PARTIAL REPLACEMENT OF SAND WITH GLASS WASTE FOR GEOTECHNICAL APPLICATIONS

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ABSTRACT

Natural sand has become a crucial building and construction material since rapid urbanization is ongoing worldwide, which shortens natural resources due to excessive extraction. In that case, waste glass recycling can substitute sand in various geotechnical applications, as sand and glass represent almost similar chemical components. Using crushed waste glass as an alternative to natural sand could provide a dual benefit by assisting in the joint solution of natural sand depletion and waste glass disposal. In this research, crushed waste glass was applied to the sand in different percentages to investigate the effect of glass powder. Crushed waste glass was mixed with sand samples containing 5%, 10%, 15%, 20%, 25%, 30%, and 35% of sand by dry weight. The effects were analyzed through compaction test, direct shear test, and California Bearing Ratio (CBR) test. The test results show that maximum dry density (MDD) increased and optimum moisture content (OMC) decreased with the increased crushed waste glass powder. The shear strength parameter and CBR value also improved significantly with increased crushed waste glass powder percentages in natural sand. The cohesion of samples increased from 0 kPa to 5.7 kPa, and the angle of internal friction increased from 41.5° to 44.4°. Moreover, the CBR value of natural sand increased by 17.42% and and found to be 46.5% for NS+30% CWG. The geotechnical test results were further supported by an imaging technique called scanning electronic microscopy (SEM). The higher angularity of CWG particles than that of the sand provides better resistance against vertical and shear forces with broken CWG filled the tiny void in the mixtures, leading to superior mechanical behavior of sand-CWG mixtures than sand. As crushed waste glass with sand shows comparable and improved geotechnical properties, it can be used in different geotechnical applications like foundations, pavement bases, and backfilling works.

Keywords: *Sand replacement, crushed waste glass, shear strength parameter, California Bearing Ratio*

1. INTRODUCTION

Depleting valuable natural resources and accumulating solid wastes in landfills are two major problems that need to be addressed immediately. Natural sand is a commonly employed raw material in the construction, ceramic, glass, foundry, and automotive industries due to its attractive properties, easy availability, and economy. Around 50 billion tons of sand and gravel are mined globally each year (Greene, 2022), putting the once-considered infinite natural resource in danger of running out (Cousins, 2019). Over-extraction of sand gives rise to major environmental issues such as changes in channel morphology and flow of rivers, flooding of cultivable lands, and the loss of habitat and biodiversity (Koehnken et al., 2020). It has become crucial to look for an alternative to natural sand to lessen the reliance on this finite resource (Kazmi et al., 2020). As glass is very similar to sand in composition (Disfani et al., 2011) and can be entirely recycled conserving its original properties (Paynter & Jackson, 2016), waste glass can become a potential alternative to sand. A massive amount of waste glass is being generated that is challenging to exclude from the environment (Pacheco-Torgal, 2020). In the year 2018, 12.3 million tons of glass waste was generated in America while 7.6 million tons were landfilled. Replacing natural sand with waste glass not only creates a scope for preserving natural sand but also addresses the major concern of a vast accumulation of waste glass in landfills (Ferdous et al., 2021). Wartman et al. (2004) conducted tests on compaction characteristics, direct shear, and permeability, revealing that CWG has excellent strength and workability characteristics and can be used in a wide range of civil, construction, and geotechnical engineering applications. Crushed waste glass can be added to soil to improve its mechanical properties, such as stiffness and bearing capacity (Johari & Sharma, 2021). The glass composition makes it an ideal engineering material with diverse applications in several fields. Glass is mainly composed of silica along with various oxides of sodium, potassium, calcium, aluminum, boron, lead, sulfur, chromium, and iron. One of the most popular uses of glass waste is as a replacement of aggregate or cement in concrete but the effectiveness of glass is very limited in this case as alkali-silica reaction (ASR) leads to a decline in concrete quality (Kazmi et al., 2020; Topçu & Canbaz, 2004). However, no such complication arises in using waste glass as asphalt aggregate, as backfill material, in embankments, as drainage material, as filter media, and in road pavements (Disfani et al., 2009).

1.1 CWG as recycled materials for civil engineering applications

Su and Chen (2002) conducted a study by substituting aggregate with glass in asphalt concrete that showed optimum asphalt content decreases with the increase in glass content and although the stability values of the asphalt concrete decrease, it is within standard limits. The low water absorption of crushed glass cullet reduces the active pressure on the back of retaining structures, making it an ideal engineering fill material (So et al., 2015). Mohajerani et al. (2017) claim that a 15% replacement of asphalt aggregate with waste glass can retain the durability of pavements. On assessing the environmental impact of using glass as pavement material, Imteaz et al. (2012) found the pH, conductivity, chloride and sulfate, organics, and surfactant below the accepted limits given by EPA Victoria Guidelines or National Australian Standards. Waste glass has also been used in clay bricks that can be used to construct load-bearing structures (Loryuenyong et al., 2009). Moreover, granulated foamed glass can be used in concrete by replacing 15% fine aggregate and 40% coarse aggregate without compromising the quality of concrete (Limbachiya et al., 2012). Fu et al. (2021) produced a new type of self-cleaning, lightweight, and high-strength porous ceramic material using glass waste ensuring additional economic benefits alongside the traditional value of glass recycling. Since the replacement of natural aggregate with waste glass has shown promising results in various civil engineering applications, this study intends to replace sand particles with crushed waste glass (CWG) while maintaining a constant fineness modulus (FM) to ensure the true replacement of sand by substituting sand particles with equal-sized glass particles. This approach helps study the true replacement potential of glass compared to arbitrary percentage replacement.

2. METHODOLOGY

2.1 Materials

The natural sand used in this research was collected from the Sari River in Sylhet, Bangladesh. The samples were oven-dried at 110°C for 24 hours and passed through a 4.75 mm sieve. The waste glass shards were obtained from a local store selling a variety of glass products. Mortar and pestle were used to crush the collected sample, and the particles that passed the 4.75 mm sieve were preserved. The specific gravity of natural sand and CWG were obtained to be 2.68 and 2.50, respectively. The particle size distribution test graph for NS and CWG is shown in Figure 1. Fineness modulus (FM) for sand was 2.7, while FM for CWG was found to be 2.9. The dry density of NS and CWG was found to be 1816 kg/m^3 and 1740 kg/m^3, respectively.

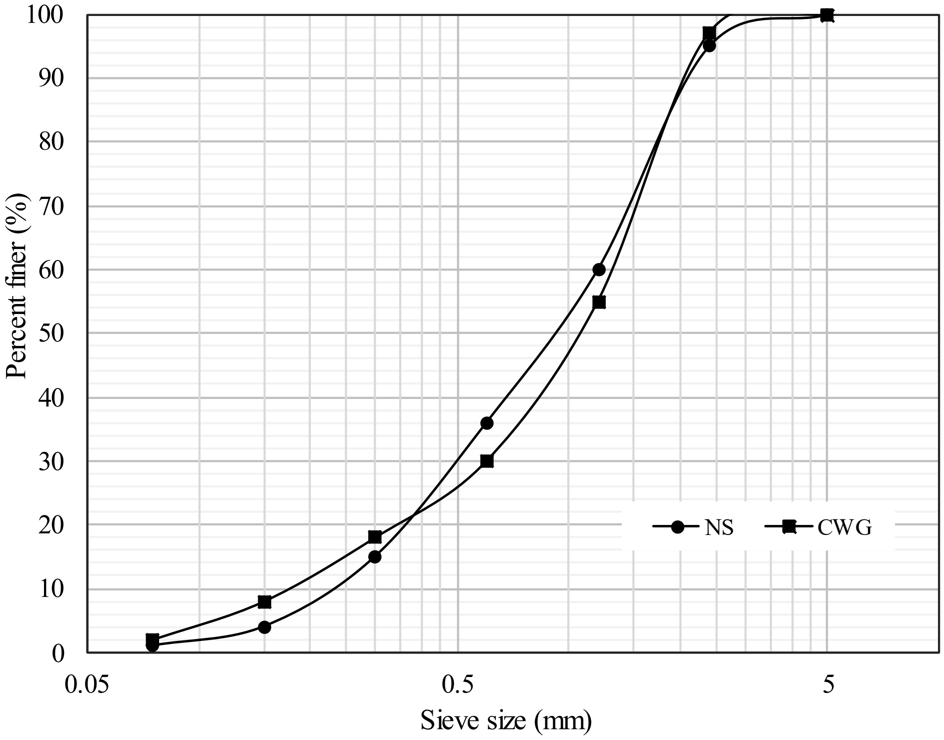


Figure 1: Particle size distribution of used materials

2.2 Tests of geotechnical properties of soil

The samples were prepared by mixing CWG with sand at 5%, 10%, 15%, 20%, 25%, 30% and 35% by dry mass. In each case, glass particles were added to soil samples maintaining a constant fineness modulus of 2.9. For the determination of maximum dry density (MDD) and optimum moisture content (OMC), compaction tests were carried out following ASTM D1557 (2012). As per the standard procedure, in each test, the modified effort of 2,700 kN-m/m^3 was applied in a mold of 10.16 cm in diameter, and the soil was compacted into five layers with 25 blows in each layer. After determining the OMC of different samples, the CBR mold having a diameter of 15.5 cm and a height of 13.5 cm was prepared with compacted samples at the optimum water contents, and California Bearing Ratio (CBR) tests were carried out under soaked conditions according to ASTM D1883 (2016). Direct shear tests were performed according to ASTM D3080 (2011) with a direct shear apparatus having a mold size of 50mm×50mm×50mm. The rate of shear displacement in the direct shear test was 1.25 mm/min. For each normal stress, the maximum load dial readings were obtained and the cohesion as well as the angle of internal friction were determined.

3. RESULTS AND DISCUSSION

3.1 Compaction characteristics

Figure 2 shows the compaction behavior of the NS-CWG composites, while in Table 1 the OMC and its associated MDD have been listed. It can be observed that NS has a MDD of 1740 kg/m^3, which is associated with an OMC of 15.8%, while CWG has a larger MDD of 1820 kg/m^3, having a smaller OMC of 11.3%. The desirable state of the composite to attain a maximum MDD, the OMC is reasonably lower. Figure 2 shows that with an increase in CWG percentage from 5% to 35%, the MDD has gradually increased by lowering the OMC value. The optimum MDD (1840 kg/m^3) was achieved for 30% CWG replacement with an OMC of 13.3%. Further increase in CWG in the NS-CWG mixture led to a decrease in MDD with an accompanying decrease in OMC. A similar trend can be seen in a study where different percentages of crushed glass were added to varying combinations of cement-stabilized sand (Salamatpoor & Salamatpoor, 2017). This can be attributed to the unique method of mixing, which kept the gradation constant before and after the mixing, replacing similar-sized sand particles with crushed glass particles, which led to the close attainment of the original MDD of CWG (1860 kg/m^3). The MDD is seen to increase up to a replacement of 30% CWG due to better interlocking and compaction provided by the jagged CWG particles. The lowering of the MDD after 30% replacement can also be explained through the complex inter-particle arrangement of the sand and glass particles. Sand particles are more rounded in nature, while glass particles are jagged, which results in poorer compaction as the replacement percentage increases beyond 30%. The decrease in OMC is seen to decrease consistently as the replacement percentage of CWG increases. This is simply because the composition of CWG mainly consists of silicone dioxide (Weihua et al., 2000), which is a non-porous material making it less water absorbent compared to sand, leading to a smaller OMC value.

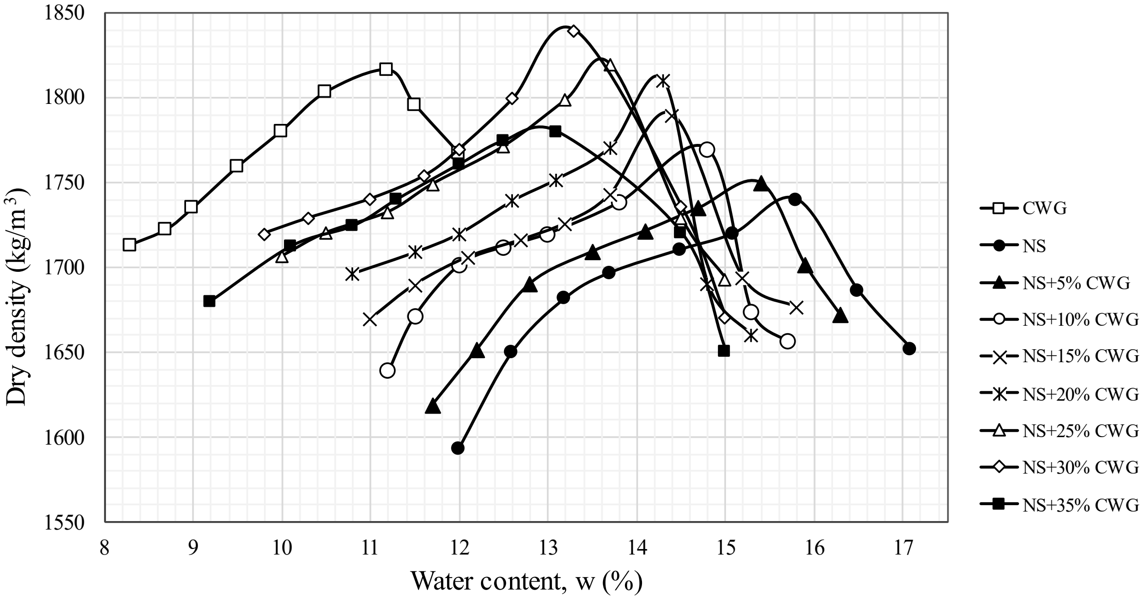


Figure 2: Compaction test results for different samples

3.2 California Bearing Ratio

Figure 3 shows the penetration or displacement of compacted soil due to loading for different NS-CWG composites in the CBR test. From the equivalent stress required for 2.5 mm and 5 mm displacement or penetration of the needle into the sand and sand-CWG samples, the CBR value was calculated and the greater one among 2.5 mm and 5 mm displacement was considered. In Table 1, it can be observed that NS and CWG have a CBR value of 39.6% and 39.4%, respectively. This similarity is attributed to the fact that the gradation of both NS and CWG were kept constant, the only difference being the mechanical characteristics of the particles themselves. For NS-CWG composites, the CBR value has increased compared to both NS and CWG. A rising CBR trend can be seen up to the addition of 30% CWG in the sand; after that CBR value decreases, making 30% CWG the optimum replacement percentage. This is also supported by the remarks made in the previous section. The larger glass particles are crushed marginally due to the compaction effort and fill the voids between sand particles while providing superior inter-particle friction (Arulrajah et al., 2013). This leads to an increase in CBR value when CWG is introduced into the mix. However, when CWG is replaced by more than 30%, the brittleness of the glass particles itself halts the increase of CBR value beyond 46.5%.

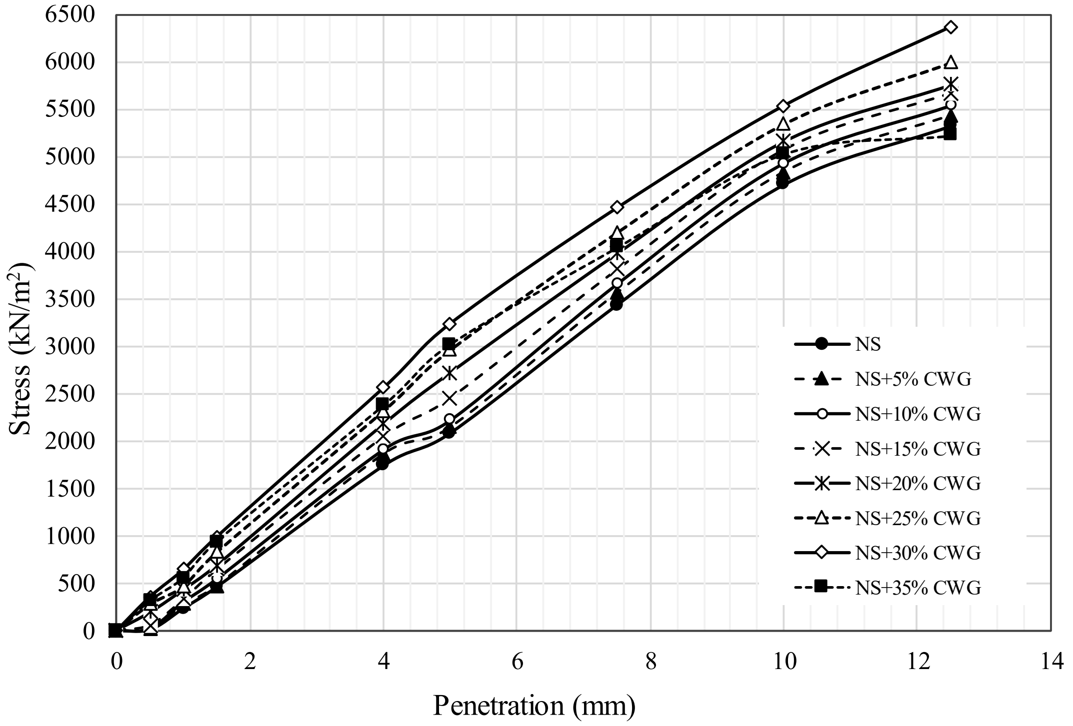


Figure 3: The equivalent stress required for penetration in the CBR test for different samples.

3.3 Direct shear parameters

The normal stress vs. shear stress graph for the shear strength behavior of the NS-CWG composites is shown in Figure 4. The cohesion and the angle of internal friction of sand, and sand-CWG composites are presented in Table 1. NS has been seen to have zero cohesion and CWG has very little cohesion of 2.4 kPa. For NS and CWG composites, it is observed that the cohesion value increases from 0 to 5.7 kPa due to adding 30% CWG; the angle of friction also increases from 41.5° to 44.4°. For 5% of CWG with sand (NS), the cohesion became 2.4 kPa. Further increment in the CWG increased cohesion and was found as 2.6 kPa, 3.1 kPa, 3.8 kPa, 4.5 kPa, 5.3 kPa, and 5.7 kPa for 10%, 15%, 20%, 25%, and 30% CWG, respectively. However, a further increase in the CWG to 35% decreased cohesion and became 4.9 kPa which is less than that of 30% CWG. Similarly, CWG increased the angle of friction in NS-CWG samples. The angle of friction was found to be 41.2, 41.9, 42.6, 43.6, 45.2, and 46.5 for 5%, 10%, 15%, 20%, 25%, and 30% CWG, respectively. The trend of the friction angle is supported by a study featuring the addition of different percentages of crushed glass in cement-stabilized sand, showing an increase in the angle of friction with an increase in crushed glass content (Salamatpoor & Salamatpoor, 2017). Another case study involving a glass cullet as an engineering fill features a similar peak of friction angle at 50% addition (So et al., 2015). The increased CWG content, although it doesn’t increase cohesion in the traditional sense, creates an interlocking between sand particles and glass particles, which leads to the subsequent increase in the shear strength of the composite. Hence, the broken small parts on the CWG particle surface play a role in interlocking the sand and glass waste in compacted conditions, which helps develop little cohesion in the sand-CWG mixtures as observed in the research.

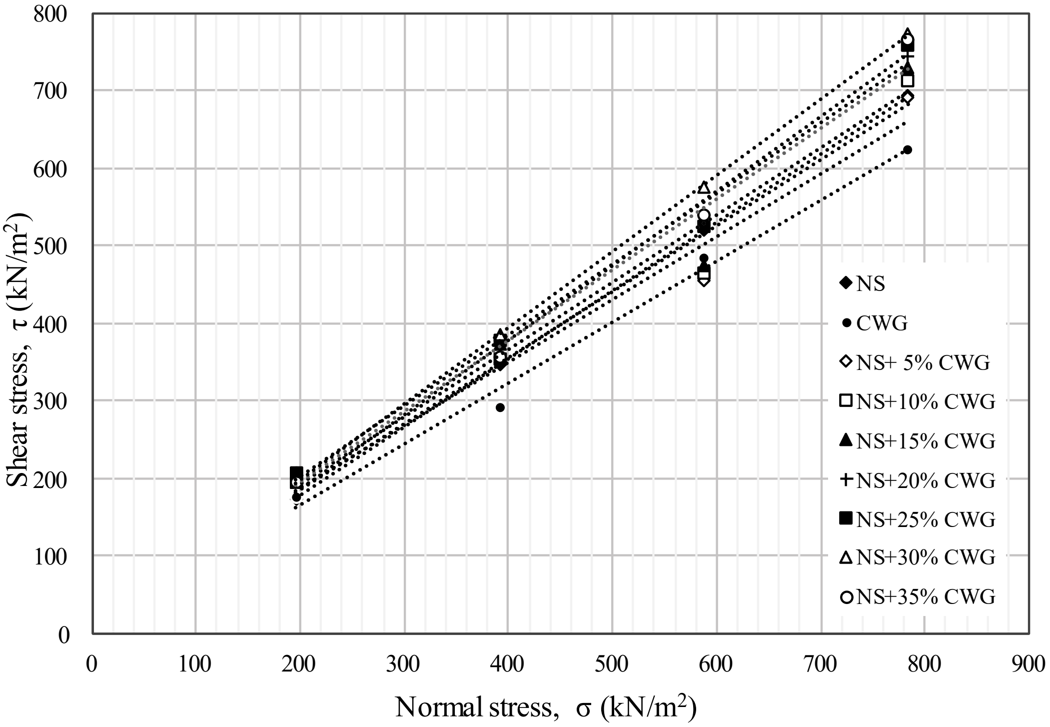


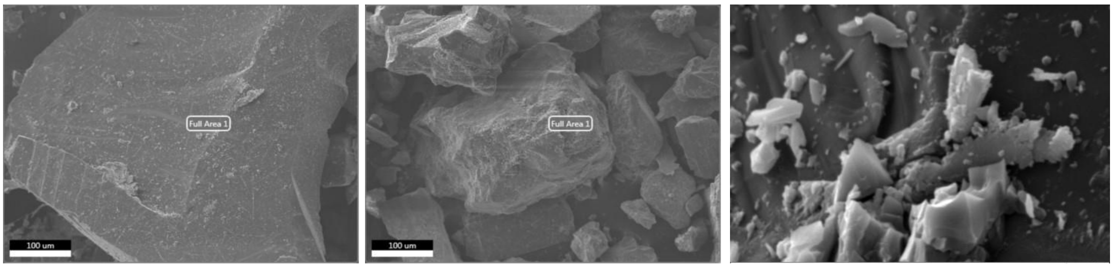
Figure 4: Changes in shear stress with the changes in normal stress from direct shear tests

Table 1: Overall observed changes in NS and NS-CWG samples

Sample	**OMC, %**	**MDD, kg/m³**	**Cohesion, kPa**	**Angle of friction, ◦**	**CBR, %**
NS	15.8	1740	0	41.5	39.6
CWG	11.3	1820	2.4	38.4	39.4
NS + 5% CWG	15.4	1750	2.6	41.3	41.2
NS + 10% CWG	14.8	1770	3.1	42.2	41.9
NS + 15% CWG	14.4	1790	3.8	42.8	42.6
NS + 20% CWG	14.3	1810	4.5	43.3	43.6
NS + 25% CWG	13.7	1820	5.3	43.8	45.2
NS + 30% CWG	13.3	1840	5.7	44.4	46.5
NS + 35% CWG	13.1	1780	4.9	43.9	44.1

3.4 Scanning electron microscopy (SEM)

The scanning electron microscopic images for natural sand, CWG, and optimum NS+CWG blend are presented in Figure 5. The full image of the CWG particle revealed the angular shape of glass waste (Figure 5(a)). Figure 5 b) shows the natural sand, which is round and irregular in shape. As can be seen from Figure 5(c), the waste glass particles are attached to the sand surfaces, and the broken particles of CWG are placed in voids between sand and CWG particles. The placement of broken glass particles in the gap between sands and CWG largely influenced the internal friction angle and resulted in better shear strength. Again, the increment in maximum dry density in the compaction test also becomes evident in Figure 5(c); the mixing of CWG and sand gave better resistance against loading in the CBR test. As described in the earlier sections, CWG improved the mechanical properties of natural sand in a significant way due to the interaction between the particles of natural sand and crushed waste glass.



a) b) c)

Figure 5: SEM images of a) CWG, b) Natural sand, c) NS+30% CWG

4. CONCLUSION

This research aimed to examine the partial replacement of natural sand with crushed waste glass (CWG) in different proportions and assessed the effects by different mechanical properties tests. The results of the tests indicate the suitability of utilizing CWG with natural sand in subgrade-subbase applications. The research theme also supports the United Nations' Sustainable Development Goal (SDG) 11 as the the findings of the results can be useful in constructing road pavements of sustainable transport network, while redcuing the depletion of natural environment. The following conclusions can be drawn from the above results of different tests:

- The CWG increased the maximum dry density (MDD) of the natural sand (NS) while decreasing the optimum moisture content (OMC).
- The effect of CWG on the angle of internal friction of NS-CWG mixtures was noticeable, but there was little influence on the cohesion. For the optimum content of NS+30% CWG, the cohesion of samples increased from 0 kPa to 5.7 kPa, while the angle of internal friction increased from 41.5º to 44.4º, and shear strength at 784 kPa normal stress increased from 693 kPa to 773 kPa.
- The CBR value of natural sand increased by 17.42% and became 46.5% from 39.6% for NS+30% CWG, which is adequate for applying to subgrade or subbase.

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