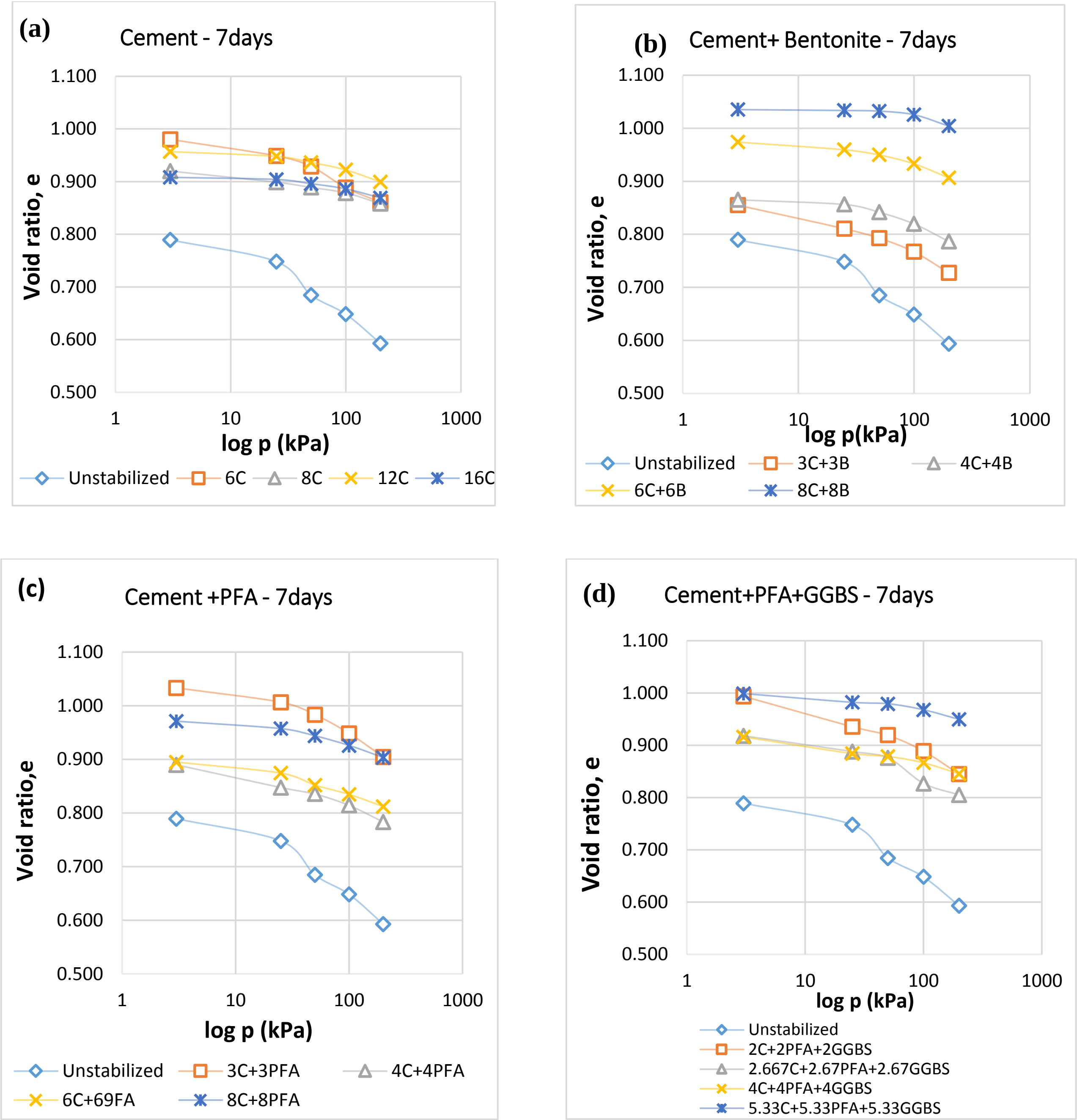

Figure 1.0(a-d): Variation of void ratio of stabilised soils with effective stress

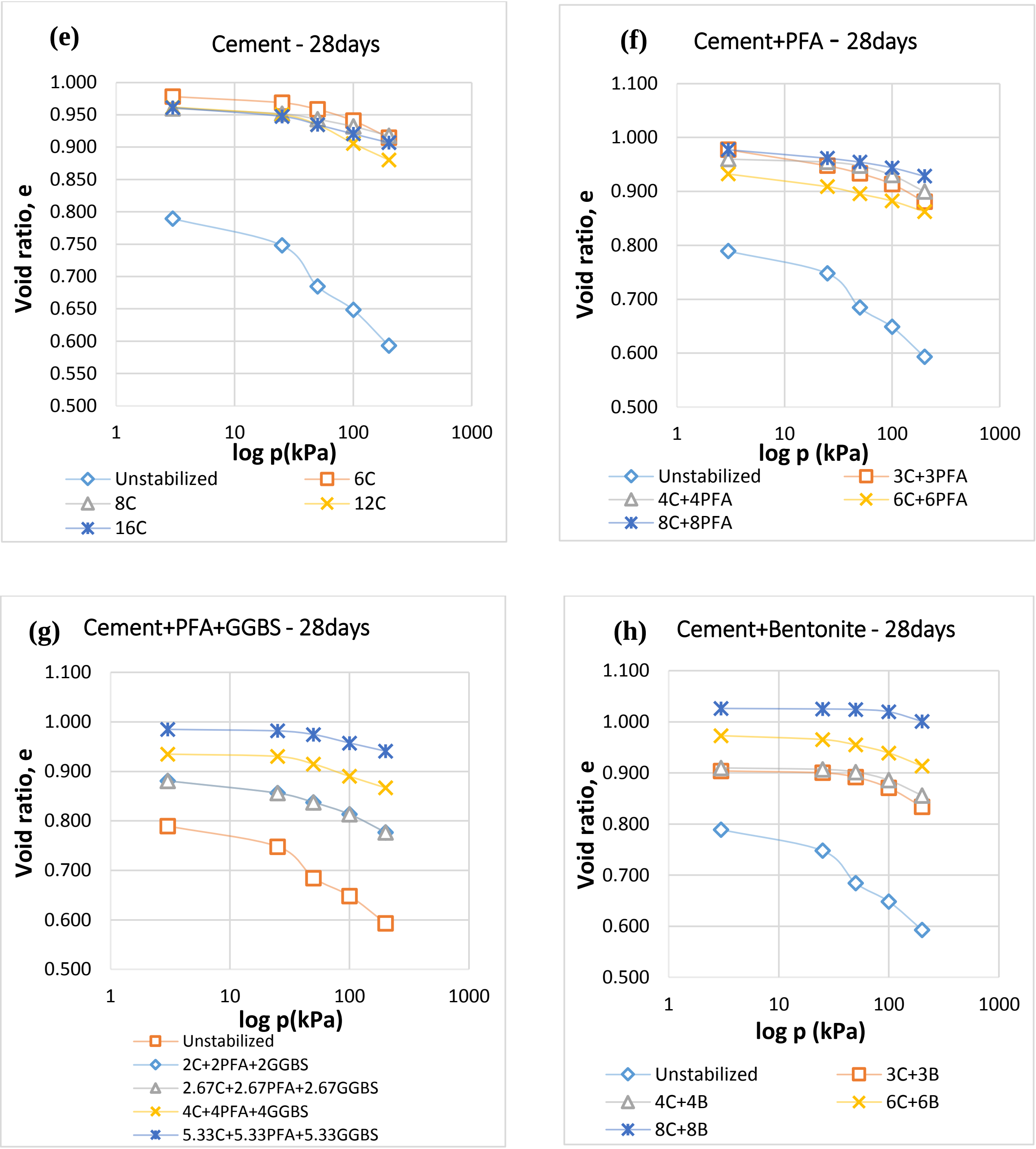

Figure 2.0(e-h): Variation of void ratio of stabilised soils with effective stress after 28-days

The results show reduction in void ratio with increase in effective stress as expected, due to increase in overburden. Irrespective of binder types, void ratio decreases with an increase in % of binder due to bonding effect of additives with solid soil particles. The inclusion of by-product cementitious materials increases the volume of solid particles and bonding area. The void ratio of the improved soils decrease as the % of binder combinations increases. However, 8% cement-bentonite mix shows almost linear and lower variation in void ratio with increasing overburden after 7 and 28days as shown in Figure 1.0(b) and Figure 1.0 (h). This is due to the expansive behaviour of bentonite when in contact with water.

Effect of porosity and density on UCS

In a study on use of fly ash and GGBS as partial replacement of cement and lime by (Chao, Songyu and Yongfeng 2015), it was observed from a microstructural analysis that fly ash mainly alters the distribution of pore volume of the soil, and produces more hydration compounds as a result of secondary hydration and pozzolanic reactions. The present study has investigated other properties of soil improved using combination of this additives with reduced amount of cement. The effect of porosity and density on unconfined compressive strength (UCS) has been investigated. The results show that an increase in % of additives causes decrease in porosity and increase in density of cement and cement/PFA stabilised soil and hence, increase in UCS. Except at higher % of additive (12% and 16% of additives) in C+PFA combinations as shown in Figure 4.0, where the density of the improved soil decreases at fairly constant porosity resulting to increase in UCS. This implies that the % of additive and type of additive controls the UCS of improved soils more than the influence of porosity and density on UCS. This means that UCS depends more on the % of additive and the type of additive than on porosity and density of the improved soil. The porosity of samples improved using C+PFA+GGBS and C+B also decreases with increase in % of additives, resulting to increase in UCS as shown in Figure 3.0, however, the reduction in density and increase in UCS shown in Figure 4.0 again, is due to predominance of % and type of additive on strength over porosity and density.

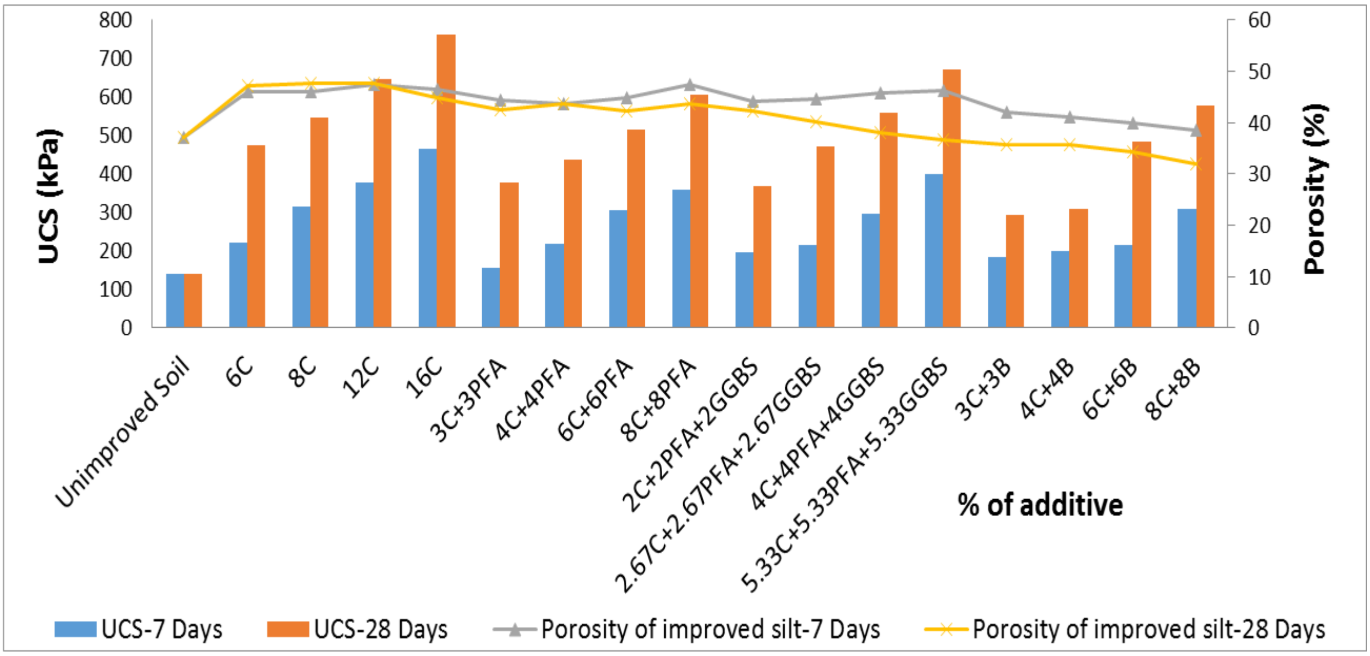

Figure 3.0: Variation of unconfined compressive strength and porosity with % of binder

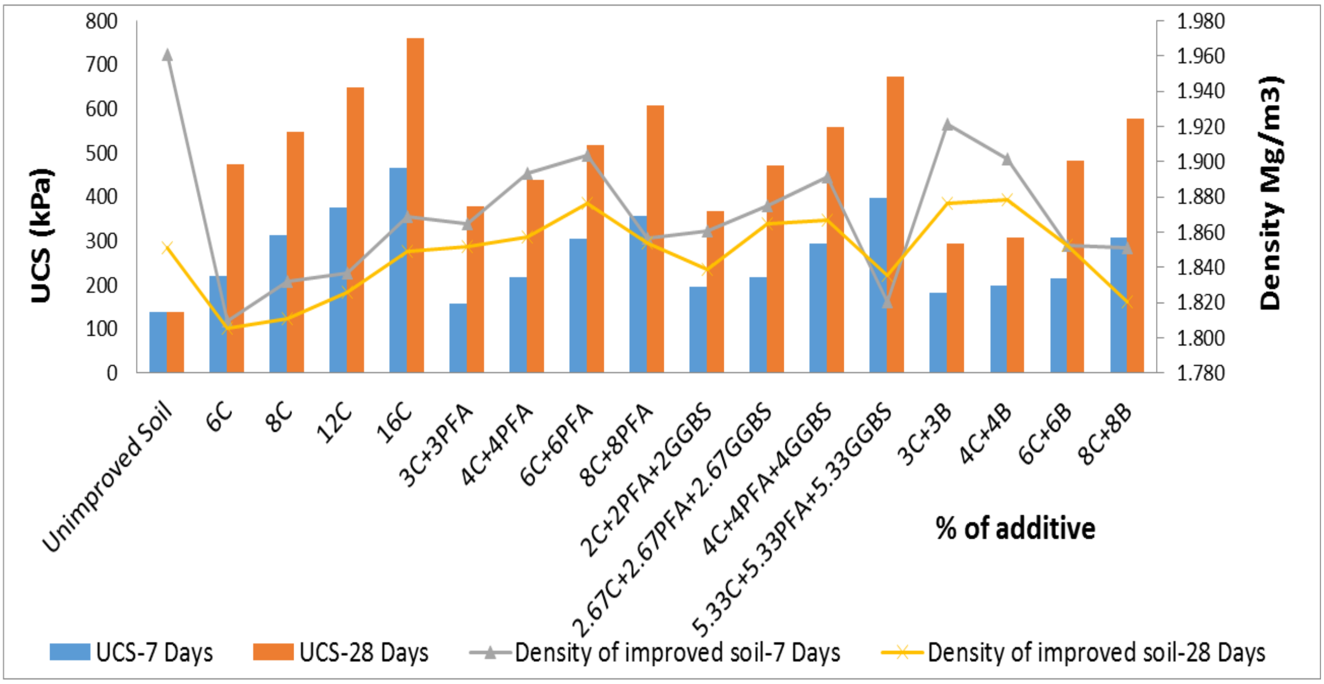

Figure 4.0: Variation of unconfined compressive strength and density with % of binder

Hydraulic conductivity changes with binder inclusion

The coefficient of permeability k values obtained from one-dimensional consolidation test showed a bit of scatter as expected however, some important trends were observed. The results plotted in Figure 5.0 and 6.0 show the variation hydraulic conductivity with degree of saturation of the improved soil materials at different binder percentages after 7 and 28 days. Figure 5.0 shows that the addition of 6% - 16% drops the degree of saturation of the improved samples below degree of saturation line of the unimproved soil due to hydration reaction of cement and water, resulting to reduction in hydraulic conductivity. A reduction in % of cement to 3%, 2% and 5.33% and inclusion of equal amount of PFA and PFA+GGBS also reduces the degree of saturation and hydraulic conductivity of the improved soil at the early stage of hydration process.

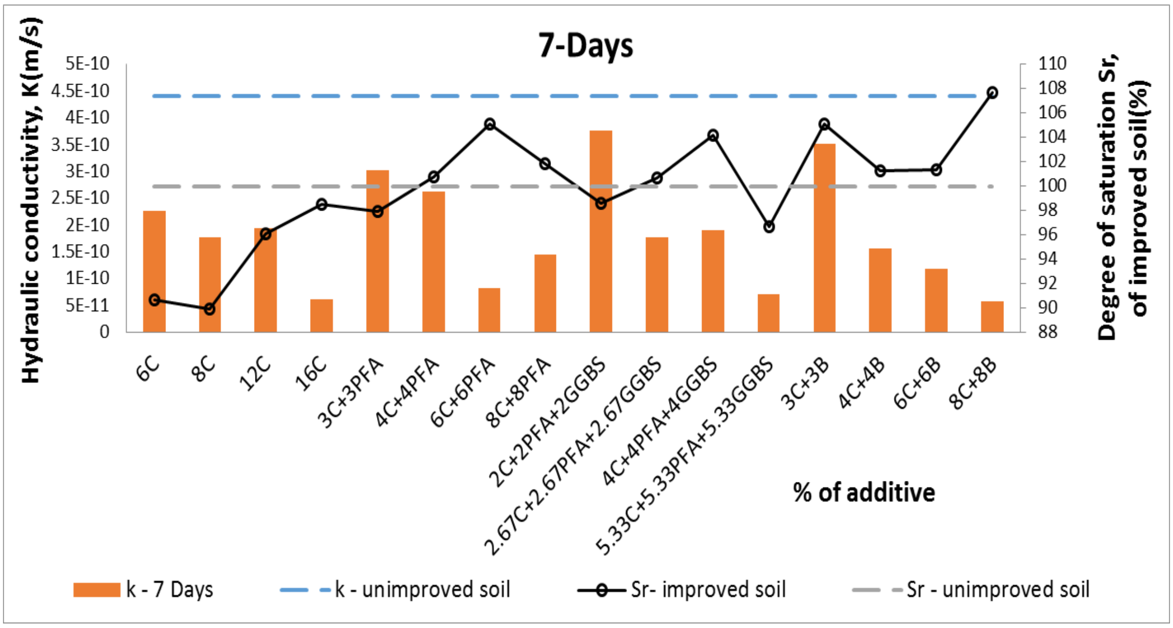

Figure 5.0: Variation of hydraulic conductivity and degree of saturation with % of binder

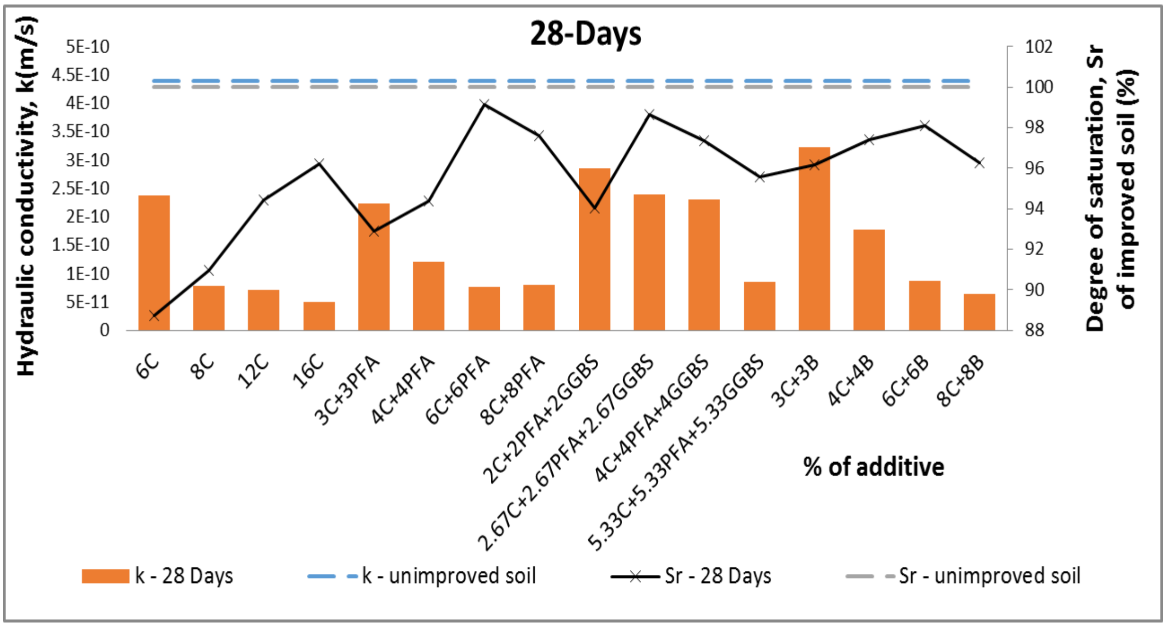

Figure 6.0: Variation of hydraulic conductivity and degree of saturation with % of binder

The permeability and compressibility of stabilized soil is also expected to vary with curing time due to the continuous binder-soil reaction that occurs because of cement hydration (Åhnberg 2003). Figure 7.0 also shows that hydraulic conductivity decreases with reduction in cement content and inclusion of PFA and GGBS contents in the different combinations of additives after 28days due to reduction in porosity of the improved soils as % of additive increases as shown in Figure 7.0. Soil matrix consists of pores of numerous different sizes, and the pores-fill performance of these additives differs and this causes the variation in porosity of the improved soil across the different additives and combinations as shown in Figure 7.0.

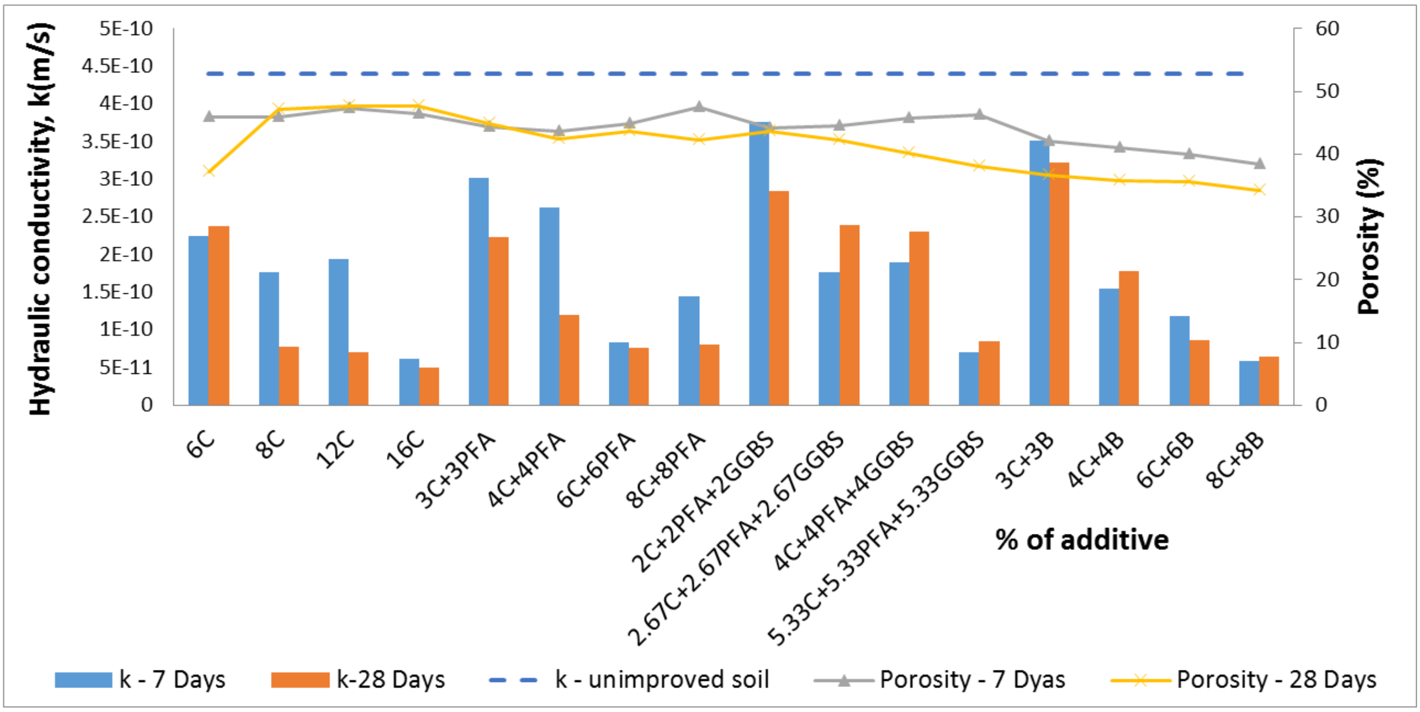

Figure 7.0: Variation of hydraulic conductivity and porosity with % of binder after 7 and 28 days.

The ease by which water flows through soil is highly dependent on porosity and it is evident that reduction in porosity accompanied by reduction in hydraulic conductivity of the improved soil is because of decrease in distances between individual soils particles due to bonding. The dependency of coefficient of hydraulic conductivity of soils on porosity has been explained using existing empirical relations as shown in Equations 1.0, (Slichter, (1899), Kozeny (1927)). Equations 1.0 empirically shows the direct proportionality of coefficient of permeability (hydraulic conductivity) on porosity (n) and pore radius (r).

$$k = \frac{nr^2}{8} = \frac{\mathrm{n}^3}{\mathrm{a}\mathrm{A}_\mathrm{V}^2} \qquad \text{Eq. 1.0}$$

From Figure 7.0, it is evident that the inclusion of GGBS and Bentonite causes a smooth reduction in porosity, hence, decrease in permeability due to consistent fineness and particle shape of the GGBS powder, and hence, increase in surface area. Equation 1.0 shows that permeability coefficient is directly dependent on porosity and inversely dependent on surface area of the particles per unit volume of porous matrix (A_v), where the parameter (a) is an empirical term and depends on porosity. This study has shown that hydraulic conductivity of the improved soil depends on porosity, % of additives, type and combination of additives as shown in Figure 8.0 and Figure 9.0.

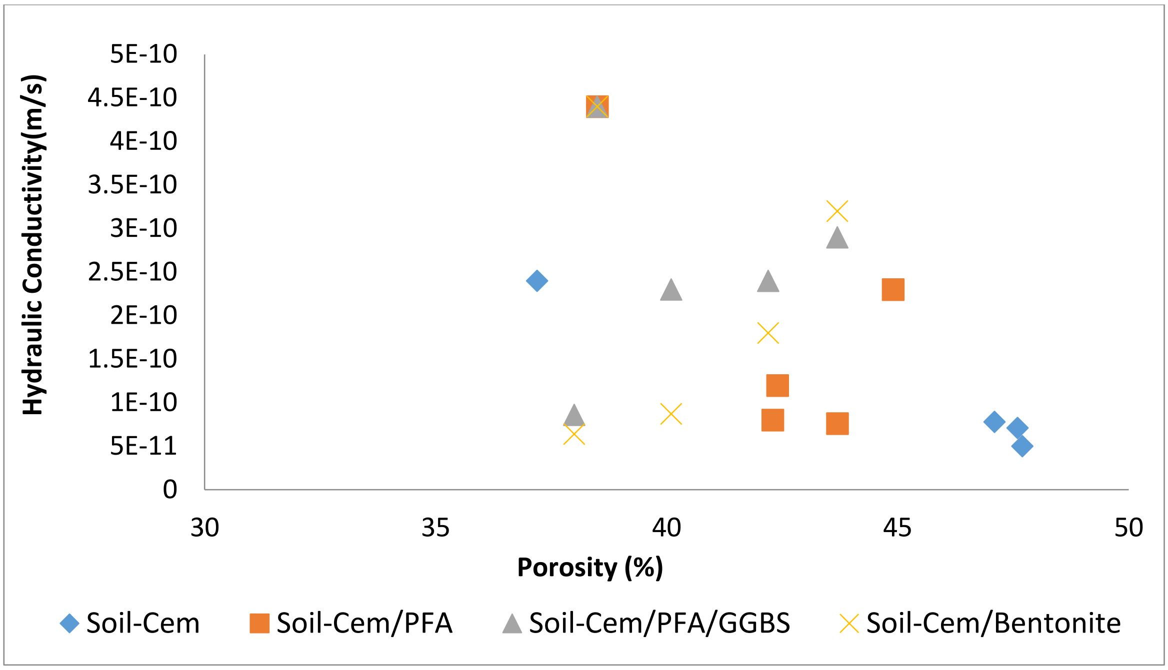

Figure 8.0: Variation of hydraulic conductivity with porosity

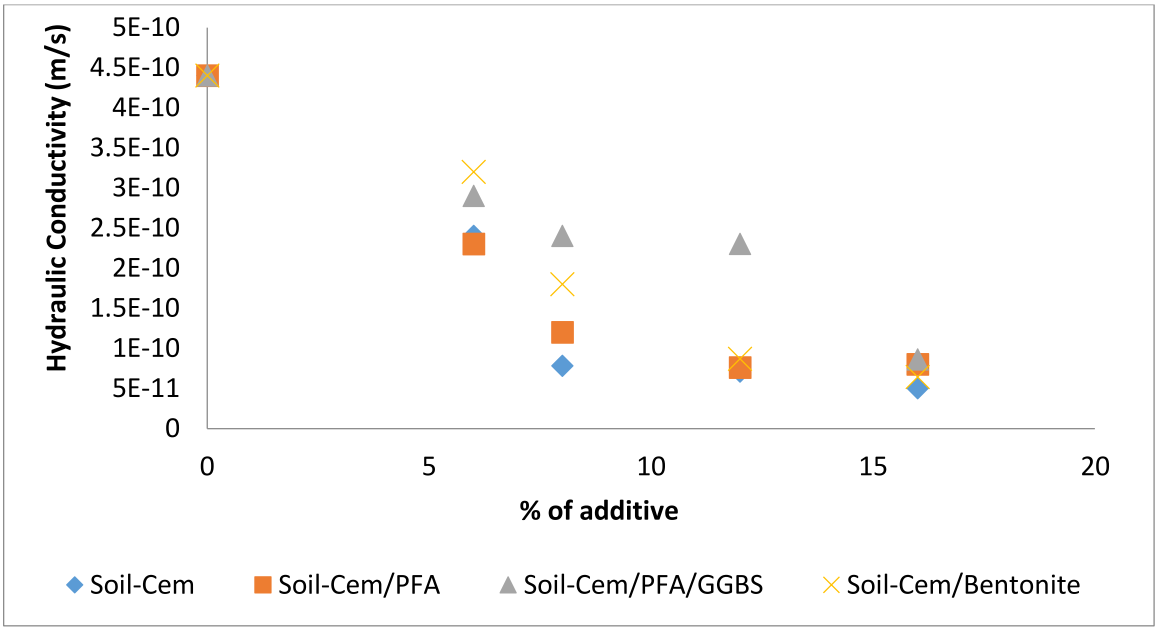

Figure 9.0: Variation of hydraulic conductivity with % of binder

The porosity in turn depends on the type and % of additive. Therefore, this study has defined the functional relationships between hydraulic conductivity and additive type based on the % of additives and combinations considered in this study as presented in Table 4.0. The values of the coefficients of determination defines how the functions explain the variability of the response data around its mean.

Table 4.0 Functional relationship between hydraulic conductivity and percentage of additive

Function	**Mixed soil type**			
	Soil-Cem	Soil-Cem/PFA	Soil-Cem/PFA/GGBS	Soil-Cem/Bentonite
	Coefficient of Determination, R^2			
Linear	0.8285	0.8417	0.9470	0.9297
Exponential	0.8792	0.8942	0.8577	0.9398
Polynomial	0.9487	0.982	0.9476	0.9454

CONCLUSION

This study has considered the effect of Cement and combinations of cement with materials such as PFA, GGBS and Bentonite on the strength and hydraulic conductivity of a fine-grained soil, and the following conclusions have been drawn.

- The strength increase and reduction in hydraulic conductivity (permeability) of an improved fine-grained soil depend on the type and amount of additives and not solely on changes in the physical properties of the investigated soil.
- The combination of Bentonite and Cement, mixed with fine-grained soil produces an improved soil with enhanced permeability compared to other additive combinations due to the hydrophilic property of bentonite.
- Small percentages of the investigated additives and combinations (<6%) have no significant effect on the permeability of the improved soil at early age (k after 7 days of curing).
- The least permeability was achieved with 8C+8B combination but additive content and combinations of 16%C and 5.33C+5.33PFA+5.33GGBS also reduced the permeability of the fine-grained soil.

List of abbreviations symbols

BS	-	British Standard
B	-	Bentonite
C	-	Cement
CASH	-	Calcium Aluminate Silicate Hydrate
CSH	-	Calcium Silicate Hydrate
GGBS	-	Ground Granulated Blast Slag
PFA	-	Pulverised Fly Ash
UCS	-	Unconfined Compressive Strength
k	-	Hydraulic conductivity

REFERENCES

[1] Abbey, S.J, Ngambi, S., and Ganjian, E. (2017) 'Development of Strength Models for Prediction of Unconfined Compressive Strength of Cement/By-product Material Improved Soils.' Geotechnical Testing Journal, Vol. 40, No. 6, pp. 928-935. doi.org/10.1520/GTJ20160138. ISSN 0149-6115

[2] Abbey, S.J., Ngambi, S., Coakley, E. (2016) 'Effect of Cement and by-product material inclusion on plasticity of deep mixing improved soils'. International Journal of Civil Engineering and Technology, 7 (5), pp. 265-274.

[3] Abbey, S.J., Ngambi, S., Olubanwo, A.O. (2017) 'Effect of overlap distance and chord angle on performance of overlapping soil-cement columns'. International Journal of Civil Engineering and Technology, 8 (5), pp. 627-637.

[4] Abbey, S.J., Ngambi, S., Ngekpe, B.E. (2015) 'Understanding the performance of deep mixing improved soils - A Review' International Journal of Civil Engineering and Technology**,** 6 (3), pp. 97-117.

[5] Ali, D.B, Kamarudin, A. and Nazri, A. (2012) 'Initial Settlement of Mat Foundation on Group of Cement Columns in Peat –Numerical Analysis'. Journal of Geotechnical and Geo-environmental Engineering 17 2243-2253.

[6] Axelsson, K., Johansson, S. E., and Andersson, R. (2002). 'Stabilization of Organic Soils by Cement and Pozzolanic Reactions: Feasibility Study'. Report 3, Swedish Deep Stabilization Research Center, Linkoping, Sweden, 51 pages.

[7] Eyo, E.U., NgAmbi, S., Abbey, S.J. (2017) 'Investigative modelling of behaviour of expansive soils improved using soil mixing technique'. International Journal of Applied Engineering Research, 12 (13), pp. 3828-3836.

[8] Abdulhussein Saeed, K., Anuar Kassim, K., and Nur, H. (2014) 'Physicochemical Characterization of Cement Treated Kaolin Clay'. Građevinar 66 (06.), 513-521.

[9] Åhnberg, H. (2006) Strength of Stabilised Soil-A Laboratory Study on Clays and Organic Soils Stabilised with Different Types of Binder. [online] Doctorate thesis or dissertation: Lund University.

[10] Åhnberg, H. (ed.) (2003) Grouting and Ground Treatment. 'Measured Permeabilities in Stabilized Swedish Soils': ASCE.

[11] Barnard, L., Bone, B., and Hills, C. (2003) Guidance on the use of Stabilisation/Solidification for the Treatment of Contaminated Soil. Bristol, UK: R&D Technical Report P5-064/TR, Environment Agency.

[12] Bruce, D. (2001) 'Practitioner's Guide to the Deep Mixing Method'. Ground Improvement 5 (3), 95-100.

[13] Bullock, A. (ed.) (2007). 'Innovative Uses of Organo-Philic Clays for Remediation of Soils, Sediments and Groundwater': WM Symposia, 1628 E. Southern Avenue, Suite 9-332, Tempe, AZ 85282 (United States).

[14] Chao, Y., Songyu, L., and Yongfeng, D. (2015) 'Experimental Research for the Application of Mining Waste in the Trench Cutting Remixing Deep Wall Method'. Advances in Materials Science and Engineering 2015.

[15] Consoli, N.C., Winter, D., Rilho, A.S, Festugato, L. and Teixeira, B.S. (2015) "A testing procedure for predicting strength in artificially cemented soft soils", Journal of Engineering Geology, 195 pp. 327- 334.

[16] Eurosoilstab (2002) Development of Design and Construction Methods to Stabilize Soft Organic Soils: Design Guide for Soft Soil Stabilization. Project No. BE-96-3177 edn: European Commission, Industrial and Materials Technologies Programme (Rite-EuRam III).

[17] Higgins, D. (2005) 'Soil Stabilisation with Ground Granulated Blastfurnace Slag'. UK Cementitious Slag Makers Association (CSMA).

[18] Holm, G., (2003) "State of practice in dry deep mixing methods," in Proceedings of the 3rd International Conference on Grouting and Ground Treatment, pp. 145–163, ASCE, New Orleans, La, USA, February.

[19] Jawad, I. T., Taha, M. R., Majeed, Z. H., and Khan, T. A. (2014) 'Soil Stabilization using Lime: Advantages, Disadvantages and Proposing a Potential Alternative'. Research Journal of Applied Sciences, Engineering and Technology 8 (4), 510-520.

[20] Keramatikerman, M., Chegenizadeh, A., and Nikraz, H. (2016) 'Effect of GGBFS and Lime Binders on the Engineering Properties of Clay'. Applied Clay Science [online] 132–133, 722–730. available from <http://dx.doi.org/10.1016/j.clay.2016.08.029

[21] Kozeny, J. *(*1927*),* Uber kapillare Leitung der Wasser in Boden*,* Sitzungsber. Akad. Wiss. Wien*,* 136*,* 271–306*.*

[22] Makusa, G. P. (2012) Soil Stabilization Methods and Materials. [online] PhD thesis or dissertation. Luleå, Sweden: Luleå University of Technology.

[23] Mousavi, S. E. and Wong, L. S. (2016) 'Permeability Characteristics of Compacted and Stabilized Clay with Cement, Peat Ash and Silica Sand'. Civil Engineering Infrastructures Journal 49 (1), 149-164.

[24] Oana, C., (2016) "Soil Improvement by Mixing Techniques and Performances" Energy Procedia 85, pp. 85-92.

[25] Slichter, C.S. 1899. Theoretical investigations of the motion of ground waters. U.S. Geological Survey 19th Annual Report, Part 2.

[26] Talfirouz, D. (2013) The use of Granulated Blast-Furnace Slag, Steel Slag and Fly Ash in Cement-Bentonite Slurry Wall Construction. [online] thesis or dissertation: MIDDLE EAST TECHNICAL UNIVERSITY.

[27] Terashi, M. (2009) 'Current Practice and Future Perspective of Quality Assurance and Quality Control for Deep-Mixed Ground'. Okinawa Deep Mixing Symposium.

[28] Wang, F., Wang, H. and Al-Tabbaa, A. (2015), 'Time-dependent Performance of Soil Mix Technology Stabilised/Solidified Contaminated Site Soils' Journal of Hazardous Materials, 285, 503–508.

[29] Yi, Y., Liska, M., and Al-Tabbaa, A. (2013) 'Properties of Two Model Soils Stabilized with Different Blends and Contents of GGBS, MgO, Lime, and PC'. Journal of Materials in Civil Engineering 26 (2), 267-274.