

Can Pumice Support Structural Foundations?

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ARTICLE INFORMATION

Article History

Received: 13th October 2022

Revised: 09th March 2023

Accepted: 03rd April 2023

Published: 10th June 2023

Keywords

Pumice
Volcanic Soils
Vesicular Soils
Crushable Soils
Problematic Soils

ABSTRACT

The current practice with regard to pumice soils is to remove them when encountered during excavation for the foundations of multi-storey buildings. Consequently, foundations become unusually deep where pumice deposits are located near ground level and extend to a significant depth. The decision to avoid pumice as a foundation-supporting soil is logical, although not supported by literature. The question of whether pumice can support structural foundations was triggered by observation of the current practice with regard to this unique geological material. The question was approached through a literature review that aimed to find out what is known so far about pumice, point out what should be known, and suggest what to do with regard to pumice as a foundational supporting material. It was revealed that pumice is abundant in many parts of the world and has peculiar characteristics in comparison to most geotechnical materials. Many studies are concerned with pumice as a building material applied in concrete manufacturing and block making, but not as a foundation supporting strata. Pumice materials are characterised by high porosity, low specific gravity, low strength, and high crushability. A limited number of studies have indicated that pumicious materials require special treatment in laboratory testing, insitu testing, and the interpretation of results. Insitu and laboratory tests on pumice materials were conducted in this study for the purpose of enriching the discussion. Further research is recommended in areas of characterisation, insitu testing, correlations between test results, and improvement of pumice materials for consideration as foundation-bearing strata.

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1. Introduction

Pumice, also called volcanic glass (Çelik and Ergül, 2015) and often related to volcanic tuff and scoria, is a soft, light rock produced when lava with a very high content of water and gases is discharged from an active volcano. As a common product of explosive volcanic eruptions, pumice is considered an important component of many pyroclastic deposits and volcanogenic sediments. The porous structure of pumice is created by the formation of bubbles or air voids when gases contained in the molten lava flowing from volcanoes become trapped on cooling. The soil classification standard (ISO 14688-1) has directed that one way of identifying volcanic soils is by examining the presence of pumice and scoria. Pumice is said to be a unique (He and Senetakis, 2019) and highly unusual geological material (Manville *et al.*, 1998) that consists of very vesicular silicic to mafic glass foam that floats in water. Due to its peculiar properties, Orense *et al.* (2013) have named pumice one of the most delicate geotechnical materials. Pumice may exist in a range of particle sizes, from boulders to silt (Pender *et al.*, 2006), with smaller particles capable of sinking before larger particles when in suspension (Manville *et al.*, 1998). The physical properties of pumice have therefore been described in terms of density (or vesicularity) and the shapes and size distributions of the vesicle population.

Characterised by low density and vesicularity, early experiments showed that cold pumice can stay afloat in water for over a year. Experiments by Whitham and Sparks (1986) concluded that the typical internal surface area of pumice is in the order of $0.5 \text{ m}^2/\text{g}$ and that pumice vesicles appear to be interconnected. However, Wesley *et al.* (1999) reported a dense network of fine holes, some interconnected and some entirely isolated, inside pumice particles. The floating nature of pumice means the materials can be transported thousands of kilometres from where they were formed. During transportation, the low density of pumice allows for some unique styles of grading

and the formation of sedimentary structures in both land and submarine environments. Other important properties of pumice include surface roughness and crushability. Due to the crushability of pumice, pumice-rich deposits are considered problematic soils, thus requiring special attention when encountered as foundation sub-strata.

It has been reported that pumiceous materials are found in abundance in many parts of the world, including New Zealand (Pender *et al.*, 2006; Wesley *et al.*, 1999; Stringer, 2019), Italy (Liguori *et al.*, 1984; Esposito and Guadagno, 1998), Turkey (Kabay *et al.*, 2015; Avşar *et al.*, 2015), Japan (Kikkawa *et al.*, 2013), Iran (AsghariKalajahi and AminiBirami, 2015), and China (He and Senetakis, 2019). Other parts of the world also known for their abundance of volcanic materials include Central and South America, the Philippines, the Canary Islands, Africa, Indonesia (Avşar *et al.*, 2015), Saudi Arabia, France (Z, 2018), as well as Greece (Ersoy *et al.*, 2010). In Tanzania, where this study is based, deposits of pumice are known to exist in several regions, including Iringa, Kilimanjaro, Arusha, and Morogoro (Mboya *et al.*, 2011), as well as Mbeya (Geological Survey Department, 1958) and its nearby places such as Tukuyu (Bucher, 1980). These studies were mainly concerned with characterisation of pumice and its use as a construction material rather than a foundation-bearing strata.

In practice, pumice is considered a problematic material (Orense *et al.*, 2013), with very limited information about its geotechnical properties. Most practising engineers would not consider pumice a proper bearing stratum due to its light weight, crushability, and compressibility. For example, the current practice in Mbeya is to remove pumice materials when encountered during excavation for shallow foundations, consequently creating deeper foundations than initially intended. This practice can have a serious cost implication for construction since the pumice layers may be as thick as two to three metres. According to Avşar *et*

al. (2015), pumice and other pyroclastic materials may exist on flat or sloping ground, reaching thicknesses of tens of metres. Contrary to the limited literature about pumice as a foundation supporting material, there is quite rich literature about the use of pumice as a construction material, ranging from application in lightweight concrete production (Hossain, 2004; Ayhan *et al.*, 2011; Kurt *et al.*, 2015) to block making (Felekolu, 2012; Sariisik and Sariisik, 2012) to road construction (Saltan and Fndk, 2008; Urio and Mwemezi, 2018). When in powder form, pumice has been used as a replacement for cement in concrete production (Kabay *et al.*, 2015) and as a filler for self-compacting concrete (Granata, 2015). This paper intends to review what is known so far, point out what should be known, and suggest what to do with regard to pumice as a foundation-supporting material.

2. Properties of Pumice

Pumice can be classified as acidic or basic (Sariisik and Sariisik, 2012), with the former being the most common type worldwide (Ersoy *et al.*, 2010). The composition of oxides, especially the percentage of SiO₂ defines the acidity or alkalinity of the pumice. Besides the difference in chemical composition, the physical attributes of basic and acidic pumice are also different. Acidic pumice is a lightweight material, whereas basic pumice has a higher specific gravity comparable to natural aggregates (Öz, 2018). While acidic pumice has found more application in light-weight concrete, basic pumice is more appropriate in semi-lightweight concrete; see, for example, Ayhan *et al.* (2011). Pumice is composed of Si, Al, K, Na, and Fe oxides, with a small percentage of Ca, Mg, Mn, and Ti oxides (Liguori *et al.*, 1984; Ersoy *et al.*, 2010). The dominant compounds are silica and alumina (Pender *et al.*, 2006; Kikkawa *et al.*, 2013). The colour may range from black to grey to white, with darker ones containing a larger percentage of Fe, which implies higher density and a possible magnetisation. Generally, basic pumice is brown to black in colour, while acidic pumice is lighter in the range of white to off-white. The two

most important components of pumice are silica and alumina, with a high percentage of silica indicating the purity of pumice (Pender *et al.*, 2006; Ersoy *et al.*, 2010; Kikkawa *et al.*, 2013).

The uniqueness of pumice as a geological material can also be described in terms of its unusually low densities. The density of pumice ranges from 0.2 g/cm³ to slightly greater than the density of water (Whitham and Sparks, 1986; Manville *et al.*, 1998). The volume of pores in pumice particles may account for up to 85% of the total volume (Liguori *et al.*, 1984). Therefore, determination of density is not a straight-forward process for pumice materials. First, it takes a long time to get full saturation of particles; hence, the common practise is to immerse pumice in water under a vacuum to speed up the absorption. Even so, the specific gravity of pumice materials was found by Wesley *et al.* (1999) to be dependent on the particle sizes, with the smaller particles possessing higher values. Stringer (2019) has shown that the light-weight property of pumice can be used to advantage by devising a methodology for separating pumice particles from a soil mix.

Pumice materials are characterised by low grain strength, a high angle of friction between grains, a high void ratio, and high compressibility (Yildiz and Soganci, 2015). Voids are mainly responsible for these characters, including the low density. Depending on the source, voids in the pumice may be interconnected or not. For example, Esposito and Guadagno (1998) described voids in pumice from Mount Vesuvius as interconnected. They categorised the voids into inter- and intra-particle voids. On the contrary, Sariisik and Sariisik (2012), who sourced pumice from Nevşehir in Turkey, found the pores to be unconnected and distant, resulting in low permeability.

Due to the peculiar nature of pumice, other important properties of pumice that may require special attention in their determination are specific gravity, dry unit weight, porosity, void ratio, and grain size distribution. The sampling process may

also pose a challenge for weakly cemented pumice and volcanic soils in general. Avşar *et al.* (2015) have demonstrated the need for special sampling techniques with regard to weakly cemented volcanic soils. They discouraged the use of reconstructive samples, especially in strength testing, stating the lack of replication of the insitu conditions, such as the fabric of the deposit. For example, instead of using the conventional method to determine porosity, Esposito and Guadagno (1998) used the mercury intrusion porosimeter to determine the pore size distribution. The high porosity and water absorption properties of pumice mean the material is susceptible to volume changes due to freezing and thawing. As reported by Avşar *et al.* (2015), the fabric and structure of pyroclastic materials are extremely variable from deposit to deposit and, in the same deposit, in vertical and horizontal directions, resulting in a broad range of their mechanical properties. Even more, the variation in mechanical properties may be caused by the sampling difficulties.

Pender *et al.* (2006) determined the specific gravity of pumice sand using two different methods: the standard method and a simple displacement method. They ended up with significantly different results, which are attributed to the vesicular nature of pumice particles, which are composed of internal and external voids (Esposito and Guadagno, 1998). Kikkawa *et al.* (2013) also discussed this uncertainty in the determination of the specific gravity of pumice, and it has an impact on the determination of the void ratio as well as the porosity of pumice materials, making the process less straightforward. In their study, Yildiz and Soganci (2015) applied three different procedures to the determination of the specific gravity of pumice particles. The results showed that the simple displacement technique and the pycnometer method without vacuum produced results that were generally inferior to those of the conventional pycnometer procedure. The values for specific gravity obtained were found to be inversely proportional to the grain size.

A close examination of pumice materials may provide useful information to further describe the volcanic material, including the determination of the distribution and sizes of both internal and surface voids. Knowledge of porosity, pore sizes, and pore volume is of fundamental importance for the characterisation of porous materials. Mercury porosimetry is the most widely used method for determining the pore size distribution of solids. According to Çelik and Ergül (2015), the pores of pumice particles exist in a very wide range of nano- to micro-sizes, and information about pores can be obtained using a mercury porosimeter.

3. Compressibility of Pumice

Perhaps the most studied phenomenon with regard to pumice as a geotechnical material is the compressibility of both individual particles and soil samples. Wesley *et al.* (1999) were able to figure out the average value of the unconfined compressive strength of cubical pumice particles made by trimming large particles. The average value was found to be 2.7 MPa, which is very low as compared to the order of 50 to 100 MPa for quartz materials. Rendering pumice as a weak compressible material. The average unconfined compressive strength of pumice particles was reported by Liguori *et al.* (1984) to be in the order of 24.5 kg/cm² (about 2.4 MPa). Similarly, Ziccarelli (2016) studied the changes in particle size distribution of pumice sand subjected to varying magnitudes of vertical one-dimensional stress and found a significant crushing of pumice particles at stresses as low as 0.2 MPa. The experiment was done on artificially obtained sand of 10–15 mm diameter made from rock fragments. Volcanic soils, especially those that are weakly cemented, are said to have low strength, generally less than 0.1 MPa (Avşar *et al.*, 2015).

Grain crushing is known to be one of the fundamental processes of granular materials because it causes the grain size distribution to undergo modification, resulting in changes in other properties like porosity, density, permeability, and shear strength of the soil. It is reported that grain

crushing is of concern in engineering projects such as high earth dams, deep wells, tunnels, and driven piles (Ziccarelli, 2016). As discussed before, stressed pumice particles are likely to crush at significantly low loads, making the stress-strain behaviour governed by particle crushing (Yildiz and Soganci, 2015). Compared to many soils, this is quite a peculiar behaviour and should be critically studied. This particle crushing modifies the density and is said to result in a reduction in shear strength due to dilatancy (Pender *et al.*, 2006). The crushability of pumice increases with the size of individual particles (Orense *et al.*, 2013; Kikkawa *et al.*, 2013). Pender *et al.* (2006) noted that the size of pumice particles may vary from boulders to silt. This means that soil deposits with a high proportion of large pumice particles can be highly deformable.

AsghariKaljahi and AminiBirami (2015) conducted tests on the mechanical properties of pumiceous rocks in Iran and compared them with literature information. They found that the Uniaxial Compressive Strength of such materials is in the range of 13 to 18 MPa in dry conditions and 9 to 13 MPa in wet conditions. The materials are characterised by very low dry unit weight, very high porosity, and high water absorption, resulting in low durability. With this information, it can be generalised that pumice materials, whether as single particles, as soil masses, or as rocks, have low compressive strength, making them susceptible to crushing.

4. Pumice as a Construction Material

Pumice can be considered chemically inert due to its insolubility in water, acids, and bases (Liguori *et al.*, 1984). This characteristic makes pumice very useful as a construction material. Some countries with an abundance of pumice take advantage of some of its properties and use it in manufacturing construction materials, mostly concrete. Using pumice, it is possible to manufacture concrete that is two to three times lighter than ordinary concrete (Hossain, 2004). Furthermore, such concrete will have good insulating characteristics, high

absorption, and low shrinkage. Pumice aggregates' high water absorption capacity in the production of concrete necessitates the use of more water when mixing or saturating the aggregates before mixing. All of which results in low early strength or a great reduction in the workability of concrete in cases where compensation is not considered for mixing water (Felekoğlu, 2012). Similarly, Yildiz and Soganci (2015) demonstrated an improvement in the strength of pumice material by penetrating its pores with cement grout in a laboratory setup. The achieved strength was said to be comparable to the strength of concrete.

Powdered pumice has also found applications in the cosmetics industry (Liguori *et al.*, 1984) and in concrete manufacturing. The powder manufactured from pumice can be used to partially replace cement. Kabay *et al.* (2015) reported some advantages of using powdered pumice in concrete, such as less water absorption, sorptivity, and voids. Additionally, such concrete was found to have a higher magnesium sulphate resistance compared to ordinary cement concrete. Pumice has also found application in the manufacturing of concrete blocks for use in building walls. A variety of buildings take advantage of the light-weight nature of pumice concrete blocks. Kuş and Uzun (2008) reported the use of pumice blocks in the construction of energy-efficient buildings in the form of school buildings, multi-storey apartment buildings, hotels, and other commercial buildings. In their book, Grassler and Minke (1990) recommend the use of pumice materials for building construction of up to four storeys but never for foundations. Pumice and other natural materials have the potential to extend the service life of concrete structures, especially in harsh environments. Tran and Ghosh (2020) demonstrated the application of volcanic pumice pozzolan to enhance the performance of concrete in strength and durability, which is significant for high-performance and environmentally friendly structures.

Saltan and Findik (2008) demonstrated that pumice, when mixed with some "unqualified" quarry material, can economically make suitable road subbase due to a reduction in plasticity achieved by mixing with pumice. Strength improvement was also observed. In Tanzania, Urjo and Mwemezi (2018) have proposed using cement or lime-stabilised pumice as subbase material for low-volume roads carrying traffic at low design speeds. This application has the potential to utilise locally available materials while saving the environment from the depletion of natural resources. The source of pumice for road construction could be from excavations for the construction of building foundations in areas where pumice is abundant.

Other non-construction uses of pumice reported in literature are garment washing, polishing silverware, glass, mirrors, and base metal; plastics manufacture; railway carriage cleaning; floor absorbent; and cosmetics (Saltan and Findik, 2008). It is said that pumice makes an excellent exfoliating or scrub bar when added to soap. Most of these uses are possible due to the abrasive nature of pumice.

5. Insitu Testing on Pumice Material

Insitu tests in geotechnical engineering are very useful for ground investigations. They are more rapid and generally more economical than sampling and laboratory testing. In some circumstances, sampling can be very difficult, if not impossible, to achieve, warranting insitu testing as the alternative. The Standard Penetration Test (SPT) is the most commonly used field test in Tanzania and many parts of the world. Also gaining popularity are the Cone Penetration Test (CPT) and Dynamic Probing (DP). However, field testing can never completely replace the need for sampling and laboratory testing. Correlations between insitu test results and design or laboratory parameters are therefore very useful in geotechnical design (Kulhaway and Mayne 1990; Hettiarachchi and Brown 2009). Relating the results of more popular insitu tests such as the SPT with other less popular methods increases the

usefulness of insitu data for design. Examples can be found in Lingwanda *et al.* (2015) and dos Santos and Bicalho (2017). It is always advised that soil property correlations be used with caution by making sure of the compatibility between how they were derived and the material that needs interpretation.

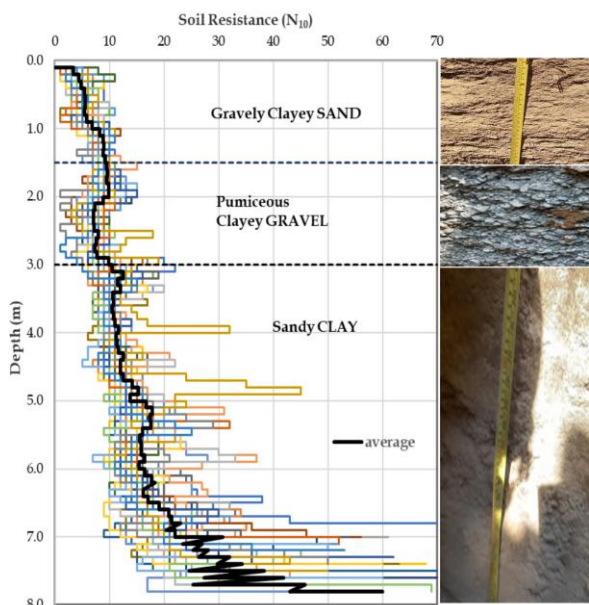
In their laboratory study, Wesley *et al.* (1999) discovered the difference in behaviour between pumice and quartz sands in resisting the cone penetrometer. They came to the conclusion that quartz and 'normal' soils show a significant difference in response between loose and dense states, whereas pumice material shows little to no difference. However, a significant difference in sleeve friction between loose and dense soils was noticed in both pumice and quartz sands. In most soils, the results of penetration testing with static or dynamic methods are normally affected by the confining pressures, such that the deeper the test, the more pronounced the effects. However, the behaviour of pumice was found by Wesley *et al.* (1999) to be less affected by the confining pressure. The difference in behaviour between pumice and quartz is an attribute of the particle's strength. While quartz sand fails in shear displacement, pumice fails in particle crushing. These findings lead to a recommendation not to use conventional correlations between density and penetration resistance in pumice materials.

In a geotechnical investigation project for building construction, insitu testing with light dynamic probing (DPL) was performed on a site located in Mbeya City, Tanzania. The geological survey report (Geological Survey Department, 1958) describes the area as composed of Karoo sediments resting unconformably on the quartz-magnetite gneisses rocks. These sediments are purple to white sandstones with minor siltstones. The sandstone is said to be comparatively soft and is associated with some mudstone. The sediments are uncomfortably overlain by pebble beds, gravels, pumice, and tuffs, which contain much material from the Rungwe volcanic province. The field investigation consisted of 24 DPL tests and

one trial pit to expose the stratification. The results of the DPL are presented in Figure 1, along with some pictures of the observed soil profile in the trial pit. As indicated in the figure, the top soil consists of gravely clayey Sand up to about 1.5 m deep is followed by another 1.5 m of clayey Gravel of pumiceous nature. This layer overlays a sandy Clay layer. The common attribute of all these layers is that they are composed of volcanic soils.

Fig 1

In situ Testing Results with the DPL through a Soil Profile Containing a Pumice Layer



The main interest in this study is the pumice layer, which needs to be examined. The general observation is that there is no steady increase in penetration resistance values (N_{10}) with depth, as would be expected in most soil layers. This observation agrees with Wesley *et al.*'s (1999) for CPT cone resistance in pumice material. It should be insisted that correlations between insitu and laboratory results for normal soils may not be appropriate for interpreting test results on this pumice.

6. Investigating the Grain Crushability of Pumice

As discussed earlier in Section 3, compressibility is the most important property of pumice, hindering its use as a bearing material in structural foundations. On the other hand, the vesicular nature of pumice means the material has good drainage properties, which could be viewed as an advantage against consolidation problems. In this study, experiments were performed to establish the crushability of pumice materials obtained at the Mbeya University campus in Mbeya. The area has an abundance of pumiceous materials found at relatively shallow depths of less than 1 m that extend to 3 m or more. For the purpose of description, a sample was taken to the lab for analysis of particle size distribution, water absorption, and particle density using standard tests as referenced from the Tanzania laboratory testing manual (MoW, 2000a). The particle size distribution test rendered the gravel material poorly graded, as indicated in Figure 2. The sampled pumice material contains about 71% gravel-sized particles, 1% sand-sized particles, and 28% fines. An average particle density of 0.5 g/cm^3 and water absorption of 119% were determined using standard procedures after soaking the sample for 24 hours. The fraction used for testing density and water absorption had particle sizes between 20 and 14 mm, and the same size was used to determine the crushing strength of the pumice using the Ten percent Fines Value (TFV) in dry state.

The TFV test is meant to measure the strength of road aggregates by determining their resistance against crushing under a gradually applied load. A 20–14 mm size fraction of the sample was used for testing with the objective of identifying the load required to crush the sample to give 10% material passing a 3.35 mm sieve as described in the standard testing manual. For most aggregates, the applied load in a TFV test ranges from 50 to 400 kN in 50 kN intervals. However, on applying the recommended loads, the pumice sample resulted in too high percentages of fines, such that A 50 kN

load yielded 37.50% fines, whereas a 100 kN load resulted in 63.64%, and a 150 kN load yielded 80.65% fines. These results are way above the intended 10% fines expected to be obtained by crushing the sample. Therefore, according to the standard procedure, the TFV value for this pumice material is way below 50 kN. In comparison, most road construction materials specified in the standard specification for road works (MoW, 2000b) have a minimum TFV of 50 kN.

After failing to obtain the TFV value using the standard procedure, it was decided to conduct a series of loading tests to determine the response of the pumice sample to loads smaller than the recommended values for the TFV test. The purpose was to establish a minimum load that would cause particle crushing. Figure 3 indicates a range of applied loads with magnitudes of 5 to 25 kN, where the corresponding fines produced ranged from 2.9 to 23.6%. It can be established from the trend in Figure 3 that the TFV value for the pumice sample is 12.8 kN, which is very small compared to specifications for road aggregates (MoW, 2000b). Even shale aggregates, which are softer than conventional road aggregates, were reported to have TFV values in the range of 120 to 170 kN in the dry state (Nweke and Okogbue). Considering the size of the plunger used to apply the load, the 5 kN force produced a stress of 0.27 MPa and caused 2.9% of the sample to crush, while the TFV value of 12.8 kN corresponds to a stress of 0.69 MPa and caused 10% of the sample to crush. These results are comparable to similar values discussed in Section 3 of this paper. Although the TFV test is recommended for road aggregates, the crushing value test results are a good indicator of how poorly the material will perform under static loading.

Fig2

Particle Size Distribution of the Sampled Pumice Material

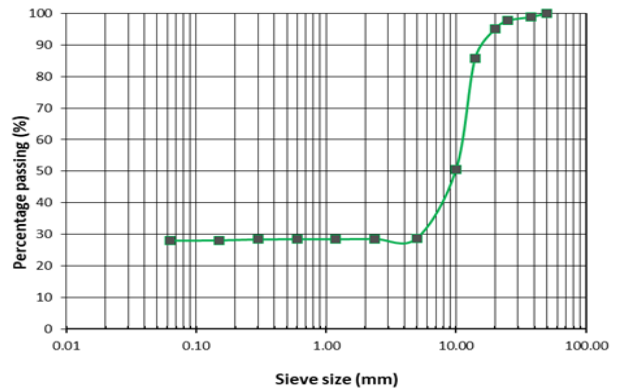
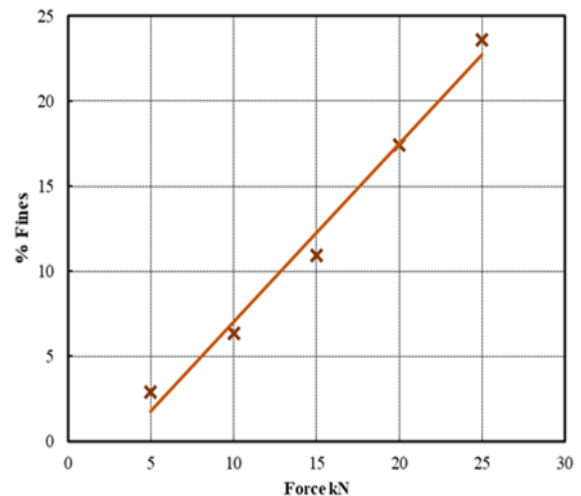


Fig 3

Relationship between Applied Load and Resulting %Fines for Sampled Pumice



7. Summary and Recommendations

The limited literature currently available has no absolute answer to the question posed in this paper about the ability of pumice materials to support structural foundations. However, the review has revealed several issues with regard to pumice as a geotechnical material:

- (i) Pumice soils require special considerations in testing. Some standard testing methods might not apply to pumice

materials due to their light weight, vesicularity, and crushability.

- (ii) Likewise, special consideration in the interpretation of test results is needed, especially for insitu tests, as pumice behaves differently in comparison to common soils. This peculiarity was observed in some dynamic probing tests conducted in Mbeya. More investigation is recommended to study insitu testing in pumice-rich soils.
- (iii) There is an opportunity to develop correlations between insitu tests, laboratory tests, and design parameters for pumice materials, as the common ones may not be applicable to the material.
- (iv) Pumice particles are easily crushable. This was verified by the laboratory Ten percent Value test (TFV) performed on a sample collected in Mbeya. The crushing load varies depending on the source, with acidic pumice more likely to crush at lower stresses than basic pumice.
- (v) Pumice might be a good candidate for insitu improvement for foundations. Their vesicular nature suggests a possible penetration by such materials as cement grout, which may result in strength improvement.
- (vi) Extensive studies are important before pumice can be used to support foundations. Until then, pumice can only be confidently used in other practises such as manufacturing light-weight concrete, facing bricks, hollow bricks, and cosmetics.

8. Funding Statement

This research did not receive any grants from funding agencies in the public, commercial, or not-for-profit sectors.

9. Acknowledgement

The author wishes to extend her sincere gratitude to Mr. Samuel Kihogo of Mbeya University of

Science and Technology for his assistance in conducting field and laboratory tests.

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