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BEHAVIOUR OF A CLAY AND GRAVEL MIXTURE

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Abstract. In most construction works, crushed rock aggregates with angular shape are used as subgrade materials. However, naturally available rounded granular aggregates could be utilized in design of subgrade layers as an alternative material for economic and environmental reasons. Therefore, a comparative study on the road pavement subgrade using aggregates of two different shapes (angular and rounded) of the same size (10–19 mm) has been conducted in this paper. The California Bearing Ratio and unconfined compressive strength tests were carried out on the mixtures of clay and different contents (0%, 5%, 10%, 15%, and 20% by dry weight) of both aggregates in order to evaluate the influence of the shape of these aggregates on the testing results. It was found that the mixtures with the rounded gravels showed a greater maximum dry density, unconfined compressive strength and CBR value, as well as lower optimum water content value, than those with the angular gravels.

Keywords: clay, gravel content, gravel shape, laboratory tests.

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Introduction

Aggregates used in the road pavement subgrade in both flexible and rigid pavements are usually obtained from rock formations in the open quarries. These rock fragments are typically shaped to the sizes required for pavements by mechanical crushing. Traditional high-quality crushed aggregates used for road pavement subgrades are becoming increasingly scarce and expensive in many countries as rock quarries are either being lost to alternative land uses or restrained from mining due to public conservation. Therefore, the pavement engineers have worked on providing road infrastructures with maximally cost-effective and environmentally friendly solutions by increasing the use of locally and naturally available rounded aggregates, which under appropriate circumstances could find their optimal use in road constructions without compromising their performance. Design of road pavement subgrades using alternative materials still remains one of the most considerable challenges in geotechnical engineering, in particular because of the economic and environmental concerns. For example, locally available river gravels as a versatile alternative can be obtained cheaply without the need to subject them to any physical treatment; their use does not have a significant impact on the environment. However, such aggregates have not been used in construction of road pavement subgrades in Turkey, although they are used in construction of truck arrester beds across the country. Actually, the main difference between the crushed rock and river gravel size aggregates is that the crushed rock broken down by machines typically has a more angular shape. In contrast, naturally available gravels are produced by the natural process of erosion, which determines their more rounded shape. The fact is that the shape of such gravels has a significant effect on various engineering properties of the soil matrix including strength (Yagiz, 2001), density (Mirghasemi et al., 2002), liquefaction (Toyota and Takada, 2019), and compressibility (Nocilla et al., 2019). For example, Monkul et al. (2017) studied the physical characteristics including the effects of aggregate shape of the silt grain matrix within sand on the static liquefaction of sand-silt mixtures. They found that the shape of grains in certain cases had more influence on the behavior of the mixture than the size of grains. Shen et al. (2018) systematically studied the effect of gradation on the compressibility characteristics of a calcareous sand, they analyzed the testing results from a mesoscopic point of view. The amount of coarse grains was found to have the greatest effect on the compressibility of the specimens tested mainly due to the high angularity of coarse fractions. Siahaan et al. (2018) presented a laboratory investigation on the response of a stone column placed in clay with a particular emphasis on the effects of grain shape and gradation. They discovered that the presence of angular grains in the stone column increased its bearing capacity, while addition of sub-rounded grains resulted in a relatively narrow bulging zone. Cabalar et al. (2021) analyzed the influence of the size and shape characteristics of sand grains on both shear wave velocity (Vs) and maximum shear modulus ($G_{\max}$) of sand-clay mixtures. The testing results have demonstrated that the mixtures with rounded sand grains exhibited a much higher Vs and $G_{\max}$ values than the mixtures prepared with angular sand grains. The studies on the influence of grain shape on the overall response of a soil matrix have been carried out for a long time (Terzaghi, 1925). In the studies by Muszynski and Vitton (2012), typical analysis of grain shape was conducted mainly using two independent properties – (i) Roundness (R), a scale indicating how much the corners and edges of a grain are rounded, and (ii) Sphericity (S), a scale indicating whether a grain approaches the spherical shape.

Although many researchers have studied the influence of grain shape on various engineering properties of road pavements, little attention has been paid to filling the gap in understanding of the effect of grain shape characteristics on the testing results. Therefore, a systematic investigation of the experimental studies employed in different forms in the design of road pavements is presented in this paper. The study aims to comprehensively analyze the amount of aggregates in the specimens prepared using gravel size aggregates and clay mixtures as well as the impact of the grain shape of the aggregates on the properties of the mixture. Accordingly, the study presents the testing results of CBR, UCS, compaction, and 1-D consolidation of two differently shaped (angular, rounded) gravel-size aggregates mixed with water and clay at different contents ranging from 0% to 20% (by dry weight) of aggregates in the specimens. It is expected that the analysis of the testing results regarding the shape of individual gravel grains, the amount of aggregate, and water content can be used as an input in further research.

1. Experimental study

1.1. Materials

Rounded Narli Gravel (NG), angular Crushed Rock Gravel (CG), clay with silt (ML), and distilled water were used to prepare the specimens tested during the laboratory tests. Naturally available NG samples were obtained from the Aksu River in Narli/Kahramanmaras Region in southern central Turkey. Commercially available CG samples were produced by crushing the rocks quarried in the same area into angular gravel size pieces. Figure 1 shows the differences in the shapes of NS and CG grains. Specific gravity (Gs) values of the grains were found to be 2.65 for NS and 2.68 for CG. The size of the aggregates was artificially selected in the range of from 10 mm to 19 mm to eliminate the effect of the size of the aggregates on the testing results and to maintain uniformity during the tests (Figure 2). The grain shapes of NG and CG were found to be rounded and angular, respectively. Roundness (R) for the CSS and NS grains was estimated at 0.16 and 0.43, and Sphericity (S) was estimated at 0.55 for CSS and 0.67 for NS grains by adopting the study by Muszynski & Vitton (2012). Eventually, the NG and CG grains have been considered as sub-rounded and very angular, respectively (Powers, 1953).

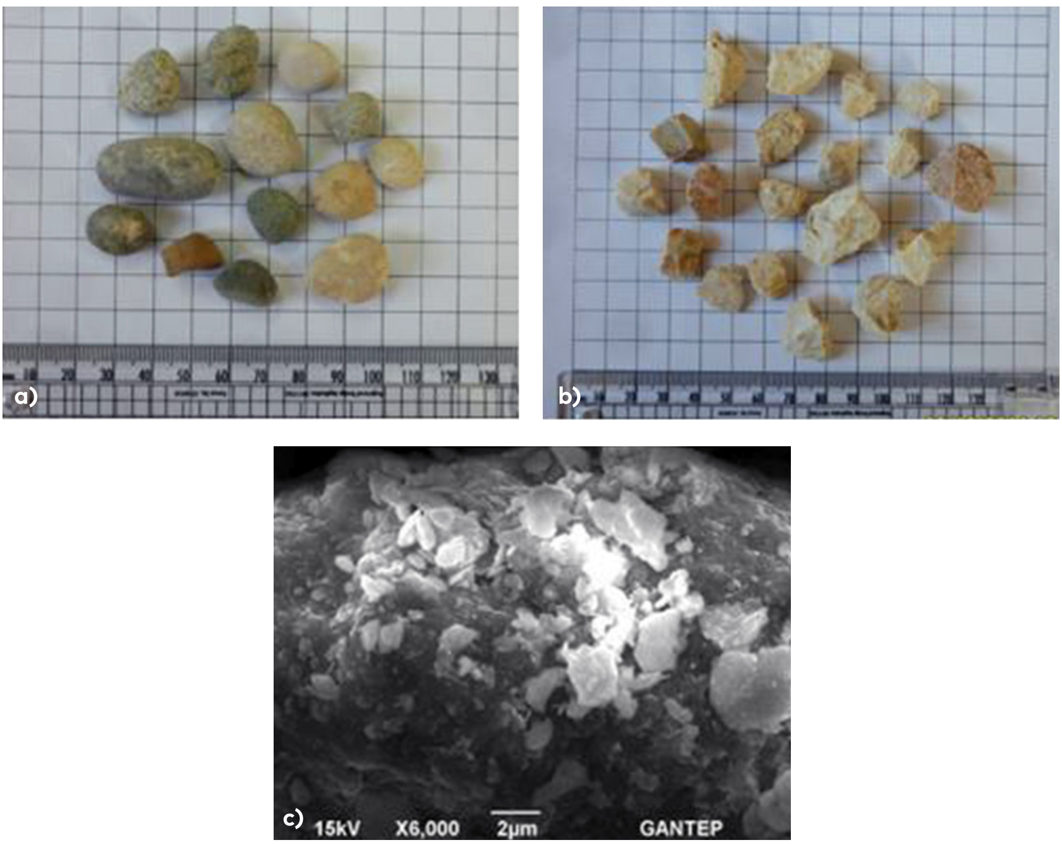

Figure 1. Images of NG (a), CG (b), and SEM of clay (c) used during the laboratory studies

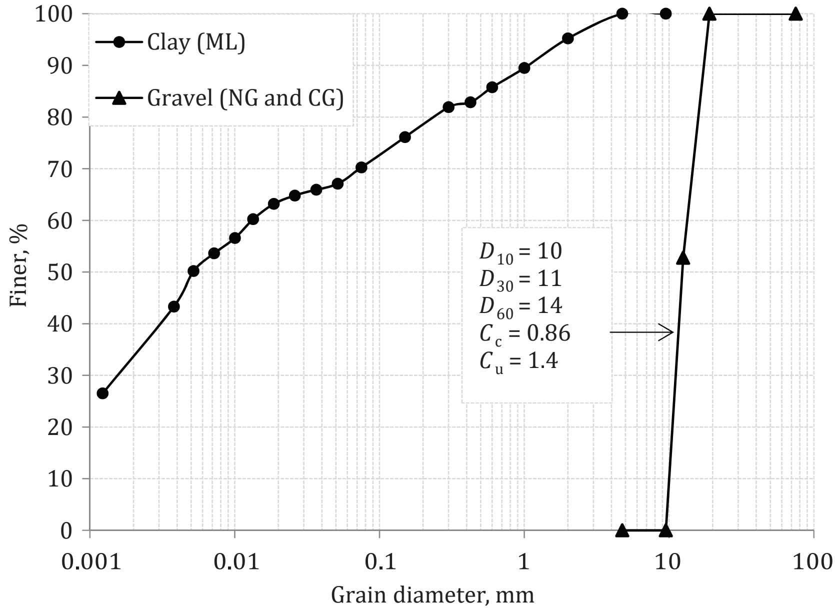

Figure 2. Grain size distribution for the clay and gravels used during the laboratory studies

The clay samples utilized in the study were obtained from the University of Gaziantep. The grains of clay have a *Gs* of 2.7. The Atterberg's limits were found to be 27 and 36 for PL and LL, respectively (ASTM D4318, 2010). Figure 2 shows the particle size distribution of the clay samples. Thus, according to the unified soil classification system (USCS), the soil has been classified as ML (clay with silt), and according to the system of American Association of State Highway and Transportation Officials (AASHTO), the soil classified as A-4(6) and its general rating of subgrade is (fair to poor). Two different types of materials were used as additive, which are naturally available rounded gravel size aggregates (NG) and crushed rock angular gravel size aggregates (CG). The NG and CG samples with diameter less than 19 mm and greater than 10 mm were synthetically selected to produce uniform specimens.

1.2. Testing apparatus and specimen preparation

The CBR testing machine was used for evaluation of the load-bearing capacity of gravel-clay mixtures. Thickness of the pavement required has a traditional loading frame with capacity 28 kN and a dial gauge with 0.01 mm sensitivity. About 5 kg of specimens with various percentage (0%, 5%, 10%, 15%, and 20%) of aggregates was mixed with the optimum water content, then compacted into five layers by giving 56 blows using a 4.89 kg weight hammer (ASTM D1883, 2011). The specimens were soaked in water for 96 h prior to penetration testing. The UCS tests were also conducted on the gravel-clay mixtures prepared at the optimum moisture content by means of a machine with 4.5 kN proving ring, and 0.01 mm sensitivity dial gauge. The UCS tests were carried out using a specifically designed equipment described by Cabalar et al. (2014). The specimens were compacted into molds by means of a custom designed hammer. The required amount of compaction energy applied using the hammer was determined by calibrating dry unit weights and adjusting the number of blows by both the conventionally modified hammer and the specially designed hammer (ASTM D1557, 2009). 1-D oedometer tests were carried out in order to define the consolidation characteristics of the mixtures at the optimum moisture content placed in the mold with the diameter of 50 mm and height of 20 mm. The tests were conducted according to (ASTM D2435, 2011).

2. Results and discussion

A wide range of laboratory tests including compaction, CBR, UCS, and oedometer tests was undertaken to fully characterize the behavior of clay with different shapes of gravel size aggregates at the ratios of 0%, 5%, 10%, 15%, and 20% by dry weight. The summary of these experimental results is presented in Table 1. The data show that the type and quantity of the aggregates have a significant effect on all testing results concerning different aspects of construction behavior. Figure 3 provides detailed information on the compaction tests performed on both clay-NG and clay-CG specimens. It is observed that the maximum dry unit weight (γ_{dmax}) values increase whilst the optimum water content (w_{opt}) values decrease irrespective of the type of gravel employed in the mixtures. For instance, 17.6 kN/m^{3}of γ_{dmax} value for the clean clay increased to 18.1 kN/m^3 with addition of 5% NG, to 18.45 kN/m^3 with addition of 10% NG, to 19.05 kN/m^{3}with addition of 15% NG, and to 19.15 kN/m^3 with addition of 20% NG to clay, while, the w_{opt} value of clean clay (18.1%) decreased to 16.0%, 14.9%, 14.2%, and 13.8% with the addition of 5%, 10%, 15% and 20% of NG, respectively. Figure 4 correlates γ_{dmax} and w_{opt} values for different gravel types and contents in the clay. According to the papers (Naeini and Baziar, 2004; Monkul and Ozden, 2007; Cabalar and Hasan, (2013); Cabalar and Mustafa, 2017), this behavior is likely to be explained by a lower water absorption capacity and higher maximum dry density of clean gravel samples in the mixtures tested in the compaction mold. It has also been recognized that the response of the mixtures is significantly affected by the shape of the gravel grains. Specimens with the NG samples were found more sensitive to water changes than those with CG samples, possibly due to the lower amount of clay grains available in the mixtures. The increase in grain shape irregularities leads to increase in voids in a soil matrix (Cho et al., 2006), which results in a lower amount of clay available in the tighter packed specimens with NG samples. These findings allow recognizing the effect of the grain shape on the mixtures.

Specimen	CBR, %	γ_{drymax}, kN/m^3	*w*opt, %	SP, %	q_u, kN/m^2
Clean clay	7.2	17.6	18.1	1.1	256
Clay + 5% NG	7.9	18.1	16	1.45	282
Clay + 10% NG	8.3	18.45	14.9	1.32	327
Clay + 15% NG	9.03	19.05	14.2	0.65	432
Clay + 20% NG	9.6	19.15	13.8	0.5	403
Clay + 5% CG	7.3	17.77	16.4	1.5	326
Clay + 10% CG	7.4	17.92	15.4	1.4	406
Clay + 15% CG	8.4	18.58	14.5	0.9	444
Clay + 20% CG	9.3	18.68	14.2	0.6	416

CBR – California Bearing Ratio, γ_{drymax} – maximum dry unit weight,
w_{opt} – optimum water content, SP – swelling percentage,
UCS – unconfined compressive strength, NG – natural rounded gravel,
CG – crushed rock angular gravel.

Figure 5 presents the stress-strain relationships for the various mixtures of clay-NG and clay-CG compacted at w_{opt} using an unconfined compressive strength (UCS) testing apparatus. Both shape of the gravel grains and amount of the gravels were observed to have a significant effect on the response of clay-gravel mixtures. It was observed that the maximum unconfined compressive strength (q_u) values increased with additions of the gravel up to 15% content, then decreased with addition of 20% content (Figure 6). Thus, the maximum q_u value of clean clay was 256 kPa, then it increased to 326 kPa by adding 5% CG, to 406 kPa by addition of 10% CG, and to 444 kPa by addition of 15% CG. However, it may be noticed that the maximum q_u value of clay with 20% CG decreased to 416 kPa. Actually, such behavior could be explained by the floating/non-floating concept of grains in the void of the soil matrices (Thevanayagam and Mohan, 2000). Initially, gravel grains were thought to be sufficiently away from each other, floating

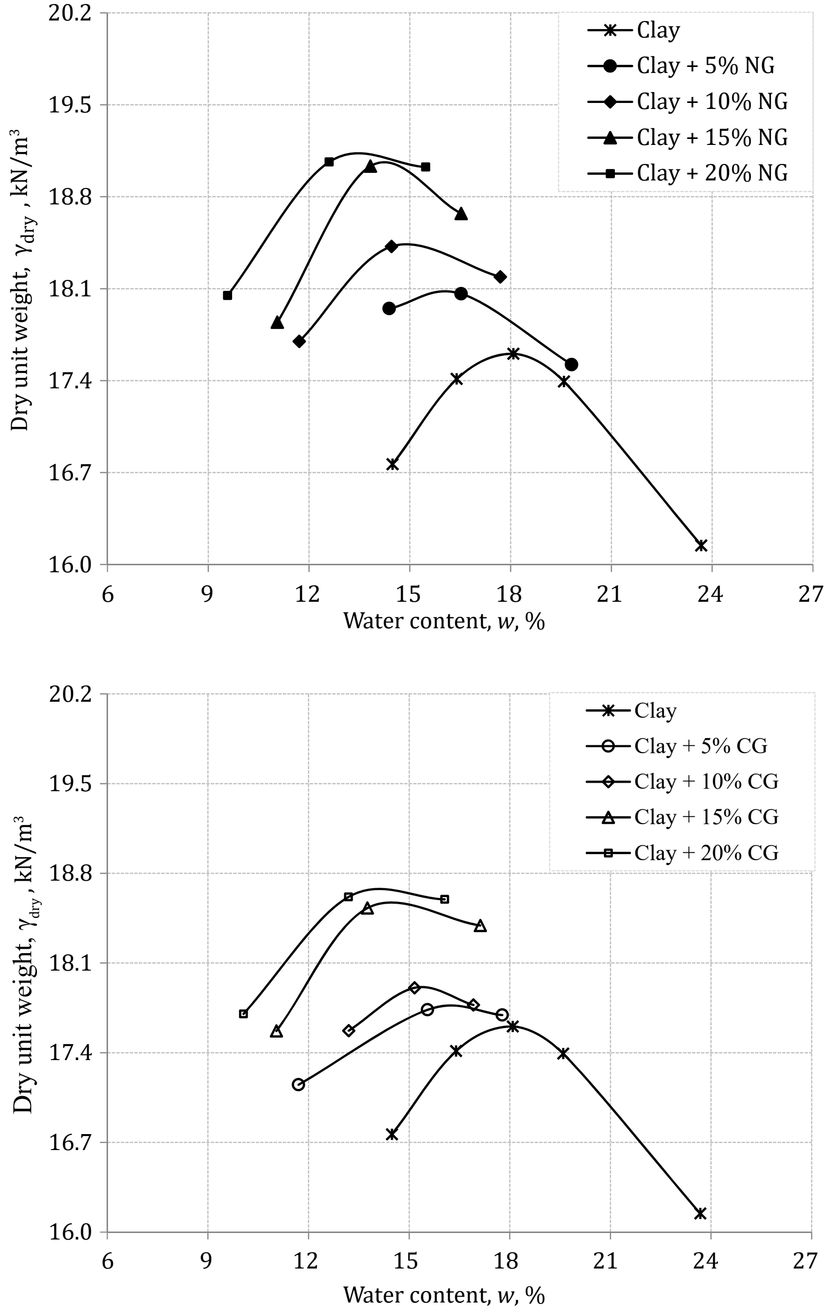

Figure 3. Compaction curves for clay with NG (top) and CG (bottom)

in the clay matrix, which governed the overall behavior of the mixture. However, the establishment of direct contacts between gravel size grains was initiated with further additions of either CG or NG, and the behavior of the mixture started to be mainly governed by these gravel size aggregates. The gravel content, at which the intergranular void ratio of the clay-CG/NG specimens (e_s) is equivalent to the maximum void ratio of the gravel aggregates (e_{max}), is described as ‚transition gravel content (GCt)'. The GCt values for both mixtures were found to be around 15%, since the soil matrix behaves in a certain way if the gravel content (GC) is less than 15% and in a different way if it increases above 15% of the gravel content in the mixture. The GCt apparently depends on e_{max} of gravel grains, which mainly changes with the shape of these grains. Eventually, the clay with CG samples seems to have higher q_u values than the clay with NG samples for all mix ratios, because more clay grains are available in a greater amount of void space between CG grains. Actually, numerous researchers have referred to the plasticity of fines, as well as grain size and shape of host materials in such mixtures in order to establish the ideal packing of coarse-fine grain mixtures (Simoni and Houlsby, 2006; Kyambadde and Stone, 2012). Furthermore, addition of gravel, particularly of CG grains, affected the energy absorption capacity positively in most cases. As shown in Figure 7, the effect of CG addition was found to be more pronounced for the specimens prepared with

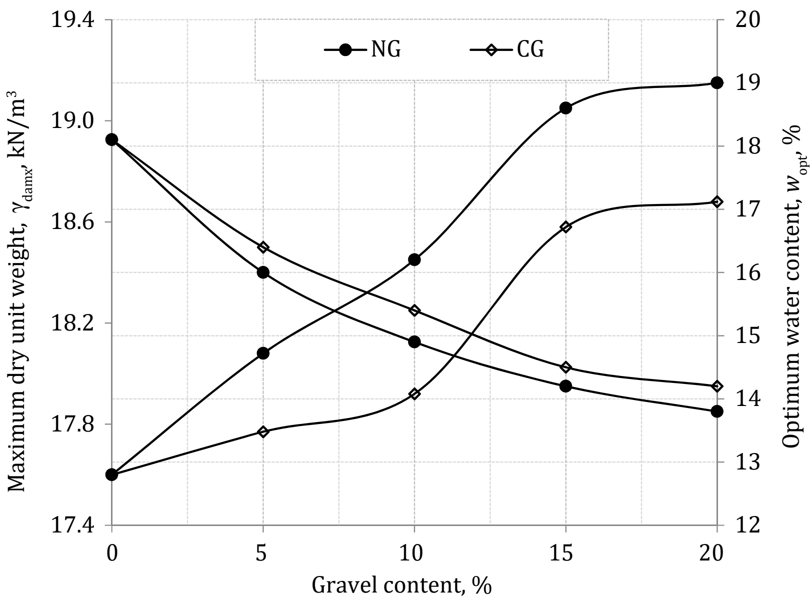

Figure 4. γ_{dmax} and w_{opt} values for clay containing different gravel types and contents

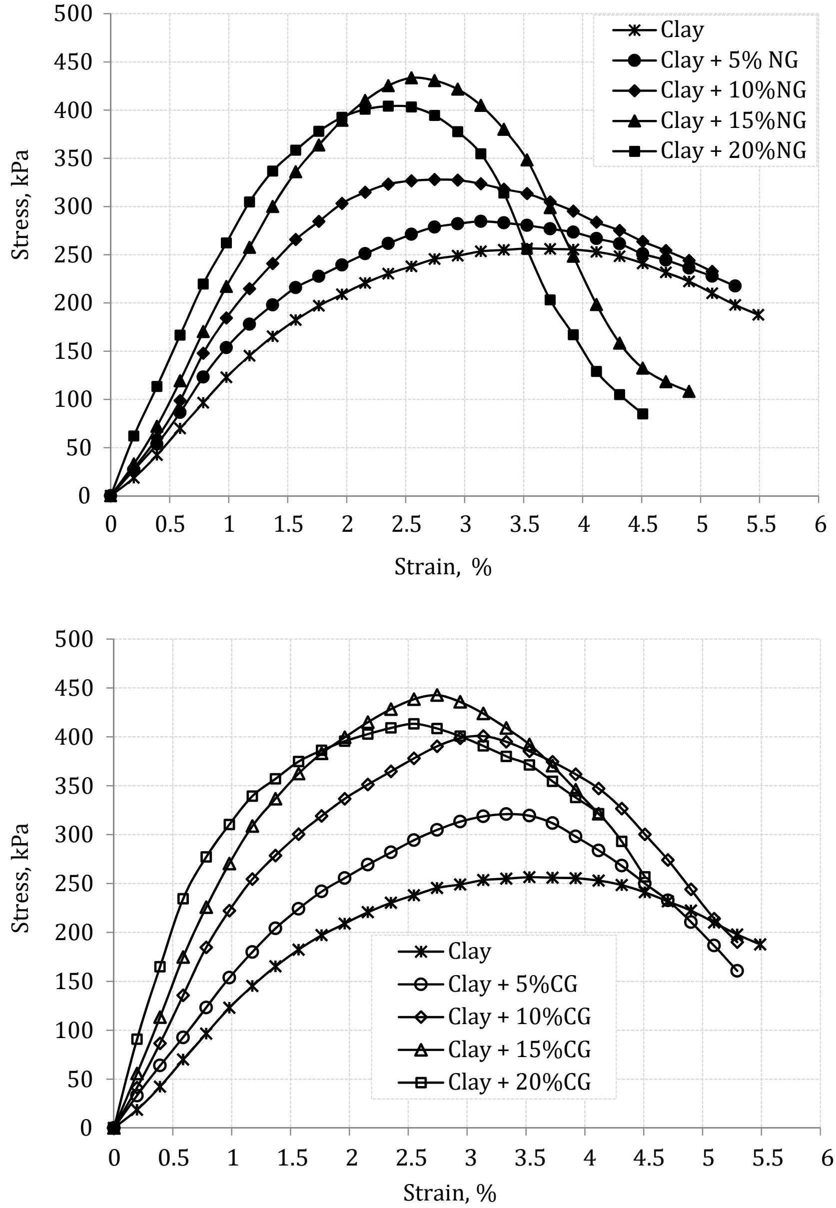

Figure 5. Stress-strain relationship for the clay with NG (top), and CG (bottom)

the same amount of gravel samples. To make a distinction between the effects from gravel additions on the behavior of clay-gravel mixtures, the authors refer to the shape characteristics rather than the grain size and mineralogical properties of the gravels, since both gravel samples come from the same parent rock and were artificially selected to be in the range between 10 mm and 19 mm in diameter. Hence, the reason for lower energy absorption capacity values of the clay-NG specimens seem to be fewer clay grains in relatively smaller void spaces between the NG grains, which packed tighter than the CG grains under the same stress levels.

The values of California Bearing Ratio (CBR) versus water content for the specimens are given in Figure 8. Today, it is widely known that the CBR values may change with certain parameters including γ_{dmax}, w_{opt}, Atterberg's limit, and permeability (Cabalar and Mustafa, 2017). The present study has recorded a significant increase in the CBR values with the addition of gravel samples. The maximum CBR value of the pure clay samples was 7.2%, although the CBR values reached 7.90%, 8.30%, 9.03% and 9.60% with the addition of 5%, 10%, 15% and 20% NG samples to the clay. Contrary to the UCS testing results, Figure 9

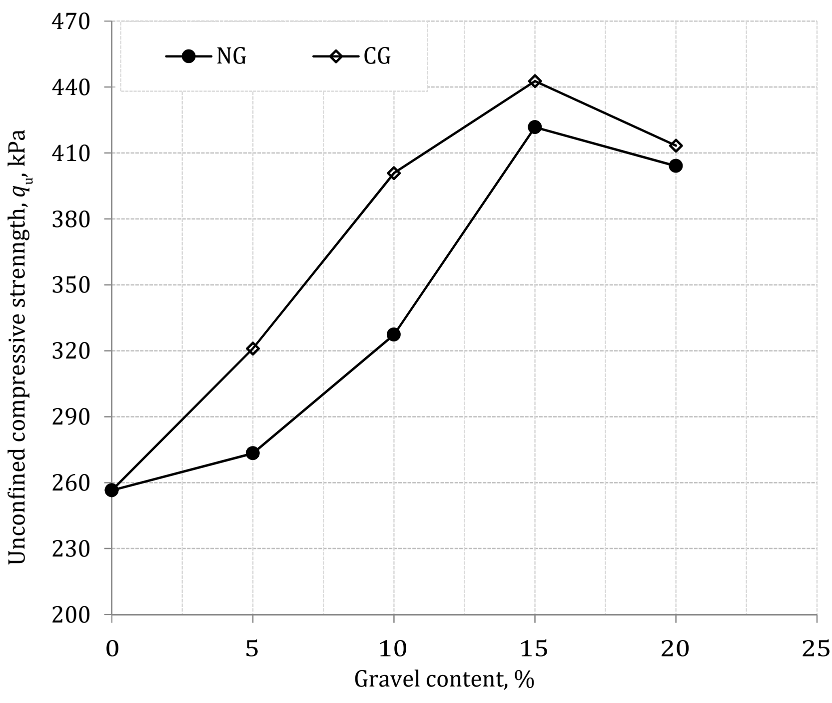

Figure 6. Change in q_u for the clay with NG and CG

shows continuously increasing values within the mix ratios employed during the experimental studies, as well as higher resistance to plunger penetration (strength) in the clay-NG specimens. This might be because of the differences between the UCS and CBR testing approaches (ASTM D2166, 2000; ASTM D1883, 2011). The authors consider that the presence of large amount of clay in the void space of CG samples, which should be expected to be greater than the amount of voids in the specimens with NG samples due to gravels' shape characteristics (Yagiz, 2001; Cho et al., 2006), was the main factor resulting in higher q_u values in the specimens with CG samples. On the other hand, quasi confining pressure applied by the CBR mold, which confines the specimens, was considered to have a significant effect on the results. The specimens with NG samples are expected to have less void space than those with CG samples, and this leads to a closer packing of grains in the specimens with the application of the normal load on top of the specimens in the mold. It has resulted in a higher CBR performance of the specimens with the NG samples compared to the specimens with the CG samples. For example, the difference between the CBR value of the specimen with 20% NG, which is about 9.03%, and the CBR value of the specimen with 20% CG, which is about 8.4%, clearly indicates a better CBR performance of the specimens with addition of NG because of the shape characteristics of the grains.

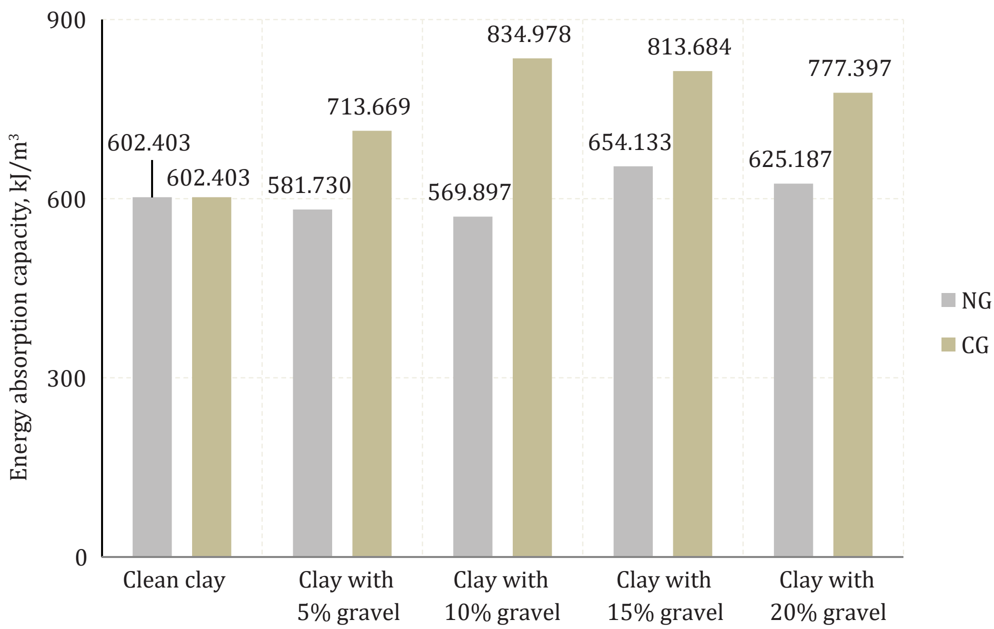

Figure 7. Enegry absorption capacity of the specimens

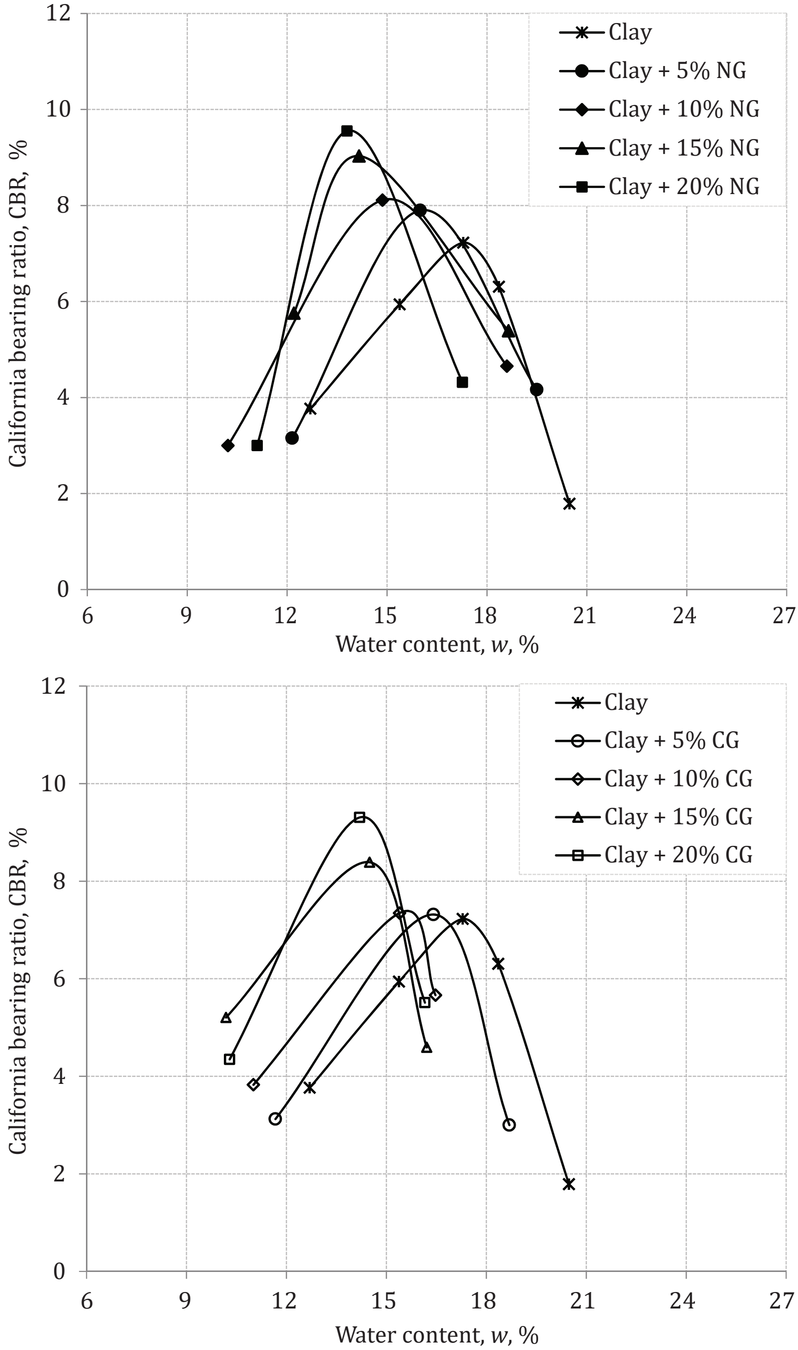

Figure 8. CBR values as a function of water content of clay with NG (top) and CG (bottom)

Void ratio was found to be the main factor affecting the overall response of the specimens. The influence of grain shape and the content of the gravel size aggregates on the initial void ratio (e_0) can be clearly seen in Figure 10, which was obtained by 1-D oedometer tests. The e_0 values of the specimens decreased gradually from about 0.53 to 0.48, and to 0.45 with addition of 15% CG and NG samples, respectively. Interestingly, no significant change in e_0 values was evident in the testing results, likely because of the presence of gravels more than GCt value (15%) in the mixtures, at which the gravels contact each other, govern the overall response of the mixtures, and do not swell during testing. It is also seen that the position of the data points for CG samples in the plot area represents high values of void ratio and the presence of high amount of clay, which causes a greater compression index (c_c) and swelling index (c_s) in all specimens tested within the range of various gravel contents up to 20% (Figs. 11–12). These findings appear to be in line with numerous studies (Yagiz, 2001; Cho et al., 2006; Yun and Santamarina, 2008).

As a result of intensive series of testing, it was experimentally observed that mixtures with rounded gravels showed a greater maximum dry density, unconfined compressive strength and CBR value, and lower optimum water content value than those with angular

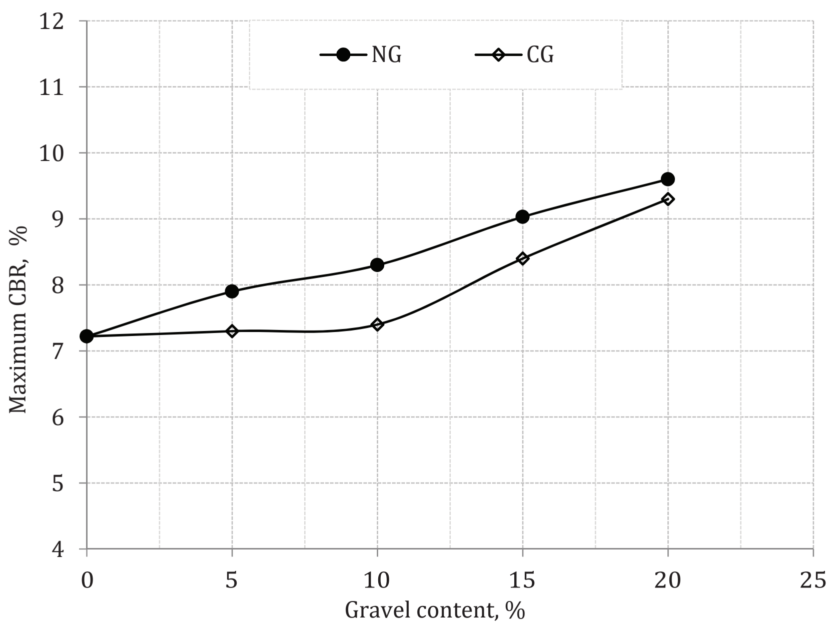

Figure 9. Variation of CBR for the clay with NG and CG

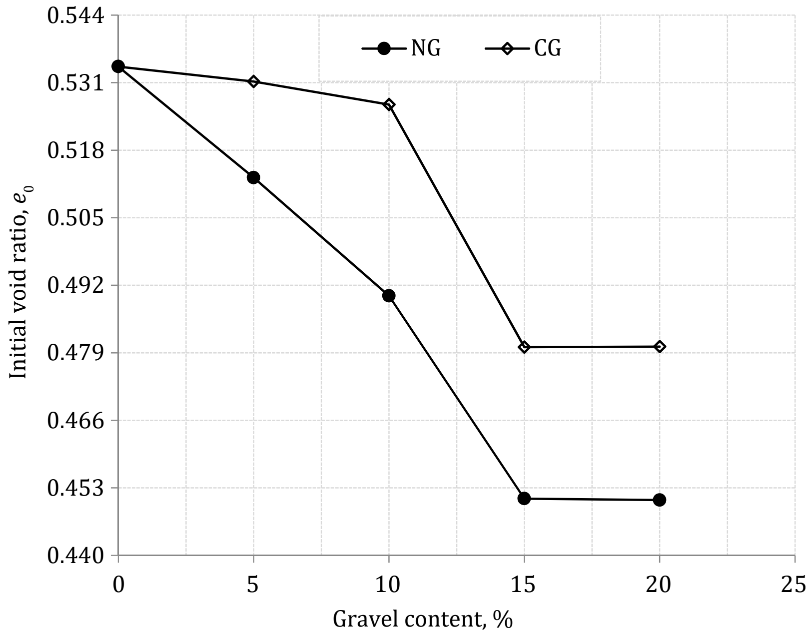

Figure 10. Variation of e_0 in the clay with NG and CG

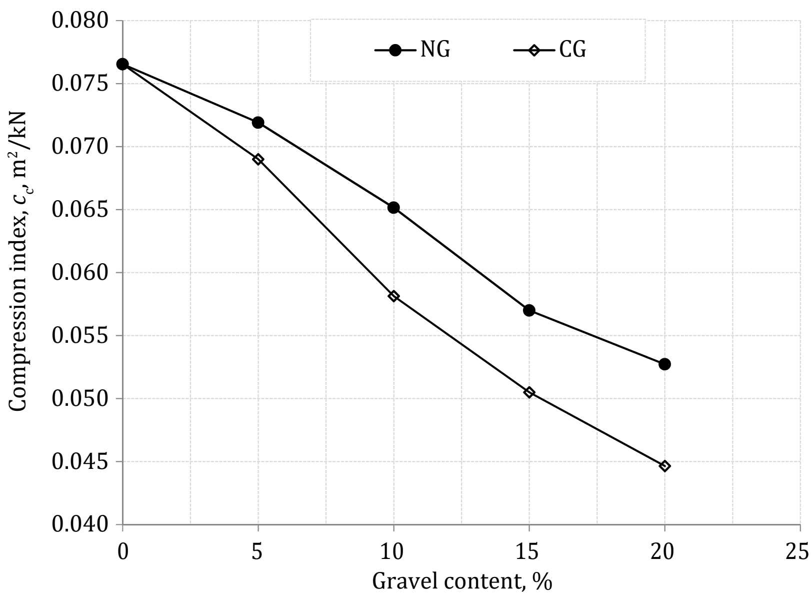

Figure 11. Variation of c_c in the clay with NG and CG

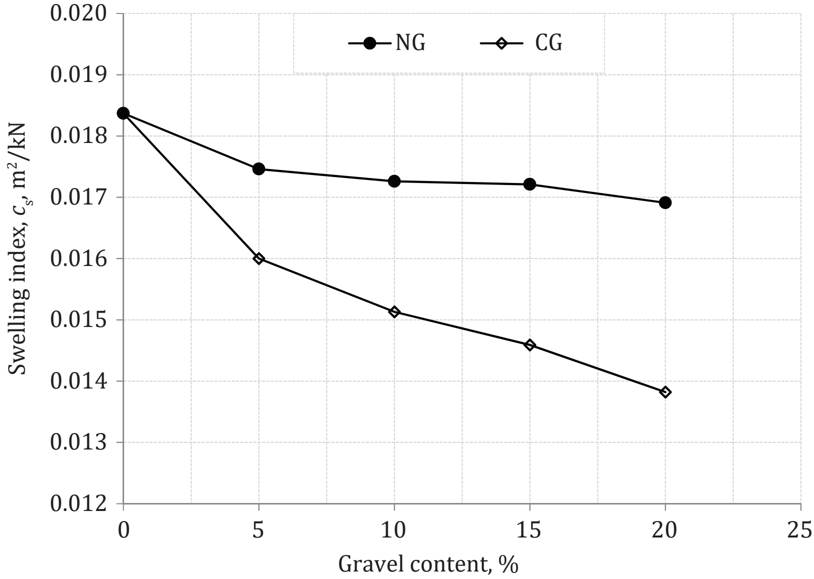

Figure 12. Variation of c_s in the clay with NG and CG

gravels. Considering these facts, the study revealed a novel outcome that rounded gravels in clay showed a better response than the angular gravels. These results are believed to have the potential to relatively decrease the environmental effects associated with the economic activities and direct or indirect effects of open mining activities of the quarry enterprises, which extract angular shaped aggregates used in road pavement constructions. Some of the worst environmental effects associated with economic activity may include (i) changes in the hydrology of waterways, (ii) resettlement of families, (iii) encroachment into forests and swamplands, (iv) encroachment on historical or cultural monuments, buildings, transport links, and (v) flooding and drainage hazards (Monjezi et al., 2009).

Conclusions

Nowadays, utilization of natural resources is closely related with both sustainable economic growth and mitigation of possible effects on the environment. Currently, natural gravel size aggregates have limited direct use in constructing road pavement subgrade. For this reason, the present study aimed to propose the use of locally available gravel size natural aggregates (NG) for road pavement design as an alternative material to commercially available gravel size crushed aggregates (CG). Accordingly, an intensive series of laboratory tests including compaction, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and 1-D consolidation have been carried out on the mixtures of low plasticity clay (CL) with NG or CG at various ratios (0%, 5%, 10%, 15% and 20% by dry weight) in order to analyze the response of gravel size aggregates in road pavement design. The tests reported in this study present four new facets of behavior of the studied materials:

1. Adding gravel size aggregates to clay has resulted in a significant increase in γ_{dmax} and decrease in w_{opt} of the mixtures prepared at various mix ratios. The clay with rounded gravel samples (NG) has a greater γ_{dmax} and a lower w_{opt} than the clay with angular gravel samples (CG) for all mixtures.
2. Addition of gravel size aggregates, regardless of the type of grains, has increased q_u values up to 15%, and then decreased them. Based on the floating/non-floating concept of grains in the voids, 15% gravel content was described as ‚transition gravel content (GCt)'. Adding of gravel samples was found to affect the energy absorption capacity positively in most mixtures.
3. CBR values of the specimens increased substantially along with addition of gravel size aggregates. Specimens with NG samples demonstrated a better CBR performance than the specimens with the CG samples due to high strength of gravel grains and quasi confining pressure applied by the CBR mold.
4. Consolidation testing results have indicated substantial decrease in e_0, c_c, and c_s values for all mixtures apart from e_0 values at 20% gravel content, which is greater than GCt. The gravel grains were in contact with each other in these mixtures. On the other hand, change in c_c and c_s values at 20% gravel content was probably due to crushing of the grains under high loads.

This suggests that behavior of clay with gravel size aggregate mixtures depends on the grain shape and content of the gravels with same mineralogy and size. Evaluation of the transitional gravel content, which is the boundary between fine-domination and coarse-domination of a mixture, is required to analyze the overall response of such composite materials made of clay and gravel size aggregates.

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