OF LIMESTONE PHYSICAL/MECHANICAL PROPERTIES AND KARST GEOMORPHOLOGY, KARANGASEM AREA, PALIYAN DISTRICT, GUNUNGKIDUL REGENCY, INDONESIA

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ABSTRACT

Karangasem Village, Paliyan District, Gunungkidul Regency, Indonesia is located in the Gunungsewu area, which has been designated as a Global Geopark by UNESCO (UGG = Unesco Global Geopark). This village has an interesting natural landscape, in the form of karst geomorphology which is reflected in the presence of dome and conical hills, dolines, uvala, locva, and caves, which can be promoted as one of the geosites in the Gunungsewu geopark. One aspect of a geopark is science. Thus, geomorphology in the Karangasem area needs to be elaborated from a scientific perspective. The aim of this study is to characterize the relationship between geomorphology and limestone physical/mechanical properties that make up this landform. The methods applied are surface mapping, geomorphological and petrological assessment, physical/mechanical properties testing, and correlation analysis. The research results show that there are three units of lithology, namely reef limestone unit, bedded limestone unit, and marl unit. The three rock units are characterized by their different values of unified compressive strength (UCS), Schmidt hammer hardness, and Mohs scale hardness. Landforms of the study area can be classified into karst hills, karst undulating, and karst plain. This geomorphology is very strong correlated with physical/mechanical properties and lithological units, with correlation coefficient (R^2) > 0.9. The strong, hard, and resistant rocks form rough relief, while weak, soft, and not resistant rocks produce smooth relief.

Key-words: *Geomorphology, Karst, Geopark, Limestone, Physical/Mechanical properties, Correlation*

1. INTRODUCTION

Karangasem in one of the villages included in the Paliyan District, Gunungkidul Regency, Indonesia. This area is located in the Gunungsewu karst range, which has been designated as a Global Geopark by UNESCO (UGGps = Unesco Global Geopark). This village has an interesting natural landscape, in the form of karst geomorphology which is reflected in the presence of domes, cones, dolines, uvala, polje, locva, and caves (Ford & Williams, 1989, White, 1988). This exotic scenery is very potential to be developed and promoted as one of the geosites in the Gunungsewu geopark area.

A geopark should provide scientific educational aspect, especially from earth sciences points of view. This is intensely relevant since education roles as one of the three principal pillars of UGGps (Henriques & Brilha, 2017; Catana & Brilha, 2020; Lakatos et al., 2023; Nyulas et al., 2024). Moreover, in the Karangasem area, there are specific landscape features, namely karst, which is a valuable subject to explore its scientific aspects for academic purposes (Masilela & Beckedahl, 2022).

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It is supposed that there a relationship between the forms of karst morphology and the physical/mechanical properties of the rocks that make it up. Thus, the association among geomorphology and physical rock properties in the Karangasem area needs to be elaborated from a scientific perspective.

The objectives of this study are to characterize the relationship between limestone physical/mechanical properties that make up the landform and karst geomorphology of the area. What is meant by physical/mechanical properties in this study is unified compressive strength (UCS), Schmidt hammer rebound hardness (SH), and Mohs scale scratches hardness (MS) of the rocks.

Location of the study area is in the coordinate of X: 445500 – 451000 E, and Y: 9118000 – 9109000 S, or latitude of 107^{o}26’30”– 107^{o}50’5.5” E, and longitude of 82^{o}01’21” – 82^{o}06’21” S. Administratively the study area belongs to Paliyan district, Gunung Kidul regency, Yogyakarta Special Region, can be reach easily, about 120 km distant from Yogyakarta city by riding either motorcycle or mobile car (**Fig. 1**).

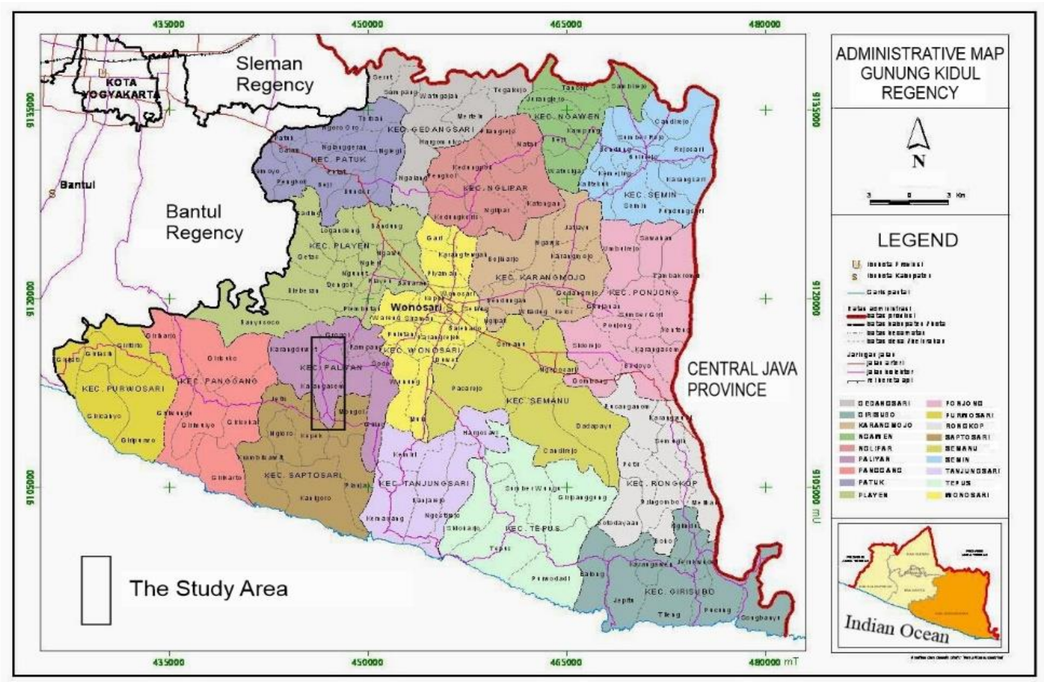


Fig. 1. Location map of the study area.

2. STUDY AREA

2.1. Geography and Geology

Karangasem village have an area of 1,268 Ha (Anonymous, 2022; Anonymous, 2018). Physiographically, Karangasem village, is situated in the Southern Zone of the Southern Mountains of Western East Java (Van Bemmelen, 1949). This zone is known as *Gunungsewu* (Javanese: A thousand mountains). It is a karst topography with a height ranges 120 m - 300 meters above sea level. As mentioned above, Gunungsewu has been designated as a UNESCO Global Geopark in 2015 (Cahyadi, 2017). It is a classic tropical karst that is built by limestone formations. In relation with that, the karst features of this area need to be protected by such a geoscientific study and geoconservation activities (Kubalíková, 2016). Karangasem Village has a tropical climate, the average rainfall from the years 2010 to 2022 is 1,954.43 mm/year with an average number of rainy days is 130 days per year. Wet months are 7 months, while dry months are around 5 months. The average daily air temperature is 27.7°C, the minimum temperature is 23.2°C and the maximum temperature is 32.4°C. The relative humidity of the air ranges from 80%–85% (https://id.wikipedia.org/wiki/Kabupaten_Gunungkidul).

The Gunungsewu karst topography shows orientation axis of west-east, with a height difference of 10 m to more than 100 m, comprises about 45,000 small and large hills of 50 m - 300 m diameter (Kusumayudha, 2005). Limestone that experiences karstification is characterized by the presence of dissolution cavities, caves, and underground drainage systems. On the surface, there can be found many closed depressions (dolines) and dome-shaped or cone-shaped hills (cone karst) (**Fig. 2**, **Fig. 3**). If the depressions in this karst are covered with an impermeable layer, they will be able to hold water, forming a locva. In Karangasem village there are several lakes, namely Berok Lake, Boromo Lake, Jambeanom Lake, Namberan Lake and Tongtong Lake. Limestone that experiences karstification often leaves rough and sharps rock reliefs, called lapies, or microkarst.


Fig. 2. Cone karst (left). Convex cone karst (right), (Kusumayudha et al, 2018.


Fig. 3. Dome karst (left), Ridge karst (right), (Kusumayudha et al, 2018).

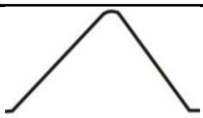
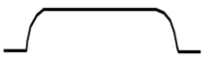
Geologically, Karangasem and the surrounding area are composed of the Wonosari Formation, which consists of reef limestone and bedded bioclastic limestone, The limestone experiences karstification, which is resulted from the interaction between limestone and meteoric water over millions of years (Kusumayudha, 2018; Kusumayudha, et al, 2022). There are two (2) lithofacieses of the limestone included in *boundstone* and *packstone* of reef limestone, and *wackestone* of bedded limestone, deposited from the middle Miocene to the late Miocene epoch. Limestone has a main mineralogical composition consisting of more than 90% calcite ($CaCO_3$), and dolomite ($CaMg(CO_3)_2$). The distribution of the lithofacies is relatively northwest - southeast, with geological tructure shows a homoclinic with an inclination of less than 15^o, to the south and southwest (Kusumayudha, 2018).

2.2. Geomorphology

Geomorphologically, the study area displays a hilly karst topography, with a height difference of 10 m - 30 m, and the hills diameter ranges from 50 m - 200 m. Macro karst is found in the form of conical to dome-shaped hills, dolines, uvalas, and locvas, while micro karst and lapies which classified as exokarst are also found in the study area.

Table 1.

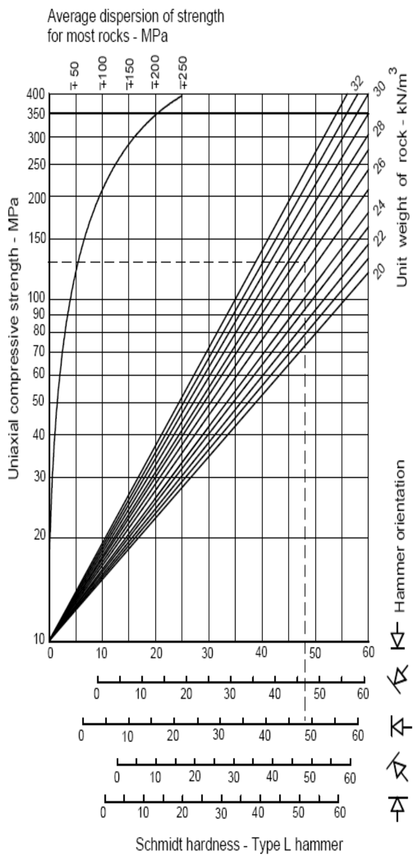
Model of the influence of lithologic physical-mechanical properties and geologic structures to positive relief karst morphology (Kusumayudha, et.al, 2015).

Morphology			Morphogenesis		
Lithology	Morphographic	Morphometric	Active morphostructure (geologic structures)	Passive morphostructure (physical properties)	Morphodynamic (exogenic processes)
Dominated by bedded limestone, grainstone and packstone	 Cone	-Steep slope -Slope: 30º-45º -Relatively top sharp -Height: 30-90 m	-Joint -Thin bedded: < 1 m -Bedding plane inclination: > 5º	hard, cavernous, lapies, φ = 32-50	Karstification
Dominated by reef limestone, boundstone	 Convex-cone	-Steep slope -Slope: 35º-45º -Top convex -Height: 30-70 m	-Joint -Massive, or thick bedded: > 1m -Bedding plane inclination > 5º	hard, cavernous, lapies, φ = 32-50	Karstification
Caliche limestone, wackestone	 Dome (Sigmoid, Mogote)	-Steep slope -Slope: 30º-45º -Height: 20-50 m	-Joint -Massive or bedded -Relatively horizontal bedding plane: < 5º	hard, cavernous, lapies, φ = 32-50	Karstification Calichification
Caliche limestone, wackestone	 Convex	-Gentle slope -Slope: 12º-20º -Height: 10-30 m	-Joint -With or without bedding plane -Relatively horizontal bedding plane: < 5º	weak, chalky, uncavernous φ = 17-31	Calichification
Bedded limestone, caliche limestone	 Ridge	-Moderately inclined -To steep slope -Slope: 20º-35º -Top plane -Height: 10-30 m	-Joint -Thin bedded: < 1 m -Relatively horizontal: < 5º	hard, cavernous, lapies, φ = 32-50 Weak, chalky, uncavernous φ = 17-31	Karstification Calichification

Cone, dome and ridge shapes as modeled by Kusumayudha, et al., 2015 (**Table 1**) can be found in the Karangasem area. The karst geomorphology of Gunungsewu has been entering in the maturity stage, marked by the intensiveness of carbonate dissolution process, resulting in the forms of caves with various ornaments such as stalactites, stalagmites, cinterflags, and flowstones. Referring to the model mentioned above (Kusumayudha, et.al, 2015), hills in the study area can be classified into cone, convex cone, and dome.

3. DATA AND METHODS

The research was applying analytical, descriptive field investigation and mapping, rock sampling, in situ rock physical testing, and laboratory rock mechanical testing. In the assessments, it utilizes two types of data, both secondary includes a variety of information from the results of existing research and studies, and primary data that were obtained through surveys, investigations, field mapping both geological and geomorphological (Korodi & Hofmann, 2016) and in situ or laboratory testing. Activities have been done including geomorphological mapping, lithological - stratigraphical identifications, and petrographic description to determine the limestone facieses. Rock sampling was also carried out for petrological and petrographical assessment, as well as 10 (ten) measurements for rock physical/mechanical properties. The method used to determine the strength of the rock, in this case limestone is unconfined compressive strength (UCS) test (Wang & Wan, 2019, Vračević, et.al, 2019). In situ physical properties testing was done by using *Schimdt hammer* for rebound hardness, and *Mohs scale* apparatus to determine the scratch hardness of the limestone (**Fig. 4, Fig. 5**). Furthermore, after UCS test has done, the UCS value was then used to estimate the value of internal friction angle using the following table (**Table 2**).



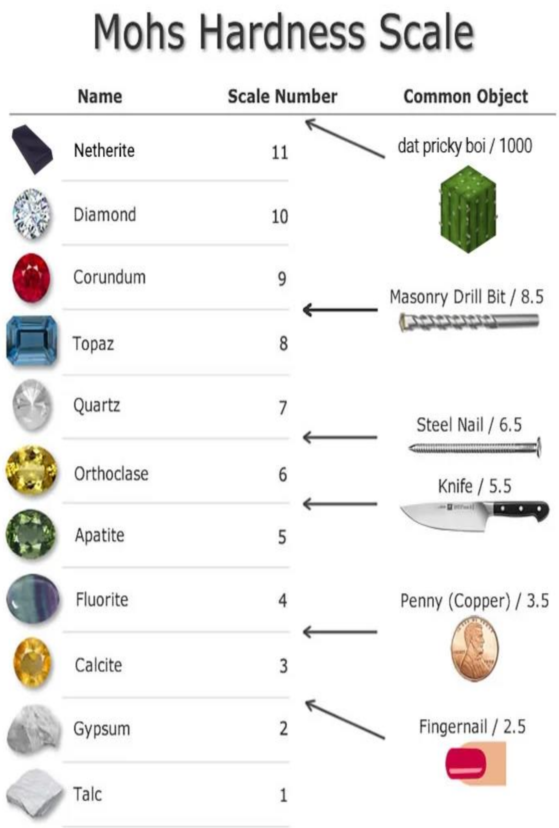


Fig. 4. Schmidt Hammer rebound chart (left) (Jumikis, 1983, Vračević, et.al, 2019), and **Fig. 5.** Mohs scale (right). (Perkins, 2020).

Compressive strength or compressive strength is the ability of rocks or materials to withstand pressure that tends to reduce their size (Bajpayee, et al., 2013). Compressive strength can also reflect the ability of rocks to withstand loads that can cause them to change shape and/or size (Goodman, 1989, Ning, et.al, 2018). Therefore, compressive strength can be used as one of the parameters in the discussion of rock geomorphology including its morphostructure (Suwarno, et.al, 2020). Another rock property taken into account in this study is the friction angle, which is defined as the slope formed between the resultant force exerted by an object and the surface on which the object rests (Goodman, 1989, Franklin & Dusseault, 1989). Of course, this will be related to how a material (rock) reacts to friction or erosion. So, this can also be used as a parameter when rocks experience friction during erosion. Rebound hardness (Schmidt) reflects the hardness of the rock surface, and the resistance of minerals and/or rocks to penetration (Goodman, 1989). On the other hand, scratch hardness is the resistance of minerals or rocks to scratches (Perkins, 2020). This is assumed to be effective in measuring the hardness of minerals/rocks to erosion. Pressure, friction, and scratches certainly influence geomorphological processes.

Table 2.

Correlation of friction angle and UCS (Mahdevari, et.al, 2020)

Rock types	Friction angle (deg.)	Applicable UCS Range (MPa)
Shale and Claystone	$\varphi = 0.090 \text{ x UCS} + 15$	10 – 80
Siltstone and Sandstone	$\varphi = 0.145 \text{ x UCS} + 25$	40 – 200
Limestone	$\varphi = 0.090 \text{ x UCS} + 33$	40 – 200

4. RESULTS AND DISCUSSIONS

Limestone Facieses and Physical/mechanical properties

Geologically, the rocks that make up the research area consist of Wonosari reef limestone units, Wonosari bedded limestone units, Kepek marl units. Referring to Dunham (1962) classification, the Wonosari reef limestone unit consists of *boundstone* and *grainstone*, while the Wonosari bedded limestone unit consists of *packsote* and *wackestone* (**Table 3**).

Tabel 3.

Description of the Gunungsewu limestone facies

No.	Lithofacies (Dunham, 1962, Wilson & Lloyd, 1995)	Description
1	*Boundstone*	Consisting of fossil algae shells with a diameter of 3 - 7 cm and large foraminifera measuring 0.5 - 3 cm, coral, with a growing structure, contains carbonate mud <10%
2	*Grainstone*	Consisting of fossil algae shells with a diameter of 3 - 7 cm and large foraminifera measuring 0.5 - 3 cm, coral fragments, containing carbonate mud <10%
3	*Packstone*	Composed of large foraminifera fossil shells with a diameter of 0.5 - 3 cm, closed packaging, containing carbonate mud <10%
4	*Wackstone*	Consisting of fossil shells of large foraminifera with a diameter of 0.2 - 1 cm, containing between 30 and 50% granules, packed open with carbonate mud between 50 sd 70 %.

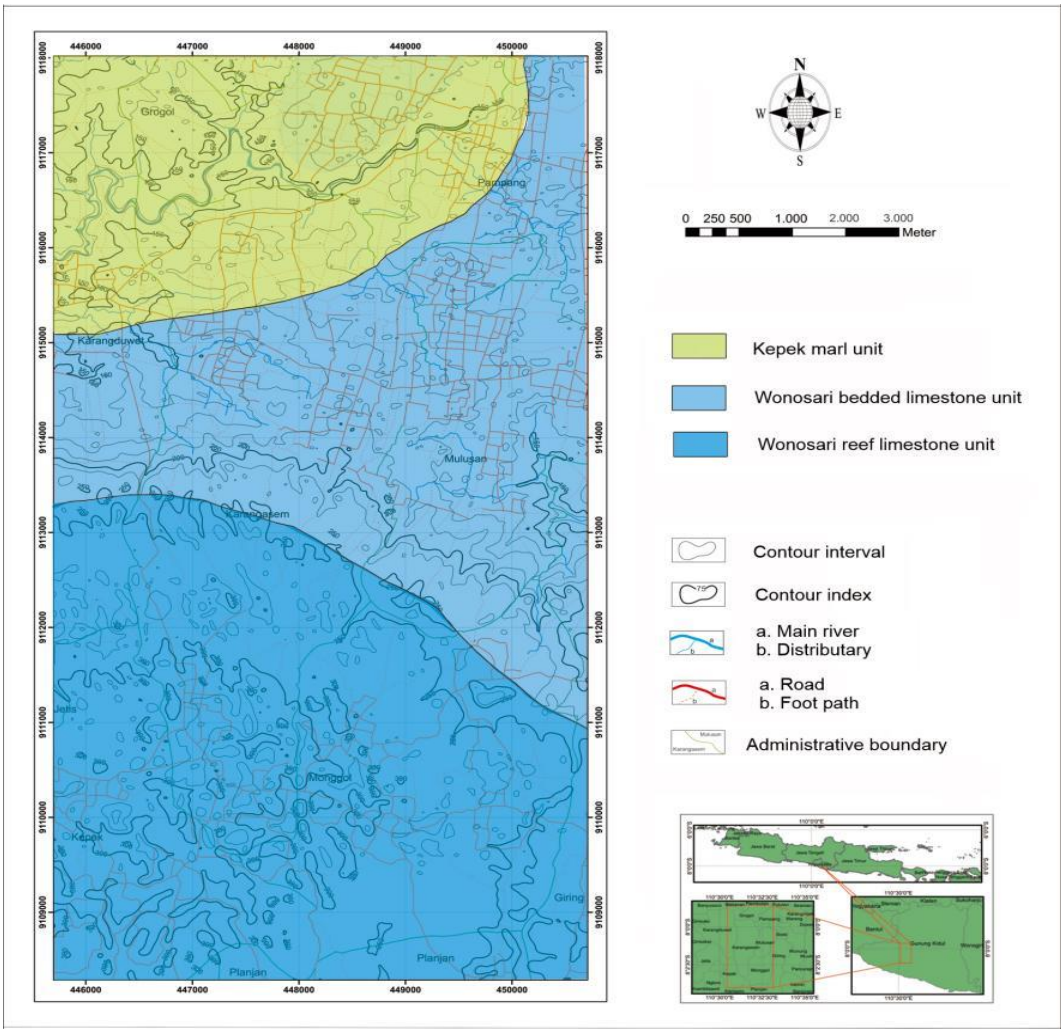


Fig. 6. Lithology distribution map of the Study Area.

The Wonosari reef limestone and Wonosari bedded limestone are Middle Miocene - Pliocene in age (Kusumayudha, 2005). The Kepek marl unit consists of marl, shale, mudstone and limestone, with an ideal layering structure. The layer thickness for each lithology ranges from 10 cm – 50 cm. The age of the Kepek marl unit is Pliocene – Pleistocene (Kusumayudha, 2005).

Stratigraphically, the relationship between the Wonosari reef limestone and Wonosari bedded limestone units is different facies, interfingering, as well as between the upper part of the Wonosari bedded limestone unit and the lower Kepek marl unit (Suyoto, 1994). The lithological distribution map of the study area is displayed in **Fig. 6.** The limestone facies in the study area, based on the results of physical-mechanical properties testing show different characteristics, between reef limestone units, layered limestone units, and marl units can be described as the following (**Table 4**).

Referring to **Table 2** (Mahdevari, et.al, 2020), the physical-mechanical properties of the rocks that make up the research area in dry conditions are as follows (**Table 4**). The results of this estimation are in accordance with the range of internal friction angle values for limestone in general, which is between 35^{o} and 50^{o} (Jumikis, 1983; Ning, et.al., 2018).

Table 4.

Physical and mechanical properties.

No.	Limestone Facies	Physical – Mechanical Properties							
		Compressive Strength (MPa)		Friction Angle (°)		Schmidt Hammer Hardness		Mohs Scale Hardness	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean
1	Wonosari Reef Limestone unit	38-41	40.02	36.42-36.69	36.60	50-62	54.68	4-4.5	4.25
2	Wonosari Bedded Limestone unit	33-35	33.60	35.97-36.15	36.03	36-52	44.75	3.5-4.0	3.75
3	Kepek Marl unit	14 -15	14.12	27.03-27.18	27.05	20-35	25.33	2.25-2.5	2.35

Landforms

The landforms of the study area can generally can be categorized as a karst area, showing varied topography with slopes ranging from flat (0% - 2%) to very steep (40% - 140%) (**Fig. 7**). Likewise, the natural landscape varies, based on observations from North to South, including undulating karst plains in the North, karst plains in the middle, and karst hills in the South.

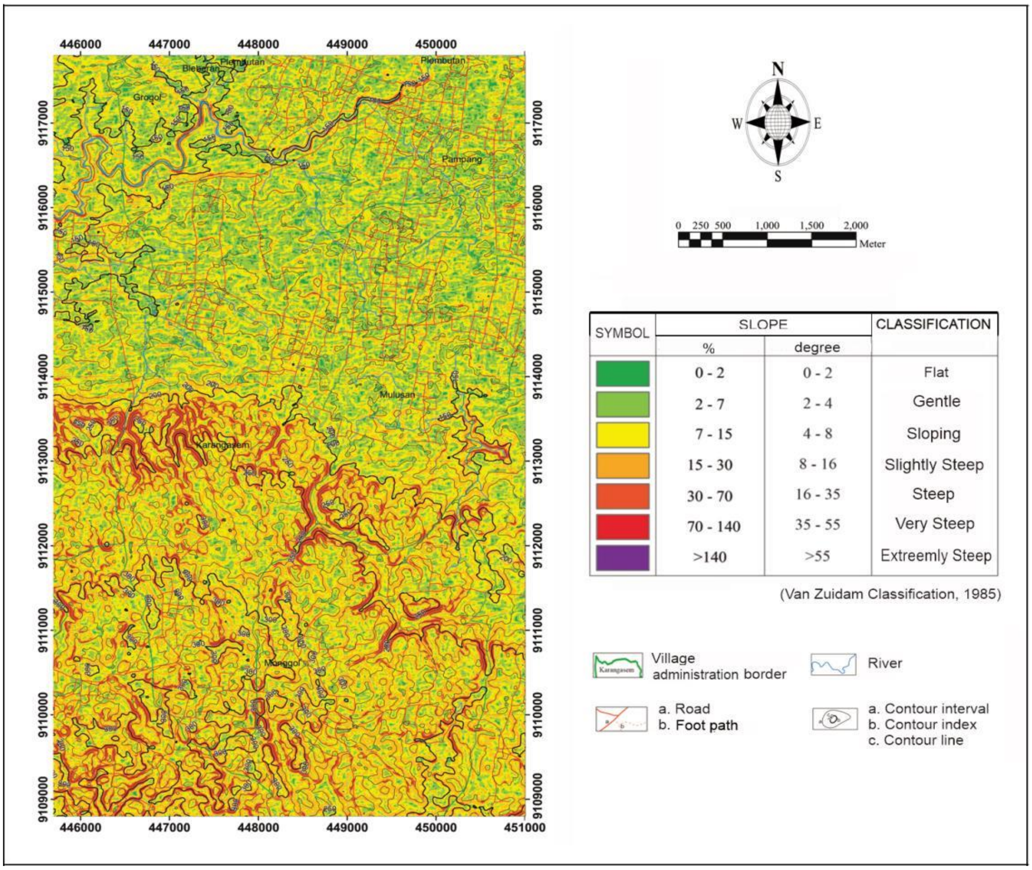


Fig. 7. Slope distribution map of the study area.

Landforms in the research area can be classified (Van Zuidam, 1983) into karst plain unit, karst undulating unit, and karst hills unit (**Fig. 8, Fig. 9**).

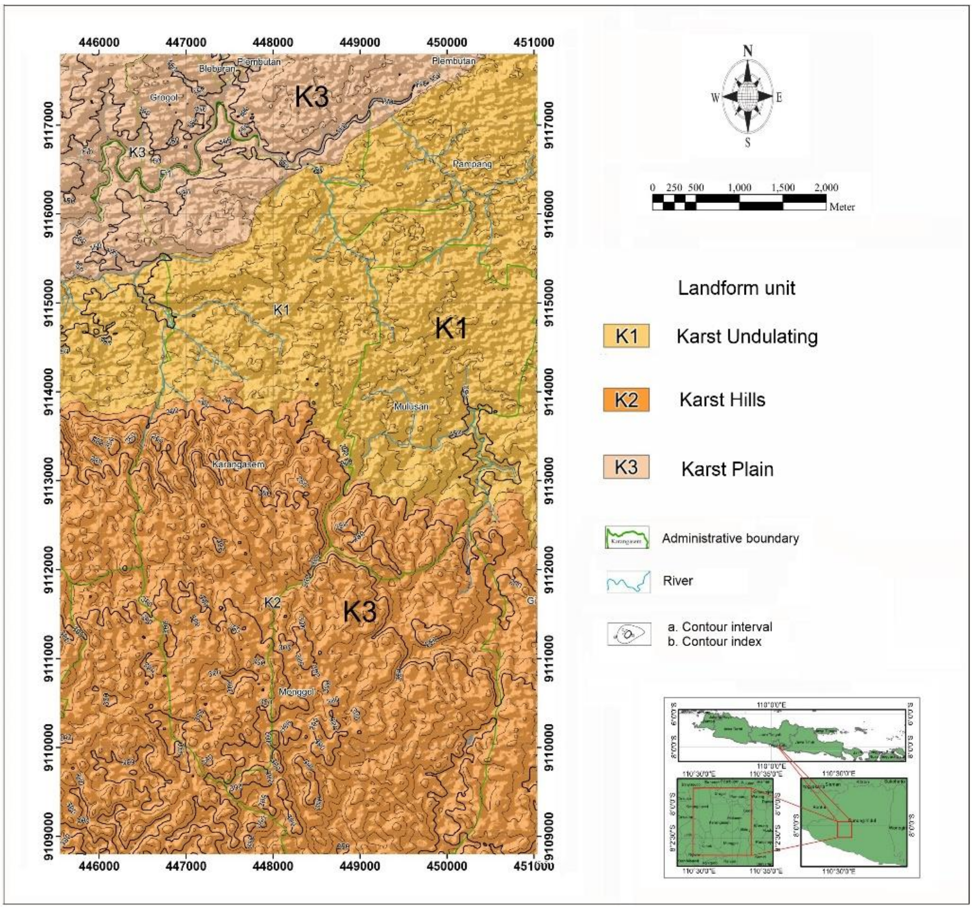


Fig. 8. Geomorphology map of the Karangasem Area.

GEOMORPHOLOGICAL ASPECTS / LANDFORM UNIT	MORPHOLOGY				MORPHOGENETICS			
	MORPHOGRAPHY	MORPHOMETRY			ACTIVE MORPHO - STRUCTURE	PASIVE MORPHO - STRUCTURE	DYNAMIC MORPHO - STRUCTURE	MORPHO - ASSOCIATION
		SLOPE		RELIEF				
		(%)	(°)					
K1 Karst - Undulating	Undulating, gently sloping	0-15	0-8	Low	Uplifting, fissures	Moderate resistance rock: bedded-limestone unit	Weathering, erosion	Karst - hills Karst- plains
K2 Karst - Hills	Hilly, conical, convex, dome	15-70	8-35	High	Uplifting, fissures	High resistance rock: reef limestone unit	Weathering, erosion	Karst - undulating
K3 Karst - Plain	Plain, relatively-flat	0-15	0-8	Low	Uplifting, fissures	Low resistance rock: marl unit	Weathering, erosion	Karst - undulating

Fig. 9. Description of the landform units.

Karst plain morphometric: has a relatively flat, sloping (0% - 15%, 0^o - 8^o), with a height difference of 0 to 2 meters. In this landform unit, surface flow is found, with a wide "U" shaped flow valley cross-section. The karst undulating Morphometric: has a flat to undulating slope level (0% - 15%, 0^o - 8^o), with a height difference of 0 to 3 meters. Plain landform unit is built bedded limestone. In this landform unit, surface flow is not found. Karst hills unit: Morphometric: has a steep slope level (15% - 70%) - sloping (8^o- 35^o), with a height difference of 30 -50 meters, and the developing flow pattern is multibasinal. The hills that make up this landform unit are cone-shaped, cone-shaped with a convex peak, and dome-shaped. The karst hill landform unit is composed of the Wonosari Formation reef limestone unit.

Correlation of physical rock properties and geomorphology

The Karangasem village area stretches along a relative North - South axis, as reflected in the topographic base map. The elevation in the research area ranges from 121 m to 300 m above sea level. Asmentioned previously, the geomorphology of the study area can be divided into karst hills landform unit, karst undulating landform unit, and karst plain landform unit.

As explained in the previous sub-chapter, the lithofacies in the research area consists of the Wonosari reef limestone unit, the Wonosari bedded limestone unit, and the Kepek marl unit, each with its own physical characteristics. Based on the physical and mechanical properties as shown in **Table 4**, the Wonosari reef unit has the highest UCS value compared to other lithofacies units, the Wonosari bedded limestone unit has medium physical/mechanical properties values, and the Kepek marl unit has the lowest physical/mechanical properties. Associated with the geomorphology occupied by each of these rock units, the Wonosari reef limestone unit is characterized by hilly geomorphology with cone-shaped hills, convex cones, and domes. The Wonosari bedded limestone occupies the undulating karst geomorphology, and the Kepek marl is located on the karst plain geomorphology.

Table 5.

Description of landform units in the study area

Description and Characteristics			Landform Unit		
			Karst Undulation	Karst Conical Hills	Karst Plain
Morphology	Morphometry		Undulating	Hilly, depressions	Plains, flat
	Morphometry	Slope	0%-15% (0^o-8^o)	15%-70% (8^o-35^o)	0%-15% (0^o-8^o)
		Relief	Low - moderate	High	Low
Morphogenesis	Active Morphostructure		Uplifting, Fissures	Uplifting, Fissures	Uplifting, Fissures
	Pasive Morphostructure		Bedded - limestone unit: packstone, wackestone	Reef -limestone unit: boundstone, grainstone	Marl, unit: marl, slate, clayston, limestone
	Dynamic Morphostructure		Weathering, erosion	Weathering, erosion	Weathering, erosion
	Morphoassociation		Karst plains, karst conical hills	Karst undulation	Karst undulation

In order to find the correlation of the physical-mechanical properties of limestone composing the landform, the maksimum, the mean, and minimum values of rock properties are plotted into line and x-y diagrams (**Fig. 10, Fig. 11, Fig. 12**).

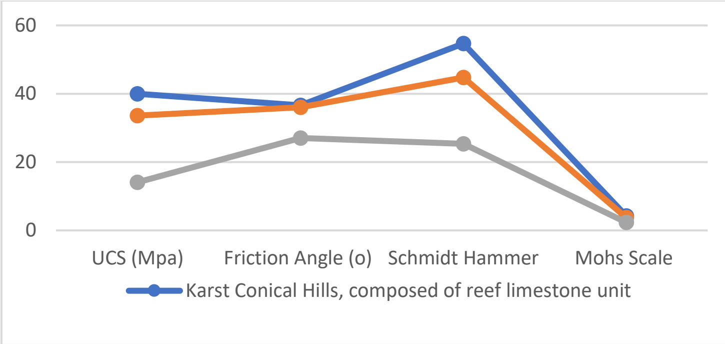


Fig..10. Graphical plots of physical-mechanical characteristics of karst geomorphology.

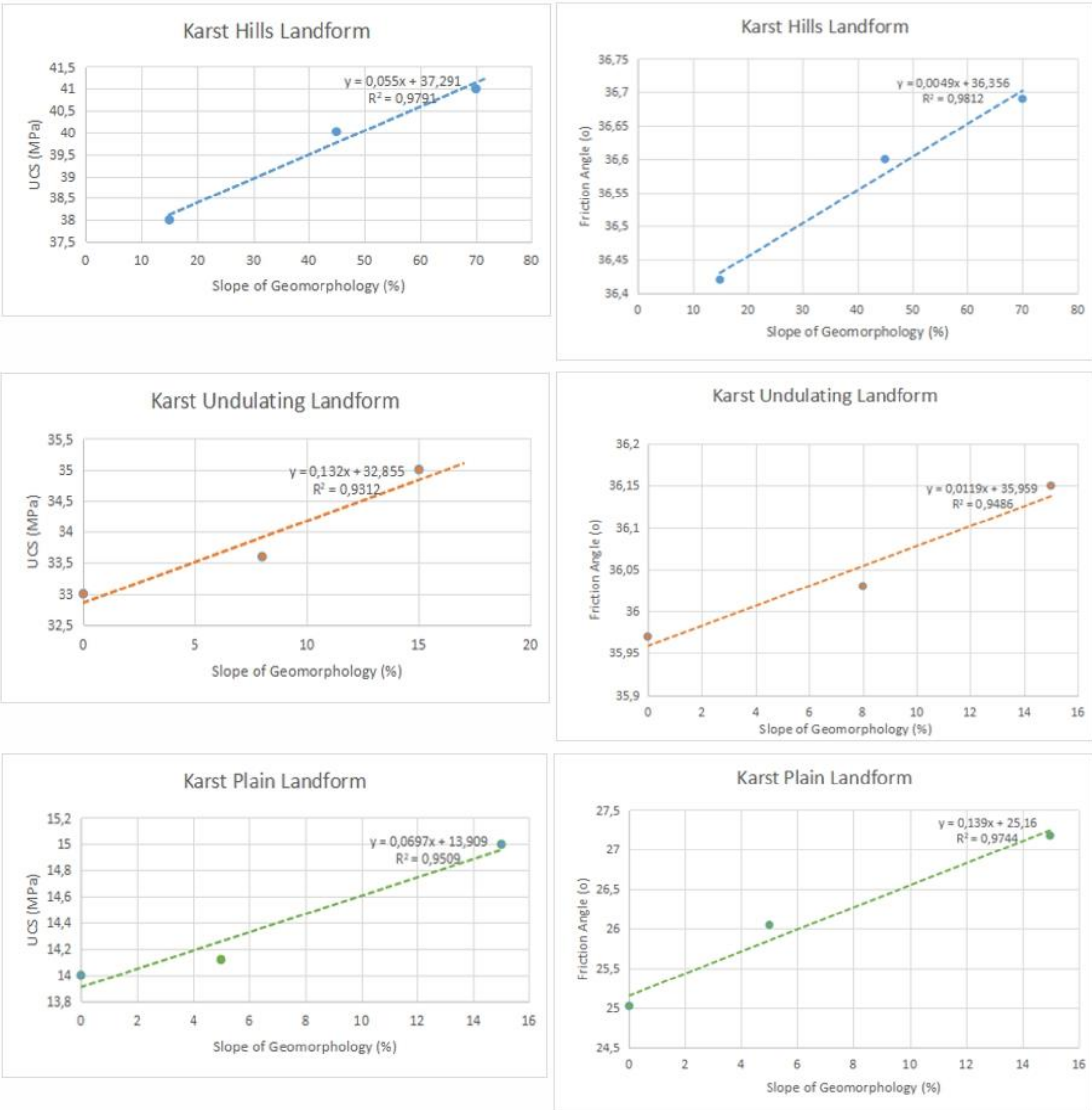


Fig. 11. Correlation of unconfined compressive strength (UCS), friction angle of limestone and karst geomorphology.

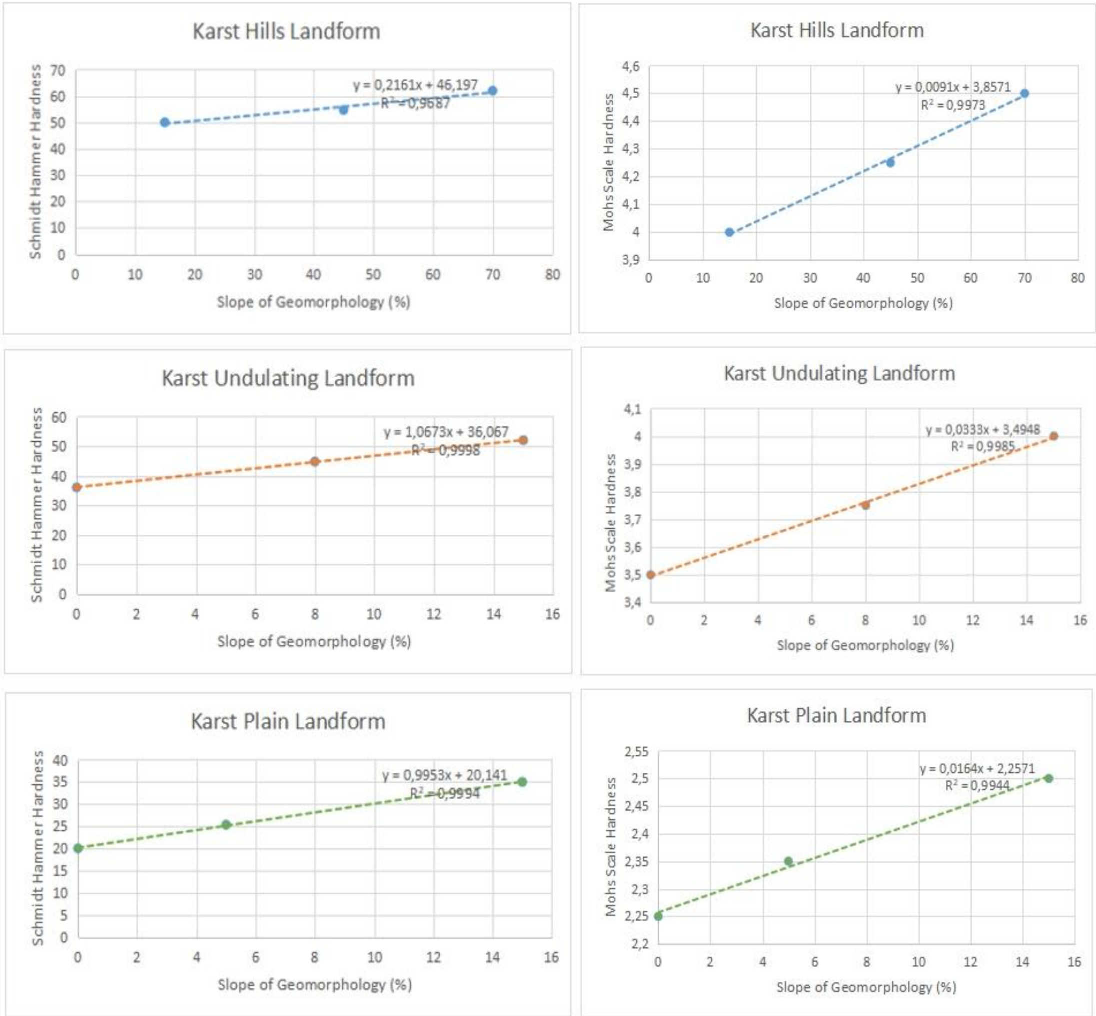


Fig. 12. Correlation of Schmidt Hammer hardness, Mohs Scale hardness of limestone and karst geomorphology.

Referring to **Table 4**, **Fig. 11** and **Fig. 12**, it can be stated that there is a very strong correlation between the physical/mechanical properties values of rocks and the landforms, with the correlation coefficient (R^2) of higher than 0.9 (Fig. 10). The higher the rock properties values (UCS, Friction angle, Schmidt hammer hardness, and Mohs scale hardness) the higher the morphological relief formed, reflected by their slope inclination distributions, and vice versa.

From the discussion above, it can be concluded that the *boundstone* and *grainstone* limestone facies which are reef limestones have the highest strength, hardness, and resistance compared to other lithofacies, forming dome and hill morphologies. *Packstone* and *wackestone* lithofacies which form layered (bedded) limestone units, have moderate strength, hardness, and resistance (intermediate) in morphology forming wavy (undulating) topography. Lithofacies of marl units, have low strength, hardness, and resistance in the exogenous process forming plain topography. Thus, this study supports that strong and hard rocks will form rough relief, while weak and soft rocks will produce smooth relief.

5. CONCLUSIONS

Some clear conclusions can be drawn from the research and discussions.

The lithology of the study area consists of Wonosari reef limestone unit, consists of *boundstone* and *grainstone*, Wonosari bedded limestone consists of *packstone* and *wackestone*, Kepek marl unit, consists of marls, shale, and sandy claystone with limestone intercalation.

Geomorphology of the study area can be classified into karst hills occupied by reef limestone unit, karst undulating compossed of bedded limestone unit, and karst plains consisted of marl unit.

The *boundstone* and *grainstone* have the highest strength, hardness, and resistance compared to other lithofacies, forming dome and hill morphologies. *Packstone* and *wackestone* lithofacies, have moderate hardness, strength, and resistance (intermediate) in morphology forming wavy (undulating) topography. Lithofacies of marl units, have low strength, hardness, and resistance in the exogenous process forming plain topography.

There is a very strong correlation with the coefficient of $R^2 > 0.9$ between physical-mechanical rock properties and karst geomorphology in the study area. The strong, hard, and resistant rocks will form rough relief, while weak, soft, and not resistant rocks will produce smooth relief.

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