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Suitability Assessment of Marble, Glass Powders and Poly-Propylene Fibers for Improvement of Siwalik Clay

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Abstract: Raising of the Mangla Dam in Pakistan submerged about 15,780 acres of land, resulting in the relocation of 8020 inhabitants to a newly developed town named New City. The new site, consisting of 1300 acres, is in the sub-tropical zone and comprises badland topography. The parent soils (Siwalik clay) pose infrastructure serviceability issues, causing immense loss to property. The study aims to improve the properties of Siwalik clay (base soil) using industrial wastes like marble and glass powders (5 to 20%) and polypropylene fibers (0.25 to 1.25%) as modifiers. Laboratory tests including grain size distribution, Atterberg limits, standard Proctor compaction, unconfined compression, indirect tensile strength, swell potential, and California bearing ratio were conducted on the control and modified clay samples. The results showed that unconfined compressive strength (UCS) and swelling strains (SS) were increased by 43% and 8% at 1.57 kPa pressure with 15% replacement of marble powder. However, the addition of the 20% glass powder and 0.5% polypropylene fibers not only improved UCS by 110% and 39%, but also reduced SS by 27% and 86%, respectively. The capital construction cost of 1 km long road with modified subgrade using 15% glass powder was reduced by 16% whereas it increased for marble powder and polypropylene fibers by 22% and 17%, respectively. All modifiers had very low hazard to adjoining aqueous environment. Conclusively, glass powder and polypropylene fibers can be used as environmentally-friendly soil improvement modifiers, leading towards sustainable solutions of the serviceability problems.

Keywords: Siwalik clay; glass and marble powders; polypropylene fibers; swelling strains; environmentally friendly

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1. Introduction

Mangla Dam was constructed in the 1960s to make up the water deficiency after the Indus Water Treaty between Pakistan and India in 1960 [1]. Initial gross storage capacity of the reservoir was 5.88-million-acre feet (MAF) and it submerged almost 69,206 acres of land in the districts of Mirpur, Azad Jammu and Kashmir, Pakistan [2]. The prime objective of the dam was to meet the irrigation water demands in the country; however, hydropower generation of 1000 MW was an additional benefit. At the time of original design, a 40 feet future raising provision was kept considering the reservoir sedimentation [3].

In the first decade of the 21st century, the reservoir capacity was depleted by 20% and the authorities decided to explore the option of dam raising to reinstate the storage deficiency. The feasibility study carried out for raising of the dam showed that 30 feet dam raising was the most suitable option on economic grounds [4]. This would enhance the water storage capacity of the reservoir by 2.9 MAF and energy generation by 772 GWh/annum (14% of prevailing energy generation). However, according to the Water and Power Development Authority, this raising would result in submergence of about 15,783 acres of additional area and relocation of about 8023 households [3].

The Government of Pakistan approved a resettlement package to compensate the affected folks through development of a new town named New City in the vicinity of the reservoir. The resettlement package was finalized in an agreement between the Ministry of Water and Power, Pakistan and the Government of Azad Jammu and Kashmir [5].

The selected New City site was located about 6 km away from Mirpur City, developed in the 1970s after the construction of the Mangla Dam. Total land allocated for development of infrastructure was 1300 acres whereas resettlement cost was estimated to be Rs. 26.257 billion (53% of total project cost) [6].

The New City site was founded in the low hills belonging to the beds of the Siwalik system (Pilo-Pleistocene age). Siwalik rocks were initially studied and termed so by Meddlicot in 1864 and 1868 [7]. In 1910, Pilgrim characterized these rocks as upper, middle, and lower units [8]. Later, Johnson et al. (1979), further investigated the Upper Siwalik rocks in the Eastern Pothwar, which also included the Mirpur-Samwal area [9]. In 1984–1985, the Geological Survey of Pakistan (GSP), in association with Harvard University, carried out the preliminary paleontological investigations in the South and Southeast areas of Mirpur, which also encompassed the New City area [10]. The stratigraphy of the site typically comprises interbedded sandstone, siltstone, and clay beds. These clay beds are hard, and their beds slake rapidly when subjected to alternate wetting and drying and yield shallow slope of debris [11].

After two to three years of infrastructure development in the area, serviceability problems like cracking of the buildings, shallow slides, slope erosion, and flexible pavement defects became prominent as shown in Figure 1a–c.

(**a**)

(**b**) (**c**)

Figure 1. Serviceability issues at the study site: (**a**) Shallow slides; (**b**) Pavement defects; and (**c**) Building crack.

Consequently, the locals became reluctant to invest in construction in the problematic area. To regain the attention of the investors for construction of infrastructure, it was necessary to address the problems through soil improvement using environmentally friendly and economically affordable methods.

The clay beds present in the area possess shear zones that were discovered during the construction of the Jari Embankment for the Mangla Dam. Thickness of these shear zones vary from a few millimeters to over one meter, and more than 67% beds contain one or more such zones. The strength of clay beds due to the presence of continuous shear zones has been reduced to residual strength, which is 75% of the peak strength [11].

Conventionally, physical and chemical stabilization methods have been used for the clayey soils, which include compaction and preloading (density improvement); electro-osmosis and dewatering (pore pressure reduction); chemical treatment with additives and ground freezing (inter particle bond improvement); and soil reinforcement using geotextile and stone columns [12]. The majority of these methods, such as dynamic compaction and electro-osmosis, are expensive and can be used only for specific projects. Therefore, these will not be feasible for lightweight infrastructure development.

Among other such techniques, use of solid waste by-products produced as a result of industrial processes like stone dust, waste glass powder, fly ash, rice husk ash, bitumen, and marble powder could be an effective method to improve the geotechnical properties of clayey soils as documented by Benny, Jolly, Sebastian and Thomas in 2017 [13]; Bilondi and Toufigh in 2018 [14]; Ibrahim, Mawlood and Alshkane in 2019 [15]; and Baldovino, Izzio, Silva and Rose in 2020 [16]. Ede et al. determined that industrial wastes, when dumped in open spaces without proper treatment, adversely affect the environment [17]. For a few decades, several researchers have made attempts to consume these wastes for soil improvement as well as the manufacturing of construction materials as reported by Peter, Jayasree, Balan and Raj [18].

Mirpur, Azad Kashmir is located in the Tax-free zone and the Government of Azad Jammu and Kashmir encourages and focuses upon the industrial development in the area. Consequently, many private factories for processing marble, aluminum and glass works, and foam manufacturing have been established in the area. Owing to the unavailability of any recycling facility in the area, the 480 tons per month of waste produced in the industrial area of Mirpur, as documented by the Environment Protection Agency (EPA) in the progress report submitted to the Government in 2019 [19], is dumped randomly in the natural ditches, which endures health and environmental hazards. If these industrial wastes are feasible for soil improvement, it could be economical as well as have a positive impact upon the environmental.

In the last decade, a few researchers have evaluated the prospects of the waste glass powder and other such materials to improve the geotechnical properties of soil. Fauzi et al. used the crushed glass (CG) in combination with the high-density polyethylene fibers (HPE) to stabilize the clayey soil and found improvement in CBR values of the parent soil [20]. Olufowobi et al. reported that the combination of 5–10% glass powder and 15% cement with respect to the total mass of the clayey soil improved its modified dry density, soaked and un-soaked CBR values, and shear strength parameters (cohesion and internal friction) [21]. I. Ikra et al. studied the influence of waste glass powder (WGS) upon the consistency limits, unconfined compressive strength (UCS), and CBR values of the cement stabilized expansive soil and recommended 20% WGS with 8% cement content as the optimum dosage to achieve the maximum improvement [22]. Ibrahim et al. used glass powder to improve the high plastic clay in Iraq [15]. The experimental study revealed an increase in the dry unit weight with subsequent reduction in optimum moisture content with increasing percentages of the waste glass powder. Blayi et al. reported that the waste glass powder had substantial influence upon the consistency and shear strength parameters of the expansive soil. Moreover, the addition of 15% waste glass powder by dry weight of the soil reduced the required sub-base thickness of flexible pavement by 63% [23].

The mechanical behavior of soils may also be improved by using the synthetic fibers. These fibers can either be placed in critical locations known as systematic fiber reinforcement or mixed randomly within the soil mass. The randomly distributed fibers in the soil increased its compressive strength, toughness, ductility and indirect tensile strength according to Maher and Ho [24]. Consoli et al. investigated the performance of fiber reinforced sands at large strains and reported that the reinforcement offers hindrance to the formation of tension crack [25]. Kumar et al. [26] and Olgun [27] studied the effect of fiber reinforcement on the strength of lime-fly ash and cement-fly ash stabilized clayey soils and observed substantial improvement. A. S. Zaimoglu and T. Yetimoglu [28] found enhancement in UCS and CBR values for the fine-grained soils strengthened with the randomly distributed polypropylene fibers. Divya et al. explored that the fiber reinforcement can improve the tensile strength cohesive soil samples [29].

Although soil improvement techniques are investigated in the open literature, scant work is available for these clays, identified as problematic soils (sheared clays) by Prof. A.A. Skempton during construction of the Mangla Dam (Binnie et al. [11]). At the time of dam construction (1960s), the embankment design was reviewed to cope with the foundation soil problems. However, since then, there have been stability and serviceability issues of the infrastructure being constructed upon these foundation soils. This has led to massive property loss during the last four decades. In this study, a sustainable improvement approach has been formulated, which will be beneficial twofold:

(1). The industrial waste being generated in the aluminum, glass and marble industry will be available abundantly and economically to improve the foundation soil and borrow pits;
(2). The waste being dumped in open ditches causing environmental pollution will be utilized in the construction and will lead to a cleaner environment.

The objective of this research is to access the sustainability of three different modifiers; namely, waste glass powder (GP), waste marble powder (MP), and polypropylene fibers (PPFs) to improve the engineering behavior of the Siwalik clay (base soil). Two former modifiers (GP and MP) were used as partial replacement of parent soil in four different percentages (5, 10, 15, and 20%) whereas, later, (PPF) was used as 0.25%, 0.5%, 0.75%, 1%, and 1.25% with respect to the air-dried weight of the base soil. The laboratory tests performed on the base and modified soils included particle size analysis, specific gravity, Atterberg limits, standard Proctor compaction, swell potential, unconfined compressive strength (UCS), and California bearing ratio (CBR).

2. Materials and Methods

2.1. Materials

The disturbed and undisturbed soil samples (one each) were collected from the New City site by manual excavation of a 3 m deep test pit. The GPS coordinates of the pit were 33°7′35.22″ E and 73°47′22.08″ N. The disturbed samples were collected through channel sampling (50 kg each) whereas undisturbed sampling was carried out using the standard procedure described in the ASTM D7015/D7015M-18 [30]. The large chunks of the soil were crushed by hammer and passed through ASTM Sieve No.4 to exclude plant roots, gravels, pebbles, and other such contents.

The base soil was 52% passing ASTM Sieve No. 200 (0.075 mm). It was classified as Lean Clay (CL) according to USCS [31] and A-7-6(9) according to AASHTO Soil Classification Systems [32].

To study the behavior of the soil with different modifiers, varying percentages of three materials, namely, marble powder (MP), glass powder (GP), and polypropylene fibers (PPFs) were added to the base soil as partial replacement. MP and GP were obtained from the local marble industry and an aluminum-glass processing factory, respectively. These materials are produced on a mass scale by cutting and grinding processes and dumped randomly in the natural ditches located near the Mirpur city creating hazard environment pollution and other potential hazards. The owners offered the waste materials free of cost if these could be used for the benefit of the community.

The third modifier, PPFs, was purchased from the Matrixx Company Karachi, Pakistan, at the cost of Rs. 350/kg including the shipment charges.

The properties/specifications of the base soil and the modifiers used in this research are presented in Table 1.

Table 1. Properties of base soil and modifiers.

Base Soil		
Liquid Limit, LL (%)	47	
Plastic Limit, PL (%)	22	
Plasticity Index, PI	25	
Specific Gravity, G_s	2.70	
Max. Dry Unit Weight [a], γ_d (kN/m^3)	16.9	
Optimum Moisture Content (%)	16.0	
Compression Index	0.042	
Unconfined Compressive Strength (kPa)	185	
Marble and Glass Powders:		
	MP	GP
Passing ASTM sieve 200 (%)	52	83
Specific gravity	2.74	2.00
Water absorption (%)	57	43
Polypropylene Fibers:		
Length	19 mm	
Tensile strength	276 MPa	
Specific gravity	0.9	
Elongation at break	12%	
Melting point	135 °C	
Acid resistance	High	
Alkali resistance	100%	

Note: [a]—based upon Standard Proctor Test.

The chemical compositions of the base soil, MP and GP, are shown in Table 2.

Table 2. Chemical composition of the base soil and modifiers.

Description	Base Soil	MP	GP
MgO	2.96	1.60	2.60
Al_2O_3	12.98	1.42	0.73
SiO_2	42.89	4.30	79.50
K_2O	2.68	-	-
CaO	10.77	49.28	3.92
TiO_2	1.17	-	-
Mn_2O_3	0.22	-	-
Fe_2O_3	13.86	0.58	0.35
SO_3	-	0.24	0.34
LoI	12.46	41.64	8.26

The Scanning Electron Microscopy (SEM) image of the base soil shown in Figure 2 depicts that the particles are sub-rounded/elongated in shape.

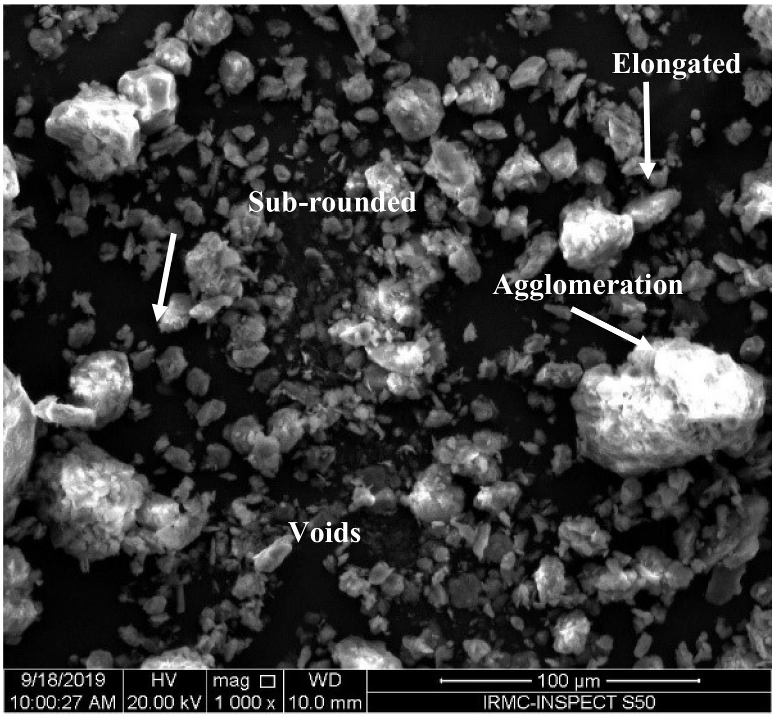


Figure 2. SEM image of the base soil.

The gradation curves of the base soil, marble powder, and glass powder are shown in Figure 3.

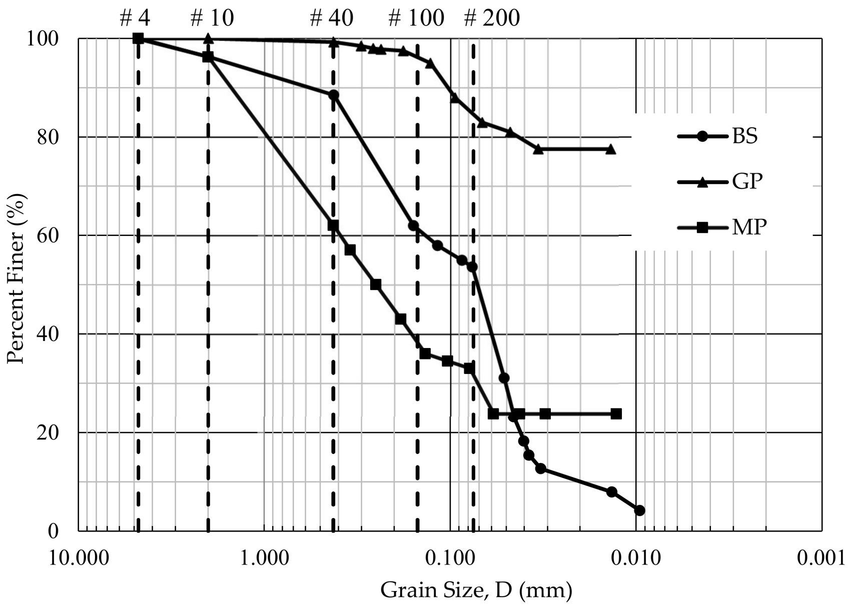


Figure 3. Gradation curves of soil, marble powder, and glass powder.

2.2. Samples' Preparation

The laboratory tests, except for California Bearing Ratio (CBR), were performed on the remolded samples at maximum dry density (γ_{dmax}) and the optimum moisture content (OMC) determined by Standard Proctor Tests following the procedure described in ASTM D698-12e2 [33]. Oven-dried chunks of the base soil were broken and passed through ASTM Sieve No.4. These were further subjected to compaction testing to obtain remolding parameters.

Initially, three specimens/test of base soil were prepared γ_{dmax} and OMC to determine the benchmark properties of the soil through laboratory testing. Later, the MP and GP were added to the base soil at the rate of 5%, 10%, 15%, 20%, and 25% whereas PPFs were added in a range of 0.25, 0.50, 0.75, 1.0, and 1.25%. These percentages of the modifiers were calculated with respect to the air-dried mass of the base soil. These modifiers were used as the partial replacement of the base soil to study their impact upon the engineering behavior of new matrix. Compaction characteristics (maximum dry density and optimum moisture content) were determined for each combination and remolded samples were prepared for further laboratory testing.

In order to ascertain the proper dissemination of PPFs within the soil mass, 12 molar KOH solution prepared in distilled water was added to the mix following Ranjbar et al. [34]. An exothermic reaction takes place when KOH pellets are dissolved in the distilled water, therefore, the solution was prepared 24 h before adding to the base soil and PPF mixture. The soil reinforced with the polypropylene fibers is shown in Figure 4.

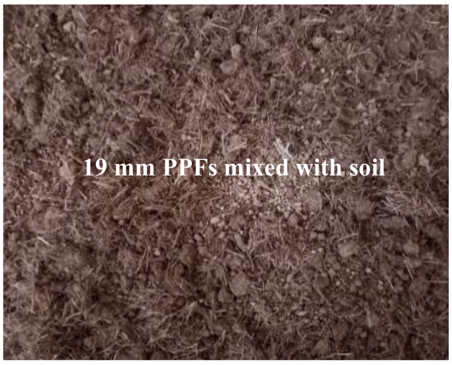


Figure 4. Base soil mixed with 0.5% polypropylene fibers at optimum moisture content.

2.3. Methodology

Standard Proctor compaction tests on base and modified soils were performed on the samples having 10.10 cm and height 11.65 cm, respectively. The standard volume of the mold used in the testing was 933.37 cm^3 whereas the mass of mold with the base plate was 3394 g. An automated compactor with a rammer with 30 cm height of fall was used conforming to ASTM D698-12e1 [33].

The unconfined compressive strength of the remolded samples was evaluated following the ASTM D2166/D2166M-16 [35]. The testing was performed in an automated servo control testing apparatus shown in Figure 5. The height to diameter ratio (H/D) of all the remolded samples varied from 1.99 to 2.05. The deformation rate adopted for all the testing was 0.5 mm/min whereas laboratory room temperature was between 20 °C and 24 °C (February & March 2021).

The indirect tensile strength of the base and modified soils after the addition of optimum proportions of the modifiers viz. 15% MP, 20% GP, and 0.50% PPF was estimated using a split cylinder testing technique in accordance with ASTM C496/C496M-17 [36]. The testing was performed on the remolded specimens at optimum moisture content and maximum dry unit weight. The height (30.50 cm) to diameter (15.25 cm) ratio was 2 + 0.01. Samples were prepared in an automated compactor using standard cylindrical molds being used in the concrete laboratory. Two metallic (stainless steel) strips 3 cm wide by 30 cm long each were placed above and below the cylindrical specimen positioned horizontally between the platens of the testing machine as shown in Figure 6.

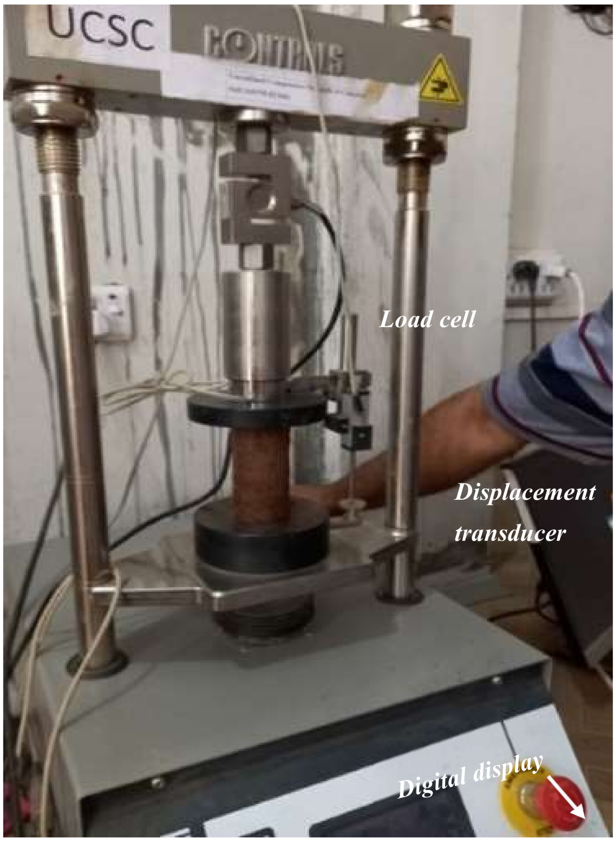


Figure 5. Test setup for the unconfined compressive strength.

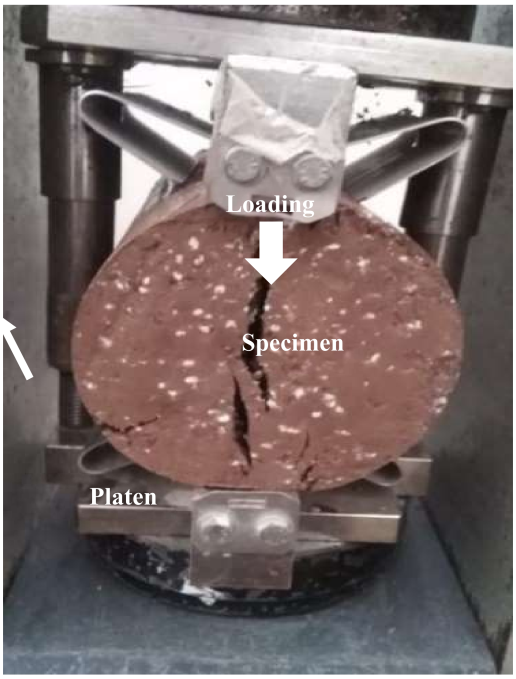


Figure 6. Setup for split cylinder testing.

The monotonic loading rate was 0.5 mm/min and the tensile strength was computed using the relationship described in ASTM C496/C496M-17 [36] as below:

$$\sigma_t = \frac{2P}{\pi LD} \tag{1}$$

where: σ_t = tensile strength; P = peak load; L = length of specimen; D = diameter.

The new city site is located in the sub-tropical zone having an average annual rainfall intensity of 29.7 cm according to the Meteorological Department, Pakistan: Quarterly News Bulletin October to December 2020, Vol. XXI Issue-IV [37]. Therefore, both the soaked and un-soaked CBR tests were conducted to evaluate subgrade improvement with and without the modifiers. The CBR tests were performed following ASTM D1883-16 [38]. The samples for CBR were prepared through compaction at optimum moisture content and modified dry density following the ASTM D1557 [39] in the molds having an internal diameter of 15.12 + 0.01 cm. The spacer disk used had a dimeter of 15.07 cm whereas, the surcharge load was 5.0 kg. The loading rate of the machine was 1.32 mm/min.

The one-dimensional swell tests were performed on the base and modified soils with 15% MP, 20% GP, and 0.5% PPF following the ASTM D4546-14, Test Method A [40]. The testing was performed on the reconstituted specimens having diameters 5.00 cm and heights 2.005 cm, respectively. The applied vertical stresses on each specimen were (1, 25, 50 and 100) kPa.

Two water samples from the adjacent stream and six samples (two each) with optimized percentage of modifiers, based upon the lowest initial cost, were collected in accordance with United States Environmental Protection Agency (USEPA) guidelines for sampling, 2016 [41]. Physical and chemical analyses of water samples without and with the optimum dosage of three modifiers used in this study were conducted in the water testing laboratory, National Institute of Health (NIH), Islamabad. Two samples of stream water were collected to determine average baseline parameters for environmental hazard evaluation.

3. Results and Discussions

In this study, different laboratory tests were performed following the ASTM procedures on the base as well as modified soils to optimize the dosage of the modifiers, if improvement transpires. The influence of the modifiers on the properties of the base soil has been elaborated in the subsequent sub-sections.

3.1. Compaction Tests

The compaction curves with the increasing percentages of the MP as presented in Figure 7 depict that the initially dry unit weight of the modified soil increases, whereas the optimum moisture content slightly decreases up to 15% addition of MP. Thereafter, the dry unit weight decreases, and the optimum moisture content increases. The increase in the unit weight may be attributed to the fact that the specific gravity of MP (2.74) is more than that of the base soil (2.68), which causes slightly higher compacted densities. Furthermore, at a higher dosage of MP (more than 15%) the water starts replacing the solids as the water absorption capacity of MP (57%) is more than the base soil, which, in turn, results in the decreased compacted densities of the modified soils. The trend was confirmed by extending the range up to 25% addition of MP. The initial decrease and then increase in the moisture content could be the result of the reaction between CaO (49% in MP) and clay minerals.

At lower proportions of MP (up to 15%), this reaction does not initiate, and grain size distribution of the base soil shifts to the coarser side, as reported by Radha et al. [42], which results in a lower optimum moisture content. However, with an increasing proportion of the MP, cation exchange reaction initiates which is exothermic and causes soil drying. As more water is required for the subsequent reaction to detach calcium hydroxide into Ca^{2+} and OH^- ions as described by Okagbue and Yakubu, 2000; National lime association 2004 [43], hence the optimum moisture content increases.

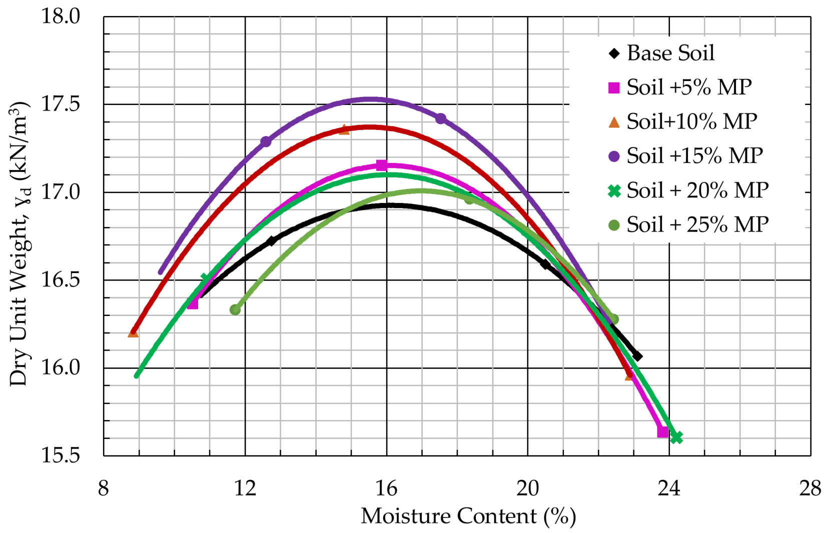


Figure 7. Compaction curves with different percentages of MP.

With the increase in the fraction of GP, the maximum dry unit weight of the modified soil decreases whereas the moisture content will increase, as shown in Figure 8.

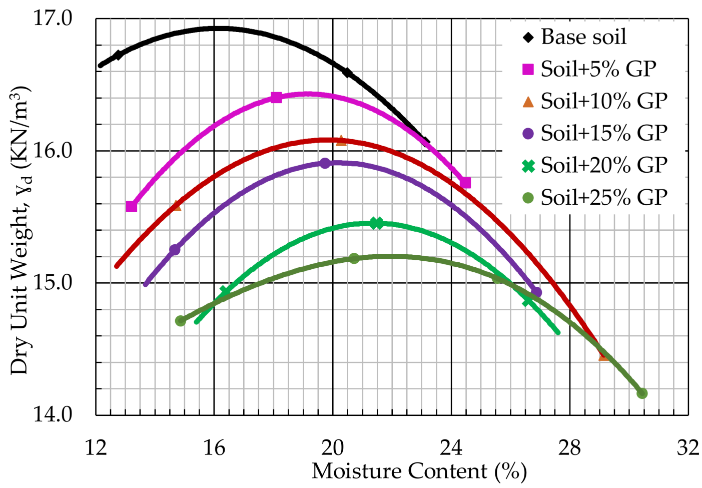


Figure 8. Compaction curves with different percentages of GP.

The decrease in the compacted density of soil is due to the lesser specific gravity of the GP (2.00) as compared to that of the base soil. Moreover, with 25% addition of the glass powder, the reduction in compacted density is only 10%, which is depicted due to finer gradation of the GP. Finer particles fill void spaces among the base soil particles and partially compensate for the effect of lower specific gravity on the modified soil. On the other hand, the optimum moisture content increases as the GP with finer particle sizes have more water absorption capacity (43%) and this water replaces a significant number of solids that are associated with the interaction between clay and glass powder particles. The trend observed in the present study agrees with the observations of N.S. Parihar [44] and M.S. Khan [45].

The variation of maximum dry density with different percentages of marble and glass powders has been present in Figure 9. The figure shows that with increasing marble contents, the variation trend follows a parabolic pattern with maximum value at almost 13% MP content whereas, in the case of glass powder, the decreasing trend yields a straight line with negative slope, respectively.

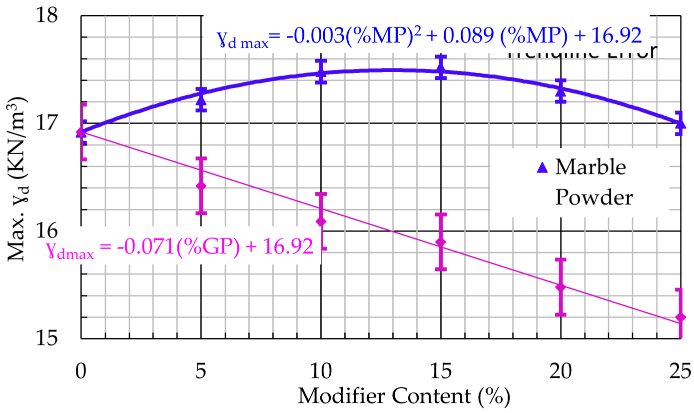


Figure 9. Relationship between modifier content and maximum dry density.

The compaction test results of PPF reinforced soil as shown in Figure 10, revealed that with the increase in the fiber content up to 0.5%, the maximum dry unit weight slightly increases (2%) whereas the corresponding optimum moisture content will reduce. Similar trends were observed by O. Ple and T.N.H. Le [46] for the silty clay and Maher and Ho [24] for the kaolinite clay. Beyond 0.5% PPF, both the maximum dry unit weight and corresponding optimum moisture content decrease. The decrease in the dry unit weight is caused by the replacement of soil particles with fibers at higher fiber content (beyond 0.5% PPF) while a reduction in the optimum moisture content may be attributed to the lower water absorption of the PPFs. Similar observations were stated by Estabragh et al. [34] while studying the effect of polypropylene fiber reinforcement on clay and Malekzadeh and Bilsel [47] on the clayey soil modified with fly ash and poly propylene fibers.

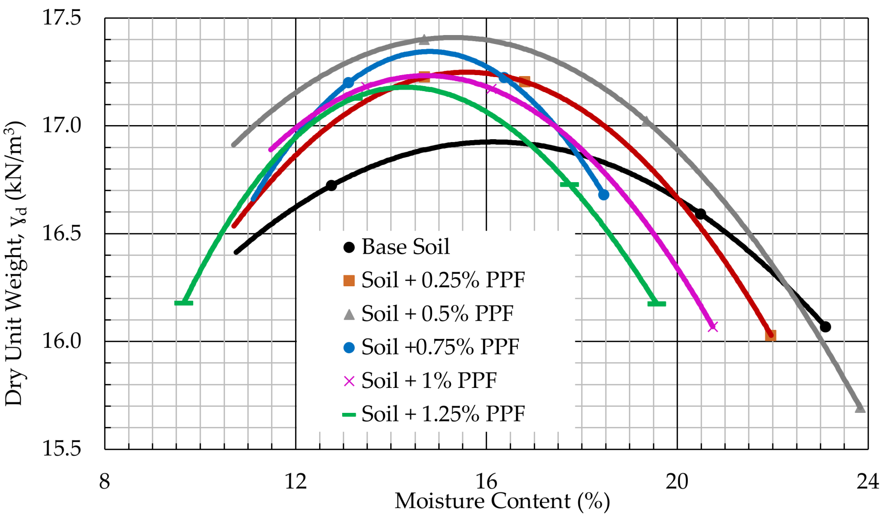


Figure 10. Compaction curves for different percentages of PPFs.

The variation of maximum dry density with increasing PPF content has been presented in Figure 11.

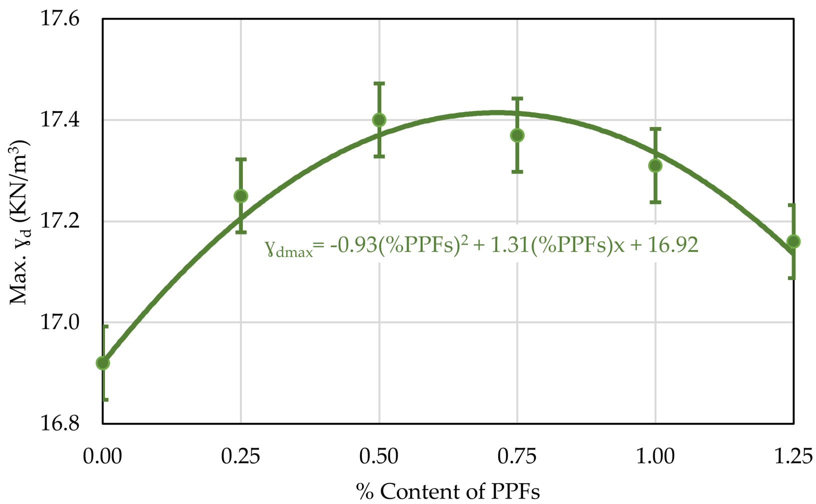


Figure 11. Maximum dry density variation with different percentages of PPFs.

3.2. *Unconfined Compression Tests*

The non-linear stress-strain plot after adding different proportions of MP is shown in Figure 12. The figure depicts that with increasing MP content in the soil up to 15%, the unconfined compressive strength increases yielding a maximum value of 152 kPa (43.64% above base soil) and 4.75% failure strain. This may be ascribed to the cation exchange phenomenon between the calcium of MP and silica and alumina of the base soil to form the respective hydrates with improved cementitious properties resulting in the higher compressive strength. The increasing trend of UCS is in line with that observed by Saygili A. [48] for the clayey soil. With further increase in marble content (beyond 15%), due to higher optimum moisture content, the soil particles are being replaced by the water which has no shear strength and consequently results in the lower UCS.

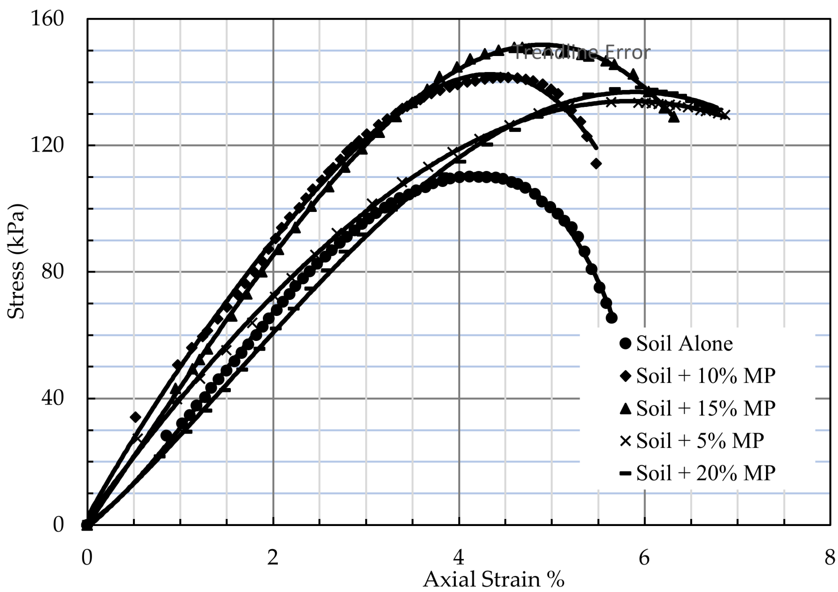


Figure 12. Stress strain relationship for different percentages of MP.

The stress-strain relationship of the modified soil with varying percentages of GP, is shown in Figure 13. A significant improvement has been observed increasing GP content. The maximum improvement of 110% (232 kPa) corresponds to 20% GP and 4% failure strain. Moreover, at 15 and 20% GP, the post-peak behavior of soil was more prominent. The increase in UCS of the modified soil is caused by the filling of voids in the base soil with silica-rich (79.50%) GP having much finer gradation. The void filling phenomenon leads to better inter-particle interaction, which in turn improves the UCS. The trend of increase in UCS of fine-grained soils after blending with GP was also observed by H. H. Ibrahim et al. [15], R.A. Blayi [23] and Dash and Hussain [49].

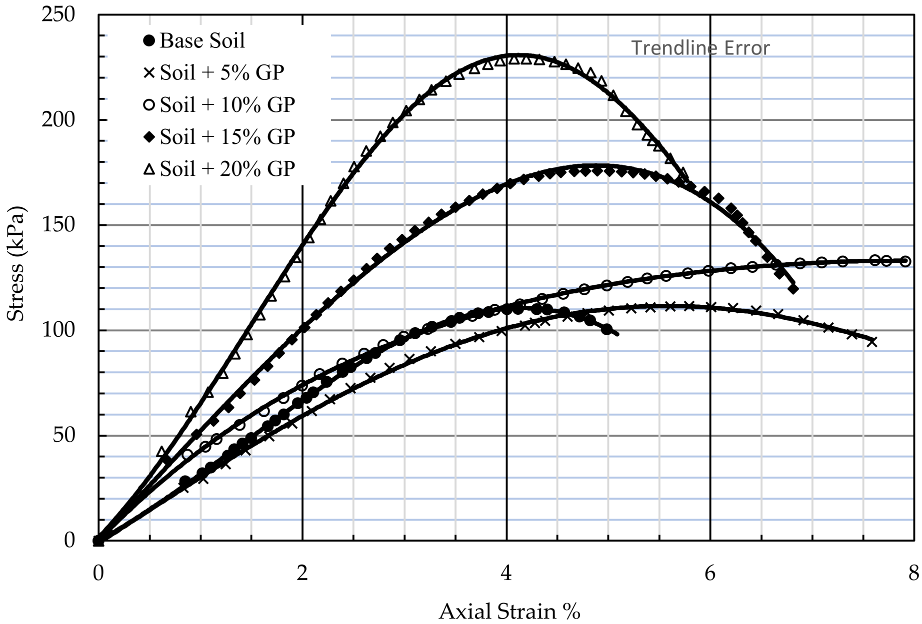


Figure 13. Stress-strain relationship for varying content of GP.

Correlations among the varying percentages of the modifiers (MP and GP) and corresponding unconfined compressive strengths are shown in Figure 14.

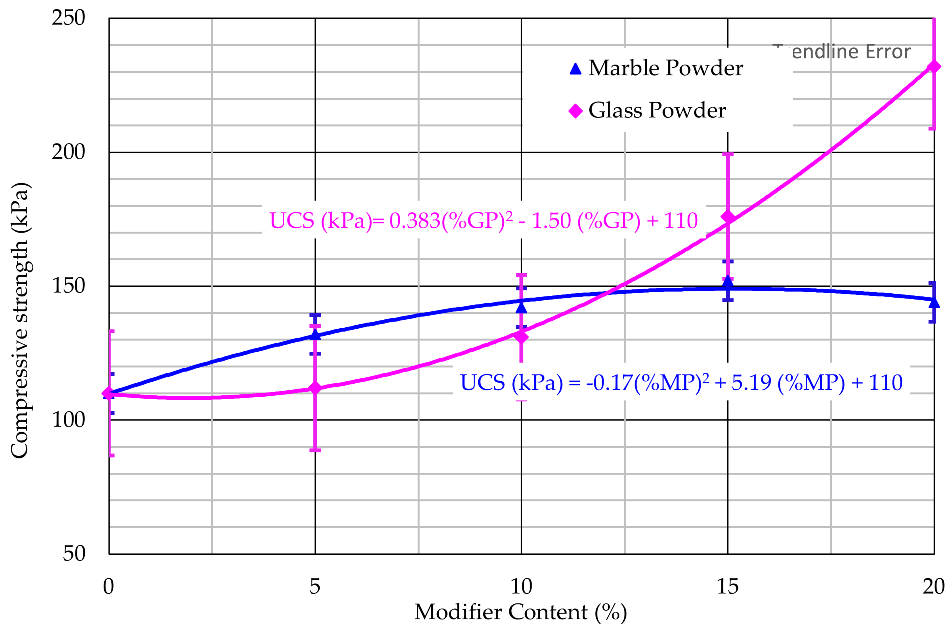


Figure 14. Variation in unconfined compressive strength with modifier content.

The stress-strain plot with increasing PPF content revealed a remarkable increase in the failure stress (UCS) as shown in Figure 15. At lower PPF content (0.25%) this increase is not substantial, however, at comparatively higher percentages (0.75, 1.0, and 1.25%), the increase becomes very prominent with a maximum value of 230 kPa (109%) at 1.25% PPF. Moreover, the failure strain increases almost three times. The role of PPFs in the soil is crack bridging, which effectively prevents the development of further failure planes within the soil mass.

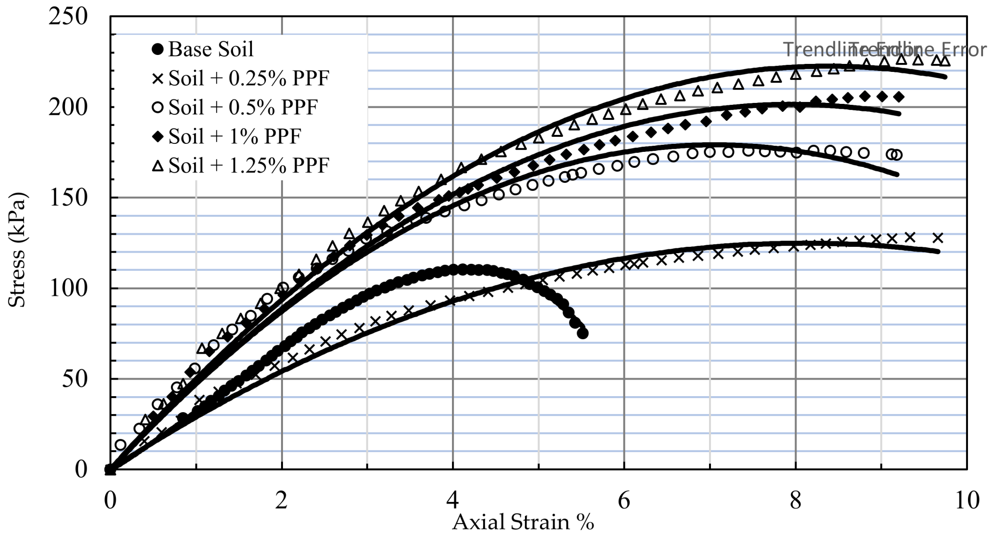
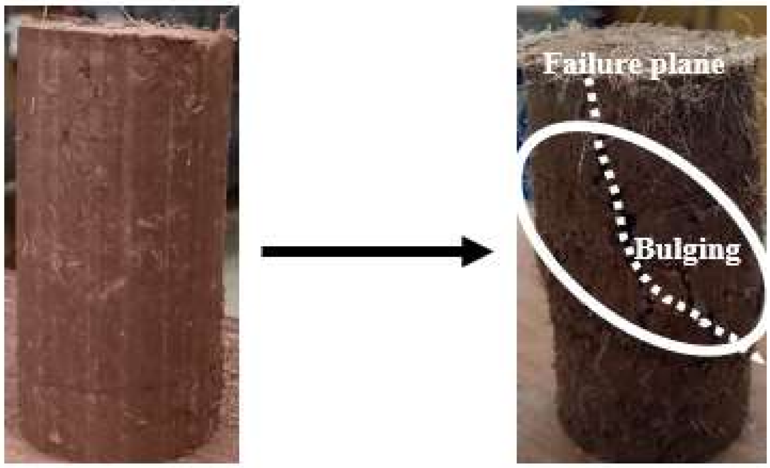


Figure 15. Stress-strain plot for different percentages of PPFs.

The reinforcement of soil with a material having high tensile strength (PPFs) alters the load transfer mechanism between the soil and fibers and hence the material behavior changes under the compressive loading. The bulging of the sample during the test indicates the localized strain concentration as shown in Figure 16b. A similar increase in the compressive strength with fiber-reinforced soils was also reported by Maher and Ho [24], Tang et al. [50], and A.S. Zaimoglu and T. Yetimoglu [28].



(**a**) (**b**)

Figure 16. Fiber reinforced soil sample (**a**) before and (**b**) after UCS test.

The increase in the unconfined compressive strength of the soil with increasing percentage of PPFs can be expressed by an equation of line showing the linear relationship as shown in Figure 17.

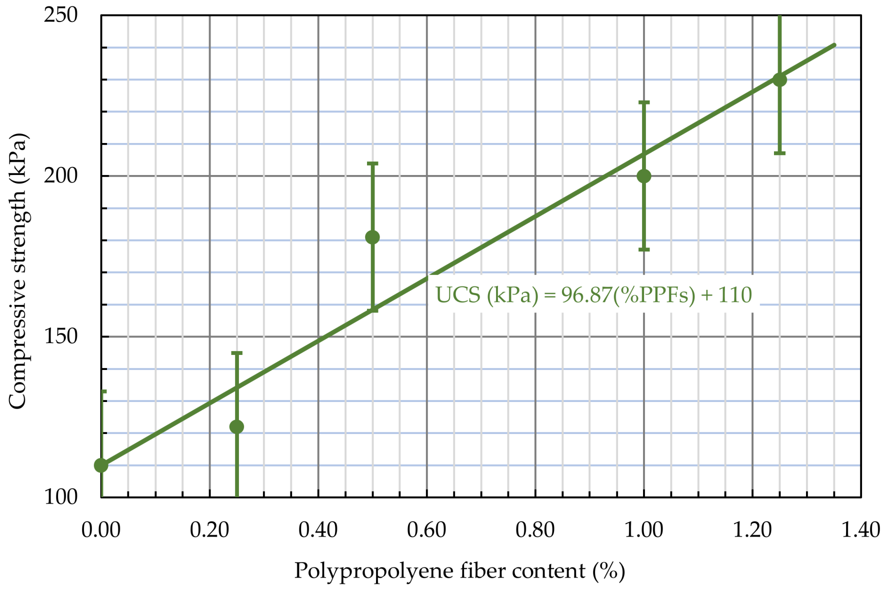


Figure 17. Compressive strength variation with different percentages of PPFs.

The secant elastic moduli corresponding to 50% of the maximum stress (E_{50}) were calculated using stress strain curves with different modifiers and are tabulated in Table 3 and shown in Figures 18 and 19, respectively.

Table 3. Comparison of E_{50} values with different percentages of modifiers.

Sr. No.	Percentage of Modifier (%)	UCS (kPa)	50% of UCS (kPa)	Corresponding Strain (%)	E_{50} (MPa)
			Untreated Soil		
1	-	110	55	1.70	3.24
			Marble Powder		
1	5	133.6	66.8	1.80	3.71
2	10	140.0	70.0	1.52	4.67
3	15	152.0	76.0	1.79	4.22
4	20	138.8	69.4	2.31	3.02
			Glass Powder		
1	5	112.6	55.8	1.90	2.94
2	10	133.2	66.6	1.74	3.85
3	15	175.9	87.9	1.73	5.05
4	20	229.0	114.5	1.69	6.78
			Polypropylene Fibers		
1	0.25	123.0	112.5	2.32	2.66
2	0.5	180.0	90.0	2.20	4.09
3	1.0	200.0	100.0	2.32	4.31
4	1.25	227.0	113.5	2.50	4.54

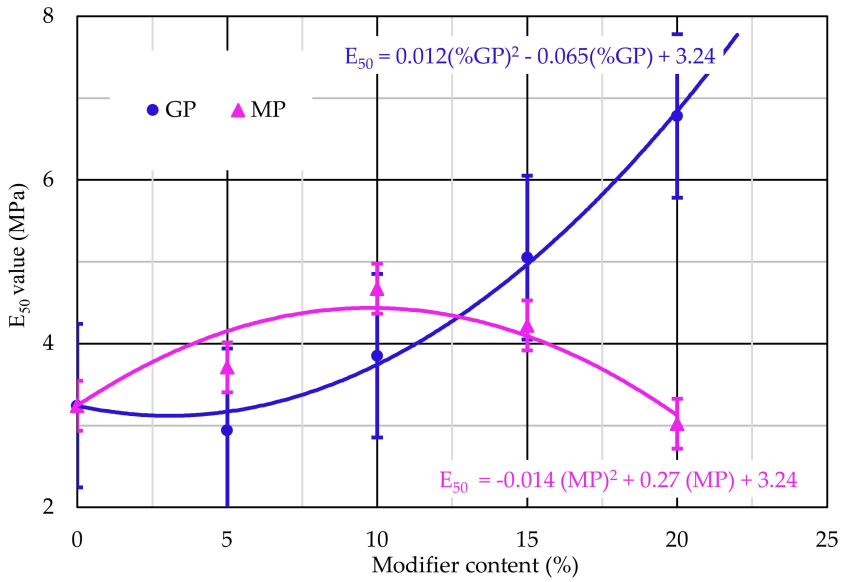


Figure 18. E_{50} values with different percentages of glass and marble powders.

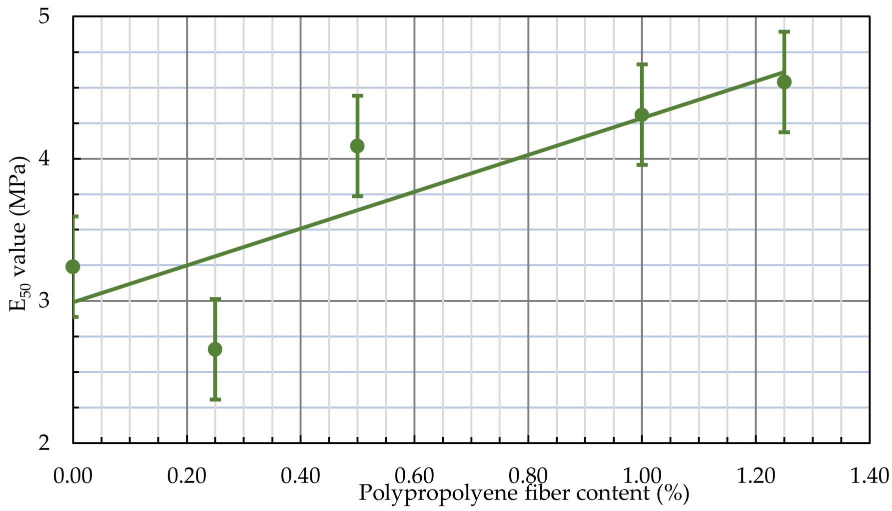


Figure 19. E_{50} values with different percentages of polypropylene fibers.

3.3. Indirect Tensile Strength

The variation of indirect tensile strength after the inclusion of various modifiers used in the study has been shown in Figure 20.

The plot of indirect tensile strength with optimum contents of MP and GP shows no significant difference as compared to the base soil. However, the indirect tensile strength after the inclusion of 0.5% PPFs has enhanced almost three times (130 kPa). This improvement can be attributed to the physical phenomenon that, with the initiation of tensile crack within the reinforced sample under loading, the fibers act as a crack bridging agent and resist its propagation, which leads to delayed failure. The friction among the fibers and soil particles facilitates load sharing among these that consequently improves the tensile strength of reinforced soil. A rise in the fiber dosage leads to a high clay-fiber contact area resulting in the development of higher friction resistance. Therefore, the tensile resistance against applied loads improves tremendously. The increase in tensile strength with the inclusion of fibers closely agrees with the observations of Estabragh, AR et al. [34], Cai, Y. [51] and Khattak M.J. [52].

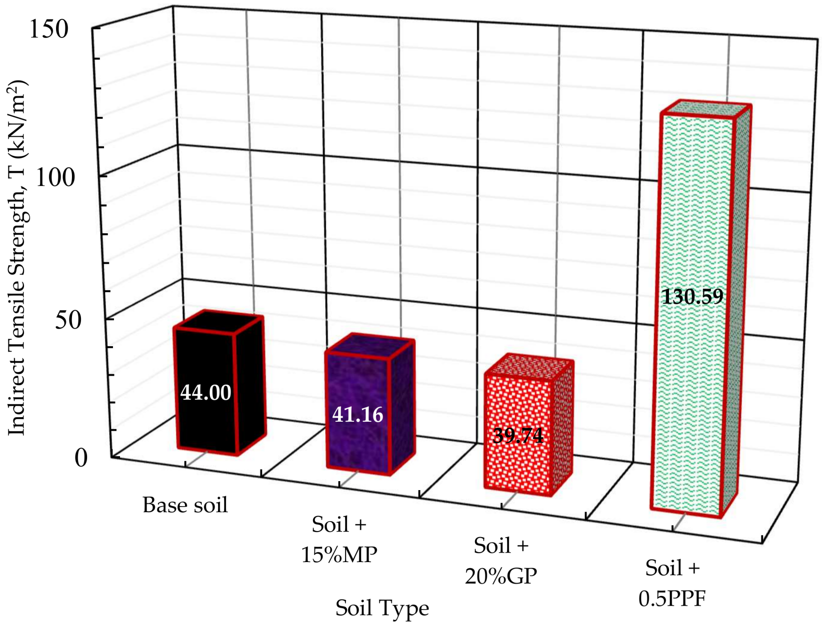


Figure 20. Indirect tensile strength with the optimum percentage of modifiers.

3.4. One-Dimensional Swell Tests

The one-dimensional vertical stress-strain relationships for the base and modified soil with optimum modifier combinations are shown in Figure 21. The base soil exhibits 23.57% swell at 1 kPa stress. However, the swelling drastically reduces up to 25 kPa stress followed by a gradual locus to approach zero at 100 kPa vertically applied stresses. With the addition of 15% MP, an increase in the swelling strain (25.39%) at 1 kPa effective vertical was observed whereas near 100 kPa stress it exhibited a compressive strain of 13.02%. For 15% MP, an inverse relationship exists between effective vertical stresses and vertical strains, which may be represented by the following Equation (2) of line yielding R^2 value equal to 0.99:

$$\varepsilon = -0.38\sigma_v' + 25.39 \quad (2)$$

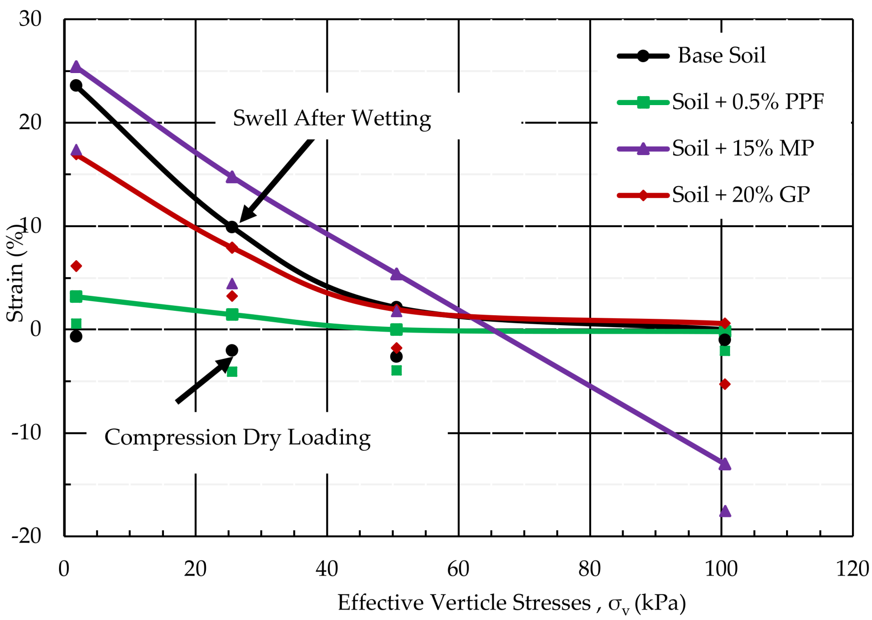


Figure 21. Swell variation with different modifiers.

Initial swelling of MP modified soil at low vertical stresses is due to the reason that modified matrix has high water absorption capacity, owing to the presence of MP (Table 1), which leads to heaving near zero loading. However, as the stresses are increased in increments and each increment remains for 24 h, adequate time is available for the completion of the primary consolidation and subsequent settlement occurs.

With the inclusion of 20% GP, the swelling reduces from 23.57% to 17.41% at 1 kPa stress. The net reduction of 26.17% is caused by two reasons (1) the finer particles of the GP fill the voids with the base soil forming a dense mass resistant to the swelling, and (2) the addition of GP, an inert material, having silica as a major content (79.50%) reduces consistency limits, which lowers the swelling potential of the modified soil. These results closely agree with the conclusions of R.A. Blayi et al. [23] and H.H. Ibrahim et al. [15]. The effective vertical stresses and one-dimensional strain relationship can be expressed by the following 2nd degree polynomial equation with R^2 = 0.99:

$$\varepsilon = 0.0028{\sigma'_v}^2 - 0.46\sigma'_v + 17.41 \quad (3)$$

The most promising results against the swelling have been yielded by the combination of base soil with 0.5% PPFs. The value of swelling strain at 1 kPa vertical stresses reduces to 3.18% in comparison to 23.57% for base soil. This remarkable reduction of 86.51% may be attributed to the strong physical interaction, enhanced friction, among the soil particles and fibers. A nonlinear relationship prevails between vertical strains and effective vertical stresses yielding R^2 = 0.99 with the addition of 0.5% PPFs. The relationship is represented by the equation:

$$\varepsilon = 0.0006{\sigma'_v}^2 - 0.095\sigma'_v + 3.39 \quad (4)$$

3.5. California Bearing Ratio (CBR) Testing

The un-soaked and soaked CBR values for different combinations of soil and modifiers are shown in Figure 22. The plot of un-soaked and soaked CBR for the base and modified soils depict substantial improvement in the un-soaked CBR of the base soil (9%) with adding different modifiers. The modified values corresponding to 15% MP, 20% GP, and 0.5% PPFs were 13, 21, and 49%, respectively. However, the soaked (96 h) CBR values of the base soil and 15% MP are too low to be used as subgrade stabilization. On the other hand, the soaked CBR with the inclusion of 20% GP and 1.25% PPFs are 10% and 23%, respectively, that are significantly higher than the soaked CBR values of the base soil and can be used for subgrade improvement. The findings of R.A. Blayi et al. [23], C.O. Okagbue [43], E. Ene et al. [53], J. Melton andC. Clark [54], Cabalar and Akbulut [55] and Cabalar and Hassan [56] support the results of the present study for un-soaked values.

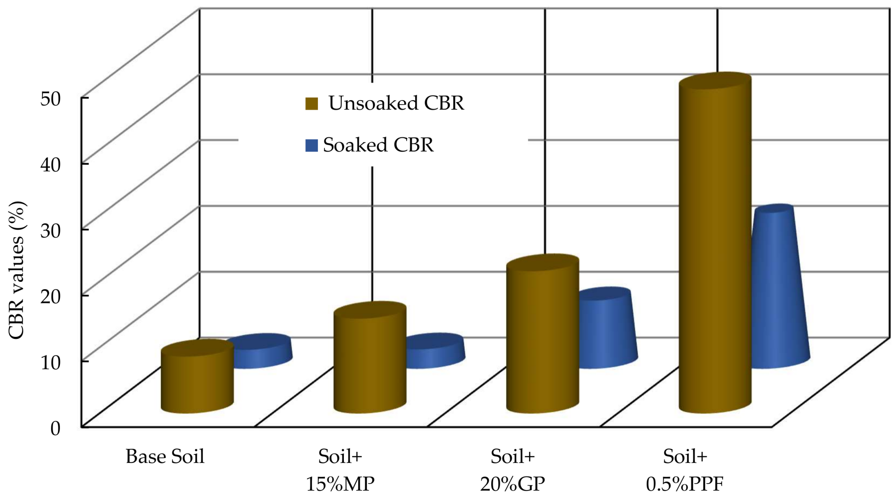


Figure 22. Variation of CBR value with different modifiers.

4. Cost Analysis and Feasibility

For the practical applicability and cost comparison of GP, MP, and polypropylene fibers incorporated soil, a cost analysis of 1 km of road section was performed in this study. The soaked CBR of values after inclusion of the modifiers were used to design the thickness of subbase layers to evaluate the initial cost for a 1 km long two-lane road. The design was carried out in accordance with the AASHTO Design Guidelines Revised Edition [57]. For the sub-tropical zone with an average precipitation of 297 mm/annum [37], soaked CBR values were used for the design process. Design parameters have been represented in Table 4.

Table 4. Road design parameters.

Design Criteria	
Parameter	**Value**
Reliability, R (%)	88
Standard Deviation, S_0	0.45
Serviceability loss, ΔPSI	1.7
Base year AADT (2% truck mix Type A)	2700
Growth rate (%)	2
Design life (years)	25
Design EASL, W_{18}	1.008×10^6
Layer Coefficients	
Hot Mix Asphalt (HMA)	
Layer coefficient	0.44
Base Coarse	
Layer coefficient	0.12
Drainage coefficient	1.0
Modulus of resilience, M_R (ksi)	37
Sub-base	
Layer coefficient	0.05
Drainage coefficient	0.90
Modulus of resilience, M_R (ksi)	19
Subgrade	
Soaked CBR (%)	3
Modulus of resilience, M_R (ksi)	4.5

Based upon the requirements, the required thicknesses for sub-base were determined and cost estimates for 1 km long road were prepared to optimize the dosage of each modifier. The economic estimates showed that 20% GP and 0.5% PPFs are the most suitable proportions yielding an acceptable result without enhancement of cost. The summary of required sub-base thicknesses and cost estimated in accordance with AJK CSR [58] for 1 km long road has been given in Table 5.

Table 5. Cost abstracts for 1 km long roadway.

Subgrade Material	Required Sub-Base Thickness (Inches)	Cost in Millions (PKR)	Change (%)
Base Soil	38	26.16	-
15% MP	38	29.79	+13.86
15% GP	7	19.85	−24.11
0.5% PPF	0	30.37	+16.08

It can be depicted from Table 5 that the GP and PPFs improve the subgrade strength, however, only GP reduced the cost per km of road by 24%, which is a substantial reduction. On the other hand, the MP and PPFs increase the cost by 14% and 16%, respectively. Moreover, enhanced swelling of MP made it unsuitable for its use as a potential modifier.

5. Environmental Evaluation

The potential contamination of a nearby stream was evaluated as, during the rainstorm, the modifier included water may leach out from subgrade and join the natural streams/nullah water. This in turn could be a potential environmental hazard for wild animals and birds who use these sources as drinking water. The results of analyses performed on water samples with and without the modifiers are shown in Table 6.

Table 6. Environmental impact analyses of water samples.

Parameter	Water	15% MP	15% GP	0.5% PPFs	WHO Standard
Physical Analysis					
Color	Colorless	Greenish white	Greyish brown	Dirty	Colorless
Odor	Odorless	Unsatisfactory	Unsatisfactory	Unsatisfactory	Odorless
Appearance	Clear	Suspended particles + sediments	Suspended particles + sediments	Suspended sediments	Clear
Turbidity	0	55	182	85	5
pH	7.6	7.4	**9.0**	7.2	**6.5–8.5**
Chemical Analysis					
Conductivity (mS/cm)	884	962	**13,310**	1143	1334
TDS (ppm)	663	722	998	857	1000
Total Hardness $CaCO_3$ (ppm)	400	250	25	100	500
Calcium (ppm)	120	70	4	28	200
Magnesium (ppm)	24	18	4	7	100
Chloride (ppm)	50	60	238	55	250
Chlorine (ppm)	0	0	0	0	0.1
Sodium (ppm)	39	96	90	167	200
Potassium (ppm)	1.6	13	96	21	100

The analyses showed that with the inclusion modifiers i.e., MP, GP, and PPFs, the physical parameters of water samples like color, odor, appearance, and turbidity and pH for GP only and one chemical parameters conductivity for GP were beyond the acceptable limits of World Health Organization (WHO). All other chemicals remained within the permissible range for drinking water standardized by the WHO. The increase in pH of GP mixed solution depicts the basic nature of the glass powder. The highly concentrated basic medium created by GP led to the dissolution of siliceous composition glass. The similar observation of increase in pH was also reported by Monique et al. [59].

It is inferred that the modifiers used in subgrade, leaching from the subgrade during the heavy rain fall, will be mixed with into the surface runoff and will travel a substantial distance to reach the adjoining stream/nullah. Moreover, as the quantity of water in the stream water will be higher than the modifier-included water in the laboratory, the concentration of the modifier will be significantly diluted resulting in a very low hazard.

6. Conclusions

The present study was conducted to assess the suitability of three modifiers; namely, marble powder (MP), glass powder (GP), and poly-propylene fibers (PPFs) for the improvement of Siwalik clay (base soil) present in the new city, Mirpur, Pakistan. This soil causes serviceability issues to the newly built infrastructure in the area. Comprehensive laboratory testing and data analyses led to the following conclusions:

(1). The base soil sample collected from the new city was classified as CL according to the USCS whereas A-7-6(9) as per AASHTO classification system. The Silica (SiO_2) being 79.5% was the major content found in chemical analysis. Soil particles were sub-round, flaky, and angular in shapes as examined by the SEM analysis. The remolded soil sample at OMC (16%) and γ_d max. (15.92 kN/m^3) had UCS of 110 kPa and indirect tensile strength of 44 kPa. The soil swells 23% under 1 kPa vertical stress that reduced to zero at 100 kPa. Un-soaked and soaked CBR values were 9% and 3%, respectively.

(2). Addition of 15% MP as modifier, improved the maximum dry unit weight and UCS of the modified matrix by 3.42% and 43.63%, respectively. However, it caused enhanced swell by 8% (25.39%) at 1 kPa and high compressibility (13 times) at 100 kPa stresses were the adverse impact upon the parent soil. Moreover, 6.8% reduction in indirect tensile strength and very low soaked CBR value of only 2% made this modifier unsuitable for improvement of the base soil.

(3). Addition of 20% GP in the base soil showed maximum in UCS (120%). Although the maximum dry unit weight of the modified soil decreased by 6%, it reduced the swelling strain at 1 kPa by 26% and enhanced un-soaked and soaked CBR of soil by 144% and 300%, respectively. Owing to low maximum dry unit weight of the modified soil with 20% GP, it is not underneath the foundations. However, GP can be used as a modifier in backfills behind retaining walls to reduce horizontal thrust, construction of embankments, improving slope stability, and subgrade stabilization.

(4). The polypropylene fibers (PPFs) were the most promising modifier and improved all the soil properties. Only 0.5% addition of PPFs to the base soil, not only increased: maximum dry unit weight (3%); UCS (39%); soaked CBR (800%); and indirect tensile strength (295%) but also reduced the swell by 86.5% at 1 kPa effective vertical stresses. Based on remarkable improvement, PPFs can be used in the soil underneath the foundations, subgrade stabilization, and backfills behind retaining walls, embankment construction, and slope stabilization. As the volume/mass ratio of the material is very high, 0.5% PPFs with respect to the air-dried mass of soil was the optimum dosage of the PPFs considering economic aspects.

(5). The proportions of modifiers to be used in the base soil were optimized on the basis of capital cost estimation for a 1 km long collector road in sub-tropical zone following the Azad Jammu and Kashmir composite schedules of rates for district Mirpur (2021). Incorporation of 15% GP in the base soil reduced the cost per kilometer by 24%, respectively. However, the addition of 15% MP and 0.5% PPFs led to cost enhancements by 14% and 16%, respectively.

(6). The water samples' analyses with and without the modifiers revealed that only physical parameters were affected. The chemical parameters except conductivity, after inclusion of GP, remained within the permissible limits standardized by the WHO for drinking water. Additionally, the contaminated water leaching from the subgrade during the heavy rain fall, will be mixed with the surface runoff and travel a substantial distance to reach the adjoining stream/nullah. As the quantity of water in the stream water will be manifolds higher than the water quantity used in the laboratory, hence, the concentration of the modifier will be significantly reduced, resulting in a very low hazard.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CG	Crushed Glass
EPA	Environmental Protection Agency
GSP	Geological Survey of Pakistan
GWh	Gigawatt Hour
GP	Glass Powder
HPE	High-density Polyethylene Fibers
MAF	Million Acre Feet
MJV	Mangla Joint Venture
MP	Marble Powder
NIH	National Institute of Health
PPFs	Polypropylene Fibers
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

Notations

γ_d	Dry unit Weight
σ_t	Tensile Strength
σ'_v	Effective Vertical Stress
ε	One-dimensional strain
ΔPSI	Loss in Serviceability
R	Reliability
S_0	Standard Diviation
M_R	Modulus of Resilience

References

1. United Nations-Treaty Series. *No. 6032, The Indus Waters Treaty 1960 between The Government of India, The Government of Pakistan and the International Bank for Reconstruction and Development*; United Nations: New York, NY, USA, 1960; pp. 126–292.
2. Sheikh, S.M. Mangla Dam-Past, Present & Future. In Pakistan Engineering Congress Century Celebration (1912–2012). Pakistan Engineering Congress: Lahore, Pakistan, 2012; pp. 131–147.
3. Pakistan Water and Power Development Authority. *Mangla Dam Raising Project, an Overview*; HAL: Lahore, Pakistan, 2004.
4. Mangla Joint Venture. *Mangla Dam Raising Project, Sedimentation Study Report*; HAL: Lahore, Pakistan, 2004.
5. Pakistan WAPDA and Goverment of AJK. *Agreement for the Raising of the Mangla Dam*; Goverment of Azad Jammu & Kashmir: Muzaffarabad, Pakistan, 2003; pp. 1–4.
6. Mangla Joint Venture. *Mangla Dam Raising Project, Feasibility Study Report*; HAL: Lahore, Pakistan, 2001.
7. Medlicott, H.B. Memoirs of the Geological Survey of India, Vol. III. Part 2. 'On the Geological Structure and Relations of the Southern Portion of the Himalayan Ranges, between the Rivers Ganges and Ravee.' By H. B. Medlicott, B.A., F.G.S., of the Geological Survey of India. 8vo. 1864. *Geol. Mag.* **1865**, *2*, 310–316. [CrossRef]
8. Pilgrim, G.E. Tertiary Fresh-water Deposits of India. In *Geology of India for Students*; Forgotten Books: London, UK, 1910; pp. 237–241.
9. Opdyke, N.D.; Lindsay, E.; Johnson, G.D.; Johnson, N.; Tahirkheli, R.A.K.; Mirza, M.A. Magnetic polarity stratigraphy and vertebrate paleontology of the upper siwalik subgroup of northern Pakistan. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1979**, *27*, 1–34. [CrossRef]
10. Iqbal, O.; Baig, M.S.; Pervez, S.; Siddiqi, M.I. Structure and Stratigraphy of Rumbli and Panjar Areas ofKashmir and Pakistan with the Aid of GIS. *J. Geol. Soc. India* **2018**, *91*, 57–66. [CrossRef]
11. Binnie, G.M.; Clark, J.F.F.; Skempton, A.W. The Effect of Discontinuities in Clay Bedrock on the Design of Dams in the Mangla Project. In *Selected Papers on Soil Mechanics*; Thomas Telford Publishing: London, UK, 1984; pp. 140–152. [CrossRef]
12. Powrie, W. Soil Mechanics Concepts and Applications. In *Soil Mechanics Concepts and Applications*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2014.
13. Benny, J.R.; Jolly, J.; Sebastian, J.M.; Thomas, M. IJERT-Effect of Glass Powder on Engineering Properties of Clayey Soil. *Int. J. Eng. Res. Technol.* **2017**, *5*, 228–231.
14. Bilondi, M.P.; Toufigh, M.M.; Toufigh, V. Experimental investigation of using a recycled glass powder-based geopolymer to improve the mechanical behavior of clay soils. *Constr. Build. Mater.* **2018**, *170*, 302–313. [CrossRef]
15. Ibrahim, H.H.; Mawlood, Y.I.; Alshkane, Y.M. Using waste glass powder for stabilizing high-plasticity clay in Erbil city-Iraq. *Int. J. Geotech. Eng.* **2019**, *15*, 496–503. [CrossRef]

16. Baldovino, J.D.J.A.; Izzo, R.L.D.S.; Da Silva, R.; Rose, J.L. Sustainable Use of Recycled-Glass Powder in Soil Stabilization. *J. Mater. Civ. Eng.* **2020**, *32*, 04020080. [CrossRef]
17. Olofinnade, O.M.; Ede, A.N.; Ndambuki, J.M.; Ngene, B.U.; Akinwumi, I.I.; Ofuyatan, O. Strength and microstructure of eco-concrete produced using waste glass as partial and complete replacement for sand. *Cogent Eng.* **2018**, *5*, 1483860. [CrossRef]
18. Peter, L.; Jayasree, P.; Balan, K.; Raj, S.A. Laboratory Investigation in the Improvement of Subgrade Characteristics of Expansive Soil Stabilised with Coir Waste. *Transp. Res. Procedia* **2016**, *17*, 558–566. [CrossRef]
19. AJK-EPA. *Industrial Waste Estimates in Periphery of the City*; EPA-AJK: Mirpur Azad Jammu & Kashmir, Pakistan, 2019.
20. Fauzi, A.; Rahman, W.M.N.W.A.; Jauhari, Z. Utilization Waste Material as Stabilizer on Kuantan Clayey Soil Stabilization. *Procedia Eng.* **2013**, *53*, 42–47. [CrossRef]
21. Olufowobi, J. Clay soil stabilisation using powdered glass. *J. Eng. Sci. Technol.* **2014**, *9*, 541–558.
22. Ikara, I.A.; Kundiri, A.M.; Mohammed, A. Effects of Waste Glass (WG) on the Strength Characteristics of Cement Stabilized Expansive Soil. *Am. J. Eng. Res. (AJER)* **2015**, *4*, 33–41.
23. Blayi, R.A.; Sherwani, A.F.H.; Ibrahim, H.H.; Faraj, R.H.; Daraei, A. Strength improvement of expansive soil by utilizing waste glass powder. *Case Stud. Constr. Mater.* **2020**, *13*, e00427. [CrossRef]
24. Maher, M.H.; Ho, Y.C. Mechanical Properties of Kaolinite/Fiber Soil Composite. *J. Geotech. Eng.* **1994**, *120*, 1381–1393. [CrossRef]
25. Consoli, N.C.; Casagrande, M.D.T.; Coop, M.R. Performance of a fibre-reinforced sand at large shear strains. *Géotechnique* **2007**, *57*, 751–756. [CrossRef]
26. Kumar, A.; Walia, B.S.; Bajaj, A. Influence of Fly Ash, Lime, and Polyester Fibers on Compaction and Strength Properties of Expansive Soil. *J. Mater. Civ. Eng.* **2007**, *19*, 242–248. [CrossRef]
27. Olgun, M. Effects of polypropylene fiber inclusion on the strength and volume change characteristics of cement-fly ash stabilized clay soil. *Geosynth. Int.* **2013**, *20*, 263–275. [CrossRef]
28. Zaimoglu, A.S.; Yetimoglu, T. Strength Behavior of Fine Grained Soil Reinforced with Randomly Distributed Polypropylene Fibers. *Geotech. Geol. Eng.* **2012**, *30*, 197–203. [CrossRef]
29. Divya, P.V.; Viswanadham, B.V.S.; Gourc, J.P. Evaluation of Tensile Strength-Strain Characteristics of Fiber-Reinforced Soil through Laboratory Tests. *J. Mater. Civ. Eng.* **2014**, *26*, 14–23. [CrossRef]
30. *ASTM D7015/D7015M-18*; Standard Practices for Obtaining Intact Block (Cubical and Cylindrical) Samples of Soils. ASTM International: West Conshohocken, PA, USA, 2018.
31. *ASTM D2487-17e1*; Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International: West Conshohocken, PA, USA, 2017.
32. *ASTM D3282-15*; Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes. ASTM International: West Conshohocken, PA, USA, 2015.
33. *ASTM D698-12e1*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12400ft-lbf/ft3 (600kN-m/m3)). ASTM International: West Conshohocken, PA, USA, 2012.
34. Estabragh, A.R.; Ranjbari, S.; Javadi, A.A. Properties of a Clay Soil and Soil Cement Reinforced with Polypropylene Fibers. *ACI Mater. J.* **2017**, *114*, 195. [CrossRef]
35. *ASTM D2166/D2166M-16*; Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International: West Conshohocken, PA, USA, 2016.
36. *ASTM C496/C496M-17*; Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2017.
37. Pakistan Meteorological Department. *Quarterly News Bulletin (October to December)*; Pakistan Meteorological Department: Islamabad, Pakistan, 2020.
38. *ASTM D1883-16*; Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. ASTM International: West Conshohocken, PA, USA, 2016.
39. *ASTM D1557-12e*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2700 kN-m/m3)). ASTM International: West Conshohocken, PA, USA, 2012.
40. *ASTM D4546-14e1*; Standard Test Methods for One-Dimensional Swell or Collapse of Soils. ASTM International: West Conshohocken, PA, USA, 2014.
41. Gray, N.F. A quick guide to drinking water problems. In *Drinking Water Quality*; Cambridge University Press: Cambridge, UK, 2018; pp. 65–74. [CrossRef]
42. Daita, R.; Drnevich, V.; Kim, D. Family of compaction curves for chemically modified soils. *Jt. Transp. Res. Program* **2005**, *98*. [CrossRef]
43. Okagbue, C.; Onyeobi, T. Potential of marble dust to stabilise red tropical soils for road construction. *Eng. Geol.* **1999**, *53*, 371–380. [CrossRef]
44. Parihar, N.S.; Garlapati, V.K.; Ganguly, R. Stabilization of Black Cotton Soil Using Waste Glass. In *Handbook of Environmental Materials Management*; Springer: Cham, Switzerland, 2018; pp. 1–16. [CrossRef]
45. Khan, M.S.; Tufail, M.; Mateeullah, M. Effects of Waste Glass Powder on the Geotechnical Properties of Loose Subsoils. *Civ. Eng. J.* **2018**, *4*, 2044. [CrossRef]
46. Ple, O.; Lê, T.N.H. Effect of polypropylene fiber-reinforcement on the mechanical behavior of silty clay. *Geotext. Geomembr.* **2012**, *32*, 111–116. [CrossRef]

47. Malekzadeh, M.; Bilsel, H. Effect of Polypropylene Fiber on Mechanical Behaviour of Expansive Soils. *Eur. J. Gov. Econ.* **2012**, *17*, 55–63.
48. Saygili, A. Use of Waste Marble Dust for Stabilization of Clayey Soil. *Mater. Sci.* **2015**, *21*, 601–606. [CrossRef]
49. Dash, S.K.; Hussain, M. Lime Stabilization of Soils: Reappraisal. *J. Mater. Civ. Eng.* **2012**, *24*, 707–714. [CrossRef]
50. Tang, C.-S.; Shi, B.; Gao, W.; Chen, F.; Cai, Y. Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotext. Geomembranes* **2007**, *25*, 194–202. [CrossRef]
51. Cai, Y.; Shi, B.; Ng, C.W.; Tang, C.-S. Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil. *Eng. Geol.* **2006**, *87*, 230–240. [CrossRef]
52. Khattak, M.J.; Alrashidi, M. Durability and mechanistic characteristics of fiber reinforced soil–cement mixtures. *Int. J. Pavement Eng.* **2006**, *7*, 53–62. [CrossRef]
53. Ene, E.; Okagbue, C. Some basic geotechnical properties of expansive soil modified using pyroclastic dust. *Eng. Geol.* **2009**, *107*, 61–65. [CrossRef]
54. Melton, J.S.; Clark, C.J.; Regis, P.T. Feasibility Study on Building-Derived Concrete Debris for Use in Highway Construction. *J. ASTM Int.* **2012**, *9*, 95–111. [CrossRef]
55. Cabalar, A.F.; Akbulut, N. Effects of the particle shape and size of sands on the hydraulic conductivity. *Acta Geotech. Slov.* **2016**, *13*, 83–93.
56. Cabalar, A.F.; Hassan, D.I.; Abdulnafaa, M.D. Use of waste ceramic tiles for road pavement subgrade. *Road Mater. Pavement Des.* **2016**, *18*, 882–896. [CrossRef]
57. AASHTO. Chapter 5—Roadway Design, 5F-Pavement Thickness Design. In *Design Guide*; Iowa SUDAS: Huxley, IA, USA, 2019; pp. 1–25.
58. AJK-P&D. 2020-21 AJK-CSR (April–June 2021) MIRPUR. In *Composite Schedule of Rates*, 2021st ed.; Govt. of AJ&K: Mirpur, Pakistan, 2021; Volume 1, pp. 21-2–21-14.
59. Tognonvi, M.T.; Konan, L.K.; Kouassi, S.S.; Doubi, H.B.I.G.; Zidol, A.; Harbec, D.; Tagnit-Hamou, A. Reactivity of Glass Powder in Aqueous Medium. *Adv. Mater.* **2018**, *7*, 9. [CrossRef]