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Analysis of Sand Grain Characteristics and Permeability Using Hazen Formula and Laboratory Test

Analisis Karakteristik Pasir dan Permeabilitas Menggunakan Rumus Hazen dan Uji Laboratorium

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Abstract

Permeability is a critical parameter in geotechnical and hydrological studies, representing a soil's capacity to transmit water through its pore spaces. The Hazen formula, an empirical method based on the D_{10} value from sieve analysis, is widely used to estimate the permeability coefficient. However, its accuracy is strongly influenced by grain shape and size distribution, which vary significantly across different geological settings such as volcanic, fluvial, and coastal environments. This study evaluates the applicability of the Hazen formula for sands derived from these three environments. The novelty of this research lies in its integrated approach, combining visual morphological analysis using sand grain imagery, particle size distribution tests, permeability estimation via the Hazen formula, and validation through constant head laboratory tests. Nine sand samples were analyzed: four from mountainous regions, two from rivers, and three from coastal areas. The findings reveal that sands with angular grains and wide gradation ranges exhibit considerable discrepancies between estimated and measured permeability values. Conversely, sands with rounded and well-sorted grains produce more consistent results. These outcomes suggest that the Hazen formula remains reliable for clean, uniformly graded sands with rounded to sub-rounded particles. This study highlights the need to consider grain morphology when applying empirical permeability estimation methods.

Keywords: sand permeability, Hazen formula, grain morphology, laboratory test, size distribution.

***SDGs*:**

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Abstrak

Permeabilitas merupakan parameter penting dalam studi geoteknik dan hidrologi, yang menggambarkan kemampuan tanah untuk mengalirkan air melalui ruang pori-porinya. Rumus Hazen, sebuah metode empiris yang didasarkan pada nilai D10 dari analisis saringan, secara luas digunakan untuk memperkirakan koefisien permeabilitas. Namun, akurasi rumus ini sangat dipengaruhi oleh bentuk butir dan distribusi ukuran partikel, yang bervariasi secara signifikan pada lingkungan geologi yang berbeda seperti daerah vulkanik, fluvial, dan pesisir. Penelitian ini mengevaluasi tingkat keterterapan rumus Hazen pada pasir-pasir yang berasal dari ketiga lingkungan tersebut. Kebaruan dari studi ini terletak pada pendekatan terintegrasi yang menggabungkan analisis morfologi visual menggunakan citra butiran pasir, uji distribusi ukuran partikel, estimasi permeabilitas melalui rumus Hazen, serta validasi melalui uji laboratorium head tetap. Sebanyak sembilan sampel pasir dianalisis: empat dari daerah pegunungan, dua dari sungai, dan tiga dari wilayah pesisir. Hasil penelitian menunjukkan bahwa pasir dengan bentuk butir bersudut dan rentang gradasi yang lebar memperlihatkan perbedaan yang cukup besar antara nilai permeabilitas yang dihitung dan yang diukur di laboratorium. Sebaliknya, pasir dengan butiran membulat dan gradasi seragam menghasilkan hasil yang lebih konsisten. Temuan ini menunjukkan bahwa rumus Hazen tetap dapat diandalkan untuk pasir bersih dengan gradasi seragam dan butiran yang membulat hingga agak membulat. Studi ini menekankan pentingnya mempertimbangkan karakteristik morfologi butiran saat menggunakan metode empiris untuk analisis permeabilitas.

Kata Kunci: permeabilitas pasir, rumus Hazen, morfologi butiran, uji laboratorium, distribusi ukuran.

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1. INTRODUCTION

Permeability is one of the key parameters in geotechnical and hydrological fields, describing the ability of a soil material to transmit water through its pores. In civil engineering practice, this parameter plays a crucial role in the design of drainage systems, slope stability, and foundation bearing capacity. Sand, as a type of coarse-grained soil, generally has high permeability; however, its value is significantly influenced by the physical characteristics of the grains, such as shape, size, and distribution (Bear, 2013; Das and Sivakugan, 2015; Liu *et al.*, 2024).

The samples in this study were collected from the Cibeet River, Garut Beach (Santolo), and Lombok Beach (Senggigi) due to the availability of samples from previous research and the distinctive grain shape and uniformity characteristics of the sand in these locations.

Among the various approaches to determine permeability, the Hazen formula is one of the most widely used empirical methods due to its simplicity. This formula calculates the permeability coefficient based on the effective particle diameter (D_{10}) obtained from sieve analysis results (Hazen, 1892). However, the reliability of the Hazen formula heavily depends on the assumption that sand grains are uniform and spherical—a condition that is not always met in the field, especially for sands derived from different geological environments such as volcanic, fluvial, or coastal settings.

Indonesia, as an archipelagic country, possesses a diverse range of sand types influenced by geological processes and their environmental origins. Sand from volcanic regions such as Malang tends to have angular and non-uniform shapes, differing from river sands like those from the Cibeet River or coastal sands found in Garut, Bali, and Lombok (Cho, Dodds and Santamarina, 2006). This variation may cause the permeability values calculated using the Hazen formula to deviate from actual values. Therefore, a more comprehensive study is needed to evaluate the applicability of the Hazen formula in estimating the permeability of sands from various natural sources.

One of the commonly used methods for estimating permeability is the Hazen formula (Hazen, 1892), which is based on the effective grain size (D_{10}) derived from the particle size distribution curve. Although this method is popular for its simplicity, its accuracy diminishes when applied to non-uniform sands, sands containing fines, or those with angular grain shapes, as commonly found in volcanic and coastal sands in Indonesia (Alyamani and Şen, 1993; Chapuis, 2004; Albarrán-Ordás and Zosseder, 2024).

The particle size distribution was analyzed using sieve analysis to determine the gradation of each sample. This study is a preliminary investigation that applies the Hazen formula to estimate the permeability coefficient (k) and compares the results with permeability correlation charts (The Permeability of Sands and Gravels) from several previous studies (Carter and Bentley, 1991; Wang *et al.*, 2024).

The Hazen formula is widely used in the literature to estimate the permeability coefficient of clean sands with a D_{10} size—defined as the particle diameter at which 10% of the sample passes through the sieve—ranging between 0.1 mm and 3 mm, and a uniformity coefficient (Cu) < 5 (Hazen, 1892). This formula is intended for clean sands with a uniform particle size distribution, free from clay or silt content, and with nearly rounded grain shapes. However, many modern studies have found that this formula is not always accurate for all types of sand, especially when applied to local sands derived from volcanic rocks or natural weathering processes in tropical regions (Alyamani and Şen, 1993; Chapuis, 2004). Therefore, further research is needed to evaluate the validity of the Hazen formula for sands from various sources in Indonesia.

However, several studies have shown that grain morphology—such as roundness, angularity, and surface texture—has a significant influence on fluid flow through porous media (Muskat and Wyckoff, 1937; Ferdinand, Dorothée and Codjo, 2023). Angular grain shapes tend to result in looser particle arrangements, increasing porosity and resistance to water flow. In addition, a wide size distribution (well-graded) can fill the voids between larger grains, thereby reducing the overall permeability (Bear, 2013; Cui *et al.*, 2024).

Laboratory permeability testing methods, such as the constant head test, provide actual results that can serve as a benchmark for values obtained from the Hazen formula. The testing standard used is ASTM D2434-22 (ASTM, 2022), which is applied to directly determine the permeability coefficient of loose sand. A study by Tan and Engeda, emphasized the importance of considering the effects of grain shape and size on permeability calculations to avoid significant deviations from actual field conditions (Tan and Engeda, 2016).

For accuracy in this study, the range of permeability values was adopted as shown in Table 1.

Table 1. Permeability Value Range (Das and Sivakugan, 2015).

Soil Type	Value Range	Information
Clean gravel	10^{-1} - 1	Very permeable
Coarse sand	10^{-2} - 10^{-1}	Very permeable
Medium sand	10^{-3} - 10^{-2}	High permeable
Fine sand	10^{-4} - 10^{-3}	Medium permeable
Very fine sand	10^{-5} - 10^{-4}	Low permeable

Most previous studies have focused on the relationship between the D_{10} parameter and permeability values without thoroughly considering the influence of grain morphology from various geological environments. In fact, sand grains from volcanic and coastal areas exhibit significantly different characteristics in terms of shape and surface texture. This gap presents a challenge for the universal application of the Hazen formula in the field. This study offers novelty by combining morphological analysis through photographs/images and sieve testing to obtain comprehensive sand characteristics, and by comparing the permeability coefficient calculated using the Hazen formula with laboratory results from the constant head method. The objective of this study is to evaluate the accuracy of the Hazen formula in estimating permeability values of sands from different geological environments (mountain, river, and coastal), as well as to examine the influence of grain shape and size distribution on permeability.

2. METHODOLOGY

This study employs a laboratory-based quantitative experimental approach the characteristics of sand from three different geological environments: mountainous, fluvial, and coastal. The research was conducted in several stages: (1) sample collection and preparation, (2) grain morphology analysis, (3) particle size distribution analysis, (4) permeability calculation using the Hazen formula, and (5) permeability testing using the constant head method. The results obtained from the Hazen formula and the laboratory tests were then compared to assess the consistency between empirical predictions and actual conditions.

This study was conducted using sand samples collected from three different geological environments: mountainous, fluvial, and coastal areas. The sand samples from the mountainous region were taken from Malang, East Java, which is geologically dominated by volcanic materials. Samples from the fluvial environment were collected from the Cibeet River in West Java. Meanwhile, the coastal samples were gathered from three different locations: Santolo Beach (Garut, West Java), Kuta Beach (Bali), and Senggigi Beach (Lombok, West Nusa Tenggara). In total, there were 9 sand samples, consisting of 4 from the mountainous area, 2 from the river, and 3 from the coastal region.

The main equipment used in this study includes:

1) Sieve set for gradation analysis with standard ASTM sizes (0.075 mm to 4.75 mm),
2) Digital camera for observing sand grain morphology,
3) Constant head permeability test apparatus in accordance with ASTM D2434-22 (ASTM, 2022) and ASTM D6913-04 (ASTM, 2017) standards,
4) Digital balance with an accuracy of 0.01 grams,
5) Drying oven, measuring cylinders, and stirring tools for sample preparation.

Data collection was carried out through the following stages:

1) Field sampling was conducted using the grab sampling method to obtain representative samples from each location.
2) Drying and sieving of samples were performed in the laboratory to determine the particle size distribution (gradation) and to identify the D_{10} value.
3) Grain shape observations were made using a digital camera and analyzed based on the grain morphology classification by Powers, focusing on roundness and sphericity (Powers, 1953).
4) Permeability testing was carried out using the constant head method in accordance with ASTM D2434-22 (ASTM, 2022). Each sample was tested at least three times to obtain an average value.
5) The permeability coefficient of each sample was then recalculated using the Hazen formula, based on the D_{10} value obtained from the sieve analysis results (Hazen, 1892).

The collected data were analyzed quantitatively. The analysis steps include:

1) Calculation of the D_{10} value from the sieve analysis results using the particle size distribution graph.
2) Calculation of the permeability value using the Hazen formula as follows:

$$k = C \, . \, D_{10}^2 \qquad (1)$$

where:

k = Permeability coefficient (cm/s)

D_{10} = Diameter of particles that pass 10% of the sieve

C = Correlation constant (generally between 1.0 – 1.5 for clean sand) (Das and Sivakugan, 2015)

3) A comparison between the permeability values obtained from the Hazen calculation and those from the laboratory tests was conducted to assess the accuracy and suitability of the empirical model for sand conditions from each environment.
4) The analysis was carried out by comparing the permeability values based on grain morphology images, the Hazen formula, and laboratory tests.
5) The results of the analysis were interpreted to assess the influence of grain shape and size distribution on permeability values and the suitability of using the Hazen formula for sands from various locations

3. RESULTS AND DISCUSSION

The results of taking images of 9 research samples are shown in Figure 1. As a comparative reference for determining sphericity and roundness, Figure 2 from Akbulut et al., can be used (Akbulut, Wiszniewski and Cabalar, 2014).

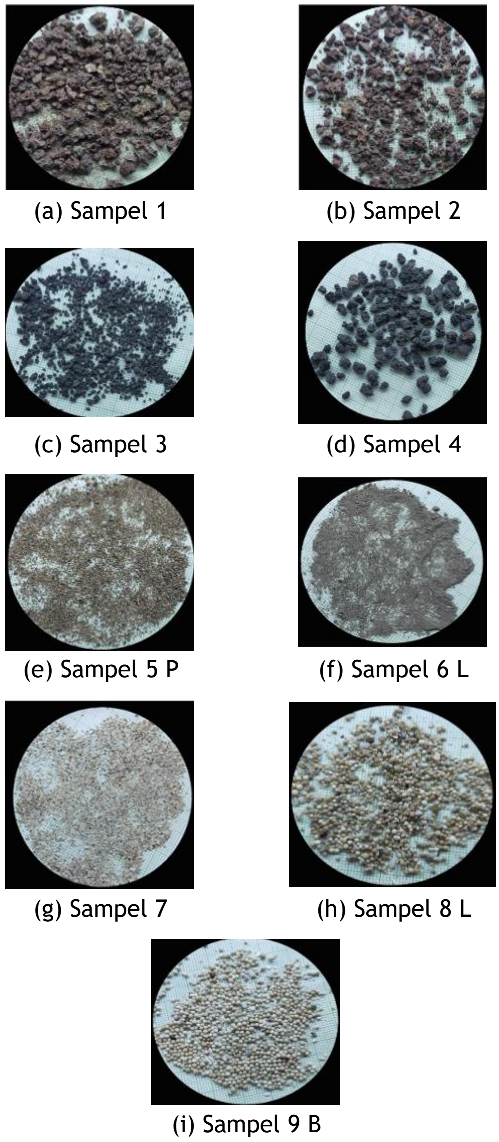

Figure 1. Image of test sample.

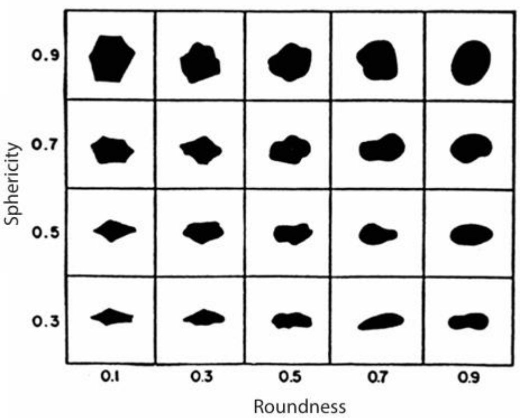

Figure 2. Comparison chart.

The image analysis of the research samples indicates that mountain sand particles exhibit angular to sub-angular shapes, river sand particles are sub-rounded to rounded, and marine sand particles are generally rounded in shape. From the results of the photo/image test, the morphological form of the sample grains is shown in Table 2.

Table 2. Results of image observations.

No	Morphology estimation results
S1	Angular to sub-angular, coarse, with variable grain sizes
S2	Sharply angular, poorly graded (wide grading), low sphericity
S3	Sub-angular, coarse, with some finer and more rounded grains
S4	Angular to sub-rounded, with abrasive surfaces
S5	Sub-rounded to rounded, surface becoming smooth, well-graded
S6	Fine to very fine grains, shape not clearly defined
S7	Rounded, highly uniform, smooth surface
S8	Rounded to well-rounded, uniform
S9	Well-rounded, relatively uniform in size, high roundness

The results of the sieve analysis test show the content of gravel, sand, and fines (silt and clay), as well as the calculated values of D_{10}, D_{30}, and D_{60} for all samples, as presented in Table 3. The sieve analysis curves are shown in Figure 3. The results of the sample sieve analysis are all sandy soil, where the sample is 66.33% - 99.98% sand.

Table 4 presents the values of Cu, Cc, permeability calculated using the Hazen formula, and the results of the laboratory permeability tests.

Table 3. Gradation of test samples.

No	Silt & Clay	Sand	Gravel	D_{10}	D_{30}	D_{60}
S1	1.69%	95.18%	3.13%	1.400	2.420	3.300
S2	2.28%	66.33%	31.39%	0.350	2.050	3.950
S3	2.83%	97.10%	0.07%	0.420	2.250	4.700
S4	2.61%	89.68%	7.71%	2.600	5.500	7.000
S5	0.72%	98.23%	1.04%	0.260	0.333	0.505
S6	10.21%	89.77%	0.02%	0.075	0.097	0.135
S7	0.02%	99.96%	0.00%	0.195	0.293	0.390
S8	0.02%	99.98%	0.00%	0.890	1.100	1.450
S9	0.06%	97.76%	2.17%	0.900	1.130	1.520

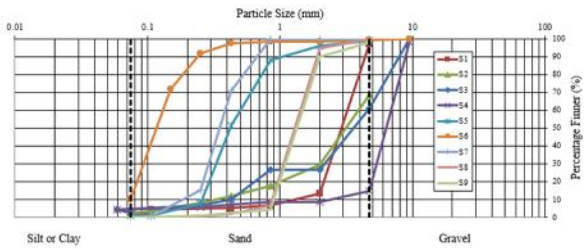

Figure 3. Results of sieve analysis.

Table 4. Results of calculating Cu, Cc, and k values from the Hazen and laboratory formulas.

No	C_u	C_c	k Upper (cm/s)	k Lower (cm/s)	k Laboratory (cm/s)
S1	2.357	1.268	$2.9\ 10^{-2}$	$2.0\ 10^{-2}$	$4.1\ 10^{-2}$
S2	11.286	3.040	$1.8\ 10^{-3}$	$1.2\ 10^{-3}$	$3.7\ 10^{-2}$
S3	11.190	2.565	$2.6\ 10^{-3}$	$1.8\ 10^{-3}$	$3.0\ 10^{-2}$
S4	2.692	1.662	$1.0\ 10^{-1}$	$6.8\ 10^{-2}$	$3.5\ 10^{-2}$
S5	1.942	0.845	$1.0\ 10^{-3}$	$6.8\ 10^{-4}$	$7.0\ 10^{-3}$
S6	1.800	0.929	$8.4\ 10^{-5}$	$5.6\ 10^{-5}$	$4.9\ 10^{-4}$
S7	2.000	1.129	$5.7\ 10^{-4}$	$3.8\ 10^{-4}$	$1.4\ 10^{-2}$
S8	1.629	0.938	$1.2\ 10^{-2}$	$7.9\ 10^{-3}$	$2.4\ 10^{-2}$
S9	1.689	0.933	$1.2\ 10^{-2}$	$8.1\ 10^{-3}$	$2.9\ 10^{-2}$

From Table 4, Samples 2 and 3, based on the Hazen formula, have Cu values that do not meet the requirements (Cu > 5), even though the grain size falls within the acceptable range. The particles are also not uniform. The permeability results from the Hazen formula and the laboratory tests show discrepancies.

Sample 6 contains fine to very fine grains with an undefined shape, Cu < 5, and the highest clay and silt content at 10.21%.

For samples 1, 4, 5, 7, 8, and 9, the permeability results from the Hazen formula and the laboratory tests do not show significant differences. These samples fall into the categories of high and medium permeability, as shown in Table 5.

Table 5. Summary of the permeability levels of the samples.

No	k Upper (cm/s)	k Lower (cm/s)	k Laboratory (cm/s)	Information
S1	2.9 10^{-2}	2.0 10^{-2}	4.1 10^{-2}	Medium sand, high permeability
S2	1.8 10^{-3}	1.2 10^{-3}	3.7 10^{-2}	Medium sand, high permeability
S3	2.6 10^{-3}	1.8 10^{-3}	3.0 10^{-2}	Medium sand, high permeability
S4	1.0 10^{-1}	6.8 10^{-2}	3.5 10^{-2}	Medium sand, high permeability
S5	1.0 10^{-3}	6.8 10^{-4}	7.0 10^{-3}	Fine sand, medium permeability
S6	8.4 10^{-5}	5.6 10^{-5}	4.9 10^{-4}	Very fine sand, low permeability
S7	5.7 10^{-4}	3.8 10^{-4}	1.4 10^{-2}	Fine sand, medium permeability
S8	1.2 10^{-2}	7.9 10^{-3}	2.4 10^{-2}	Medium sand, high permeability
S9	1.2 10^{-2}	8.1 10^{-3}	2.9 10^{-2}	Medium sand, high permeability

4. CONCLUSION

This study demonstrates that the Hazen formula can still be used to estimate the permeability coefficient of sand quickly and efficiently, but only under certain conditions. The results indicate that the accuracy of the Hazen formula is highly influenced by the morphological characteristics and particle size distribution of the sand. For samples with rounded to sub-rounded grains and uniform size distribution, the permeability values calculated using the Hazen formula closely matched the laboratory test results. Conversely, for sands from volcanic environments or those with angular grains and wide gradation, significant deviations were observed. Therefore, the use of the Hazen formula should be limited to clean sands with D_{10} values between 0.1–3 mm, a uniformity coefficient (Cu) < 5, and no silt or clay content. This study emphasizes the importance of considering grain shape and gradation when applying empirical methods for permeability analysis.

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