

CHAPTER 5

RESULTS AND DISCUSSION

5.1 RAW POME SLUDGE PARAMETERS

Moisture content and specific gravity of the waste sludge are discussed in the previous Sub-sections 4.3.1 and 4.3.2. Both properties were determined in triplicate to ascertain the accuracy of data.

5.1.1 Moisture Content

Appendix C shows the moisture content results of the raw POME sludge with three attempts. The results obtained could be considered quite consistent since the differences in value from the three runs were quite insignificant. The average moisture content of raw POME sludge was 80.58 %. The weight of the sludge needed (kg) in cement to dry sludge ratio was calculated based on this result. The moisture content was used to estimate the quantity of water needed for the mixtures so that a desirable workability can be obtained.

5.1.2 Specific Gravity

The average specific gravity for the raw POME sludge was 1.06. The specific gravity of OPC used in these studies was 3150 kg/m^3 . The full calculation of specific gravity of the sludge is shown in Appendix D. The weight of the sludge (kg) needed in cement to dry sludge ratio was calculated based on both results. The specific gravity is important because if there is a significant difference in the densities of various phases in the sludge, phase separation and layering will occur. This can make the homogenization difficult and cause withdrawal of fluid from the wastes.

5.2 CHARACTERISTICS OF HEAVY METALS IN RAW POME SLUDGE

The main objective in the leaching studies is to examine the concentration of contaminants in the leachate. In order to achieve this objective, the crushed block leaching based on TCLP was conducted as a measurement of the performance of S/S technique to immobilize the heavy metals concentrations in the raw sludge. It was carried out so that the percentage of heavy metals released for the treated sludge can be measured. The determination of heavy metal concentrations in the raw sludge was done by using ICP-OES. Nitric acid digestion method (see sub-section 4.5.3) was used to prepare the samples before analysis of the metals.

Table 5.1 shows the characteristics of raw POME sludge prior to S/S treatment. The most commonly used systems for POME treatments are ponding system, open tank digester, extended aeration system, closed anaerobic digester and land application system. These ponds can be utilized to contain the solid concentrate and the solid can be used later as fertilizer, animal feed and feedstock for fermentation (Manahan, 1990). Referring to Table 5.1, the heavy metal contents that is, Fe, Cu, Zn, Pb are fairly low but still exceed the regulatory limit as given in Tables 4.2 & 4.3. Plate 5.1 shows the raw POME sludge.

Table 5.1 Characteristics of raw POME sludge

Parameters*		Metal (ppm)	
pH	4.7	Potassium	22700
O & G	4 000	Magnesium	615
BOD ₃	25 000	Calcium	439
COD	50 000	Boron	77.6
TS	40 500	Iron	46.5
SS	18 000	Manganese	31.3
TVS	34 000	Copper	35.8
AN	35	Zinc	38.7
TN	750	Lead	9.2

* All parameters in ppm, except pH

Plate 5.1 The raw POME sludge



5.3 WATER-CEMENT RATIO (W/C)

The W/C ratio of various mixtures is shown in Appendix G. In general, the W/C ratio increases with increasing PFA addition. At the same time, the recorded W/C demonstrated that the W/C decreases with increasing C/S_d . These observations were expected because increasing the CRM content means some amount of OPC used were reduced and replaced by the PFA. This causes the W/C to be increased. On the other hand, when C/S_d increased the quantities of cement used also increase resulting in higher W/C ratio.

5.4 DEVELOPMENT OF UNCONFINED COMPRESSIVE STRENGTH TEST (UCS)

The objective of this test was to investigate the strength development of stabilized/solidified wastes. Therefore, UCS tests have been carried out to gauge the strength of the treated wastes at 1, 3, 7, 14, 28 and 56 days of curing (see Appendices H, I, J, K, L, M, N and O). Samples were cured at room temperature and therefore designated dry curing. This curing method is to simulate the worst condition normally encountered in a field situation.

Appendix G presents the fully prepared set of data for the POME sludge solidified samples with various C/S_d ratios, percentages of PFA and W/C ratios. From strength development results, the influence of C/S_d ratios, percentage of PFA and curing period for raw POME sludge and influence of various concentration of metals and curing period for pure model studies had been examined and studied. However, the influence of W/C ratios was not directly comparable. This is because the W/C ratios applied for various C/S_d ratios are different in order to gain a desired workability for the mixtures. The quantity of water added to the mixtures was measured by the k-slump test. Generally, the sludge used in the various mixtures varies in their moisture content. Thus,

the quantity of water needed in a particular mixture have to be determined experimentally. If the same W/C ratio was applied to all the C/S_d mixtures, some of the mixtures will not be able to set because of excess water and some will provide in low workability. The results indicated that the strength of the S/S waste specimen increase with the increment of PFA or at higher C/S_d ratio.

5.4.1 Influence of Cement-Dry sludge Ratio (C/S_d)

Suggested C/S_d ratios of 6, 7, 8, 9 and 10 were derived from the initial trial runs and these ratios would ascertain whether cementitious materials that were mixed with sludge would set or solidify after 24 hours. Impression factors of cement-sludge paste such as compaction method, temperature, chemical composition, preparation methods and setting period were assumed to be uniform.

Figures 5.1-5.5 show the UCS development of various C/S_d. Referring to these figures, the compressive strengths were found to increase with increasing C/S_d ratio. The strength development at 1, 3, 7, 14, 28 and 56 days were found to be higher with increasing C/S_d ratios and constant PFA content. When the C/S_d increases, a higher strength development line was obtained. Therefore the compressive strength for C/S_d ratio of 10 indicated the highest of all the stages during curing period. This is because increasing the amount of OPC is equivalent to increasing the amount of C₃S and C₂S, therefore more calcium silicate hydrate (C-S-H) will be produced which contribute to the strength of the samples (Hills *et al.*, 1992). These figures also show that most of the strength exceeded the UK regulatory limit of 0.34 N/mm².

The highest compressive strength of 3.38 N/mm² was achieved for specimen with C/S_d of 10 and 20 % PFA content at 56 days of curing. The lowest 28-day compressive

strength of 0.581 N/mm^2 (see Figure 5.1) was obtained at $C/S_d = 6$ and this strength also far exceeded the UK regulatory limit of 0.34 N/mm^2 . In fact at all C/S_d ratios, the values of compressive strength were much higher than 0.34 N/mm^2 . Therefore C/S_d ratios of 6, 7, 8, 9, 10 would easily meet the UK consent strength requirement although other types of test, such as permeability, porosity and leachability may also be needed to establish conformance to these durability requirements.

Referring to Figure 5.2, the compressive strength dropped at the curing age of 56 days. The reason for this strength drop-back may be due to the tropical climate, possible high C_3A content in the OPC and the conversion of hexagonal CAH_{10} crystals possibly in a combined role in this regard. Under tropical climate, strength of treated samples developed very fast due to high temperature at early stage. High temperature also encourages the transformation of hexagonal CAH_{10} crystals into cubic crystals of C_3AH_6 , which increases the porosity of cement paste leading to a certain reduction of strength of the cement paste (Chen & Ho, 1997)

The more the C_3A content in OPC, the higher the strength loss. If this loss is not compensated by the strength gain from the ageing of concrete, the compressive strength of the cube may decrease. Besides, the waste sludge also contains high concentration of iron (Fe^{2+}). The Fe^{2+} ions will react with sulfate ions from gypsum to form iron sulfate ($FeSO_4$). Therefore the amount of sulfate ions in OPC will be reduced and this will encourage the formation of cubic crystal (C_3AH_6) that will reduce the strength of cement-sludge paste.

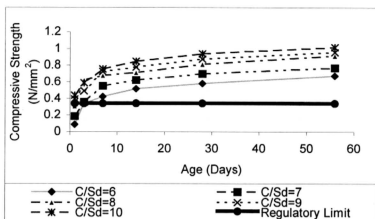


Figure 5.1 UCS development for various C/S_d, 0 % PFA

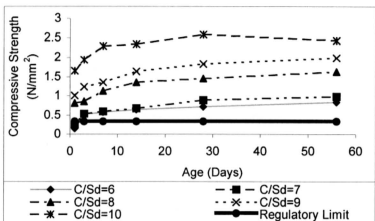


Figure 5.2 UCS development for various C/S_d, 5 % PFA

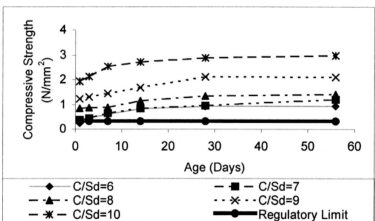


Figure 5.3 UCS development for various C/S_d, 10 % PFA

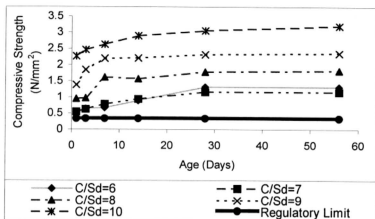


Figure 5.4 UCS development for various C/S_d, 15% PFA

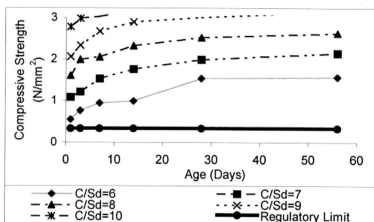


Figure 5.5 UCS development for various C/S_d, 20 % PFA

5.4.2 Influence of Various Concentrations of Simulated Metals for Pure Model Study

Metals of concerned were zinc, copper and iron. The concentrations of zinc were 7 ppm, 34 ppm, 134 ppm, 232 ppm and 327 ppm. For iron, the concentrations used were 7 ppm, 34 ppm, 133 ppm, 230 ppm and 323 ppm while the concentrations of copper used were 7 ppm, 34 ppm, 133 ppm, 228 ppm and 321 ppm. These concentrations were derived from the initial trial runs, and the tests were conducted to ascertain whether cementitious materials would set or solidify after 24 hours at these concentrations. Generally, referring to Figures 5.6 –5.8, metal concentration of 34 ppm gave the highest compressive strength for all metals and metal concentrations of 327 ppm, 323 ppm and 321 ppm gave

the lowest strength for zinc, iron and copper respectively. Referring to these figures, irrespective of the metal concentration, the values of compressive obtained were much higher than 0.34 N/mm^2 and the compressive strength of all the samples increase speedily after the first 24 hours.

5.4.2.1 Iron

Compressive strength tests which was conducted at 1, 3, 7, 14, 28 and 56 days showed that the value of compressive strength for Fe-containing samples varied depending on the concentration effects of Fe and the age of the samples (Figure 5.6). From the graph, it was found that sample containing 34 ppm Fe concentration exhibited the highest compressive strength and marginally higher than the control sample. This is probably related to the role of Fe as it was found to inhibit the formation of ettringite, which may be related to its role as a hydration accelerator. There was also a presence of the two major products of hydration (C-H) that contributed to the strength development of Fe-containing samples (Hills *et al.*, 1992).

At all curing ages, 321 ppm of Fe concentration gave the lowest compressive strength compared to 1 ppm, 7 ppm, 34 ppm, 133 ppm and 228 ppm of Fe-containing samples. The compressive strengths at these concentrations sample were slightly lower than the control. This was due to the increased amount of Fe, which has strong effects in retarding the setting time and hydration rate of the sample. The more Fe present in the sample, the lower the hydration rate will be and thus contributing to a slower setting time. As a result, the sample will harden at a slower rate and therefore a lower compressive strength.

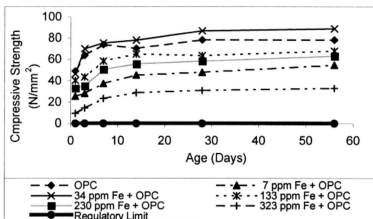


Figure 5.6 UCS development for various concentration of iron

5.4.2.2 Zinc

Compressive strength tests were conducted at 1, 3, 7, 28 and 56 days. Results showed that the value of compressive strength for Zn-containing samples also varied depending on the concentration effects of Zn and the curing age (Figure 5.7). From the graph, it is found that the compressive strength for 34 ppm of Zn concentration sample was similar to the control. This is probably related to the role of Zn itself in determining the composition of the elements in the samples. Zn was found to promote the formation of ettringite, which may be related to its role as a hydration retarder. Because of the hydration retarding effect of Zn, it makes sense that the compressive strength at earlier stages are lower because longer time was needed for the cement paste to fully set. Two major products of hydration were also present, i.e., calcium - silicate - hydrate (C-S-H) and calcium hydroxide (C-H) which contribute to strength development of Zn containing samples at later ages (Hills *et al.*, 1992).

At 56 days, the compressive strength of 34 ppm of Zn-containing samples was slightly higher than the control samples while at the other concentrations, the compressive strengths were lower than the control. This was due to the increased amount of Zn,

which have strong effects in retarding the setting time and hydration rate of the sample. The more Zn present in the sample, the lower the hydration rate will be and this will contribute to a slower setting time. As a result, the sample will harden slower and thus producing lower compressive strengths.

At all curing ages, 327 ppm of Zn concentration gave the lowest compressive strength compared to other concentrations. So it can be understood and conclude that the role of Zn in this study is to retard the hydration rate of cement. Presence of the two major products of hydration, that is, calcium-silicate-hydrate (C-S-H) and calcium hydroxide (C-H) along with other products such as Si, Al etc were noted. Retarders from insoluble salt tend to precipitate as dense coatings on the hydration phases (Manahan, 1990).

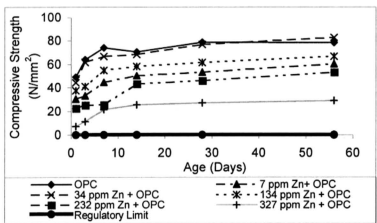


Figure 5.7 UCS development for various concentration of zinc

5.4.2.3 Copper

Compressive strength test which was conducted at 1, 3, 7, 14, 28 and 56 days showed that the value of compressive strength for Cu-containing samples also vary depending on concentration of Cu and the age of test (Figure 5.8). From this figure, it is found that the compressive strengths for 34 ppm of Cu concentration are slightly lower than the

control sample at 1, 3 and 7 curing age but similar the ages of 14, 28 and 56 days. At all curing days, 321 ppm of Cu concentration gave the lowest compressive strength compared to 1 ppm, 7 ppm, 34 ppm, 133 ppm and 228 ppm of Cu-containing samples.

The compressive strength of the sample a containing these concentrations was slightly lower than the control. This was due to the increased amount of Cu, which has strong effects in retarding the setting time and hydration rate of the sample. The more Cu present in the sample, the lower the hydration rate will be and this will contribute to a slower setting time. As a result, the sample will harden slower and thus will produce lower compressive strengths (Hills *et al.*, 1992).

So it can be understood that the role of Cu in this study is to retard the hydration rate of cement. Cu is chemically, rather than physically contained within the cement structure. This appears to be a feature of a retarder that tends not to be chemically contained. Cu greatly retards hydration of OPC and PFA by forming a layer of amorphous gel on particles with concomitant promotion of ettringite formation that results in drastic increase in pore volume.

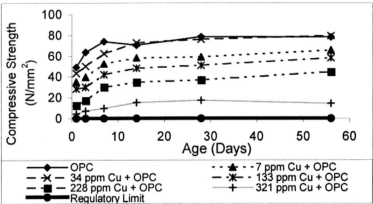


Figure 5. 8 UCS development for various concentration of copper

5.4.3 Influence of Cement Replacement Material (CRM) – Pulverized Fly Ash (PFA)

Lower cement utilization was part of the intention of this proposed study in response to the cement price fluctuation and volume availability in the open market. Therefore, CRM such as PFA was proposed to be included in the mixtures at various percentages to the cement-sludge paste. Referring to Figures 5.9 – 5.13, the compressive strength of the S/S specimens for various C/S_d ratios with different percentages of PFA were higher than the strength of the specimens without PFA. The silicate (SiO_2) will react with lime ($Ca(OH)_2$), which is produced by the hydration of the principal calcium silicate compound (i.e., C_3S) of OPC to form more calcium silicate hydrate (C-S-H). The additional C-S-H will increase the compressive strength of the samples (Hills *et al.*, 1992).

In other words, the strength of the samples with added PFA will increase continuously from the beginning and as long as moisture is present and it will not be affected by the tropical climate. Normally higher 56-day compressive strength will be obtained by increasing the percentages of PFA because more silicate can be used in the pozzolanic reaction. The smaller amount of OPC used in the mixtures, lesser lime will be produced through the cement hydration, therefore increasing the amount of silicate from PFA will not increase amount of C-S-H that contributes to the compressive strength of the cement-sludge paste. It was observed that for C/S_d of 6, 7, 8, 9 and 10 the highest strength was obtained at 56 days of curing age with 20 % PFA.

From these results, it is indicated that the PFA can increase the long-term strength of the samples. Basically, the addition of PFA tends to increase the number of the fine particles in the system. The replacement of cement particles by PFA is believed to increase the available space in the floc structure created by the cement grains. The acceleration of cement hydration in presence of PFA is mainly related to the preferential adsorption of

calcium ions on the PFA particles. This phenomenon contributes to the decrease in calcium ions concentration in the liquid phase that subsequently favours the dissolution of calcium phases from the cement grains.

It was shown that the influence of PFA on the early hydration of cement is influenced by the relative solubility of the sulfate and alkali sources of the cement and by the soluble alkali contents of the PFA itself. Anywhere, the cement-PFA reaction process is complicated by the fact that the chemical and physical properties of PFA tend to differ markedly from one source to another. Even with one source individual grains are highly variable in nature (Scar, 1998).

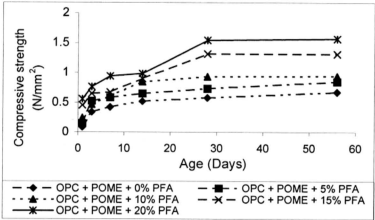


Figure 5.9 UCS development for C/S_d = 6

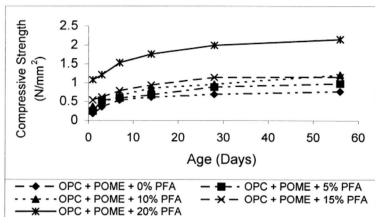


Figure 5.10 UCS development for $C/S_d = 7$

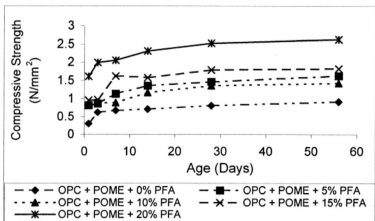


Figure 5.11 UCS development for $C/S_d = 8$

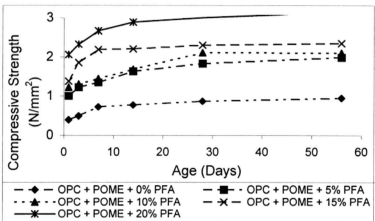


Figure 5.12 UCS development for $C/S_d = 9$

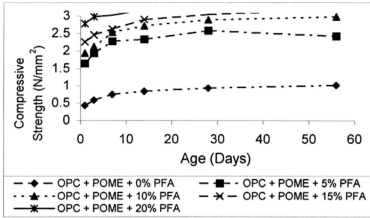


Figure 5.13 UCS development for $C/S_d = 10$

5.4.4 Influence of Curing Age on Solidified Samples

Figures 5.14 – 5.19 show the unconfined compressive strength development of various percentages of PFA at various curing age. Referring to these figures, the compressive strengths were found to increase with each increment of PFA percentages and curing age. The strength development at various C/S_d ratios were found to be higher with greater PFA percentage and at increasing curing age. The sample containing 20 % PFA gave the highest compressive strength at all curing age. For all the curing ages, we could see that the compressive strengths are very low at C/S_d 6 but increased gradually at higher C/S_d except for 0 % PFA sample. Influence of curing age to the solidified simulated samples could not be carried out as the concentrations of the metals were different.

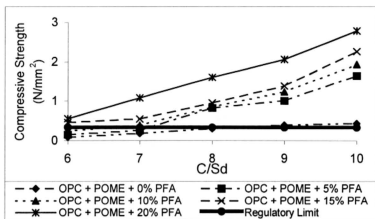


Figure 5.14 UCS development for various percentages of PFA at 1 day of curing age

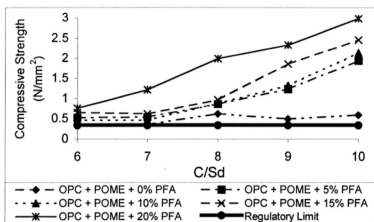


Figure 5.15 UCS development for various percentages of PFA at 3 days of curing age

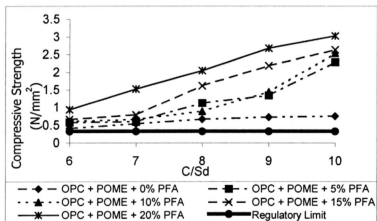


Figure 5.16 UCS development for various percentages of PFA at 7 days of curing age

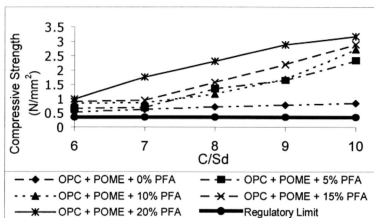


Figure 5.17 UCS development for various percentages of PFA at 14 days of curing age

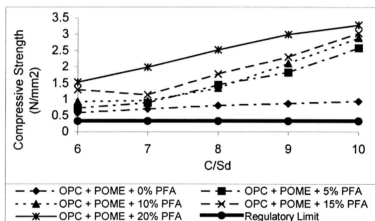


Figure 5.18 UCS development for various percentages of PFA at 28 days of curing age

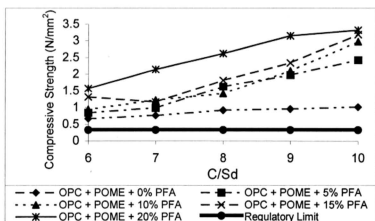


Figure 5.19 UCS development for various percentages of PFA at 56 days of curing age

5.4.5 Effects of Organic and Inorganic Compound on Ordinary Portland Cement and Pozzolanic System.

Comparisons were made between the solidified cube and the cement-paste cube samples for compressive strength. The cement-paste was carried out at W/C = 0.34 based on good workability. The samples of cement paste were tested at 1, 3, 7, 14, 28 and 56 days and the results are shown in Table 5.2. The results indicated that the compressive strengths of cement paste are much higher than the strength of the cement-sludge paste (see Appendix H). Thus, this shows that organic compounds presence in the sludge influenced the strength development of samples. From Table 5.1, heavy metal concentrations of Zn, Fe, and Cu in raw POME sludge exceed the regulatory limit. The concentration of Fe can react with sulphate ions from gypsum to form FeSO_4 . As a result, the sulfate ions in OPC were reduced and this could encourage the formation of cubic crystal (C_3AH_6), which is responsible for reducing the strength in cement pastes. It is believed that the hydration and mechanical strength of cement are retarded by the presence of these metals (Clair *et al.*, 1994).

The results from the UCS test for various C/S_d ratios have demonstrated that the hydration reactions of cement were modified by the incorporation by heavy metals. In other words, certain metals will influence the hydration and microstructure of the hydrated cement in the stages of hardening, thus affecting strength development. It is believed that the hydration and mechanical strength of cement are retarded by the presence of these metals. The previous studies on the interfering effect of Cu, Pb, Zn, Cd and Hg showed that these elements have detrimental effect on the compressive strength of S/S sludge (Wiles & Barth, 1990, Chessemann *et al.*, 1993). Cartledge *et al.*, 1981 had carried out another related study on the Pb/cement and the study revealed that in the presence of OH^- , SO_4^{2-} and NO_3^- , mixed salts are precipitated that contains all

three anions. These salts retard cement hydration reactions by forming an impervious coating around cement clinker grains.

Table 5.2. The compressive strength of cement paste for W/C = 0.34

Curing Day	Compressive Strength (N/mm ²)
1	49.274
3	64.108
7	74.673
14	70.647
28	78.675
56	78.543

5.4.6 Relationships of UCS, C/S_d and Curing Age

The compressive strength development of stabilized and solidified waste will be affected by the C/S_d ratio and curing period. Surfer program with surface and topography plots could present an overview of strength development of cement-sludge paste based on different percentages of PFA added (see Figures 5.20 - 5.24). It was observed that the strength development depended on C/S_d ratio and the curing period. Referring to figure 5.20, for sample with 0 % PFA, the compressive strength improve with curing age and C/S_d. The strength at various C/S_d ratio increase gradually with increasing curing age.

For cement-sludge paste with 5 % PFA (see Figure 5.21), the compressive strength of the samples improved with curing age and C/S_d ratio. The strength development at different curing age is very slow with increasing C/S_d ratio. The strength at various curing age increased gradually with increasing C/S_d ratio but decreases at 14, 28 and 56 days. Referring to Figures 5.22 – 5.24, for cement sludge paste with 10 %, 15 % and 20 % PFA, the characteristic of strength is almost the same with 5 % PFA.

5.4.7 Relationships of UCS, Simulated Metal Concentration and Curing Period

From the surfer and contour plots, it was observed that the surface plots with different concentrations of copper, iron and zinc used show similar shape (see Figures 5.25 – 5.27). The plots show that the surface of the graphs moved toward minimum at the area where the concentration of simulated metals increased. The highest compressive strength obtained at metals concentration of 34 ppm and at increasing curing age except for copper that decrease after 21 days of curing age.

5.4.8 Overview of the Result of UCS

It was observed that the strength development depended on the C/S_d ratio and the curing period. The strength generally increases with increasing of C/S_d ratio and the curing period. The highest C/S_d ratio with the longest curing period would result in a maximum strength. Similar trend was obtained at different percentage of PFA used. These observations show that the C/S_d and the curing period were interrelated in the effects on strength development. Most of the strength obtained far exceed the UK regulatory limit of 0.34 N/mm^2 (see Tables 4.2 and 4.3). It was also found that the inorganic compounds present in the cement-sludge pastes reduce the strength development.

Figure 5.20 Development of UCS on Various Samples of C/Sd + 0 % PFA

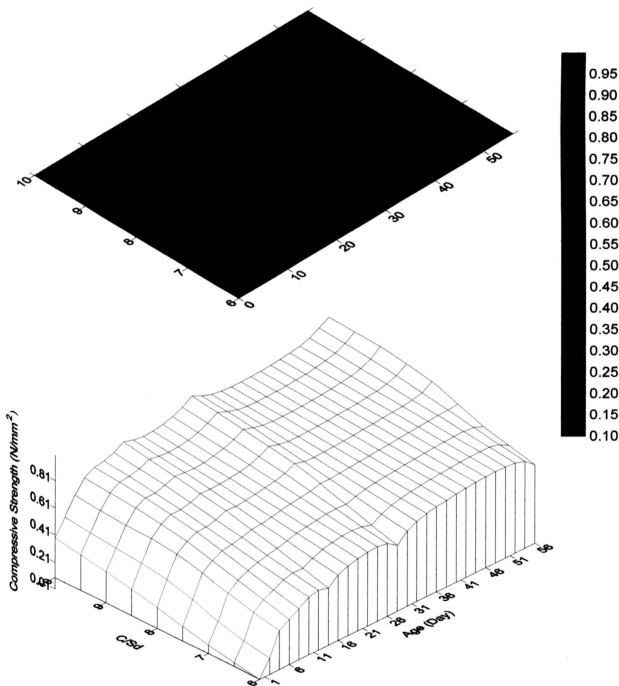


Figure 5.21 Development of UCS on Various Samples of C/Sd + 5 % PFA

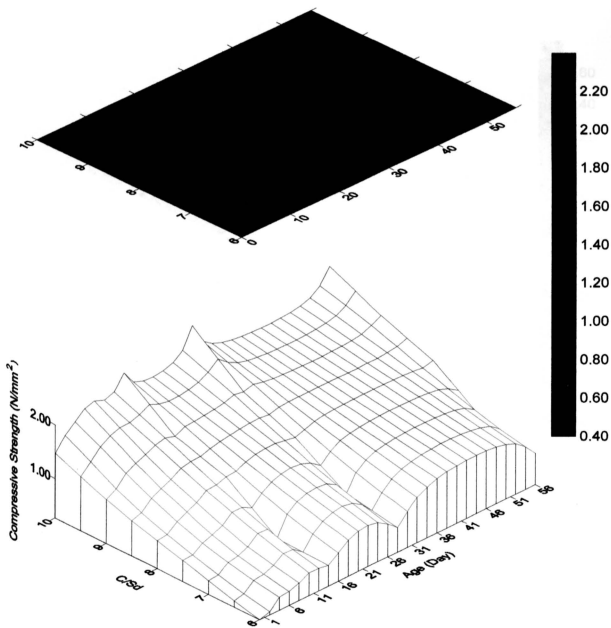


Figure 5.22 Development of UCS on Various Samples of C/Sd + 10 % PFA

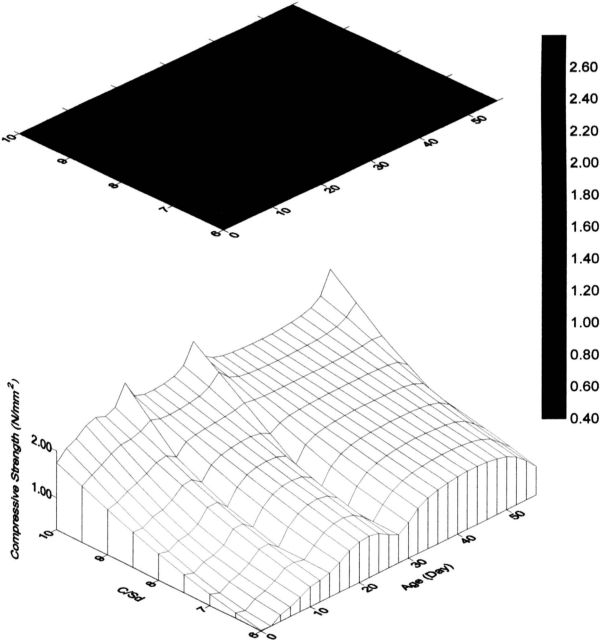


Figure 5.23 Development of UCS on Various Samples of C/Sd + 15 % PFA

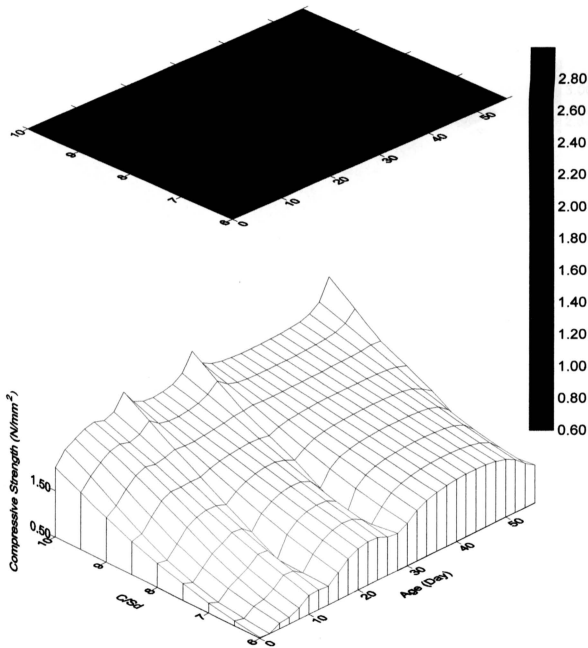


Figure 5.24 Development of UCS on Various Samples of C/Sd + 20 % PFA

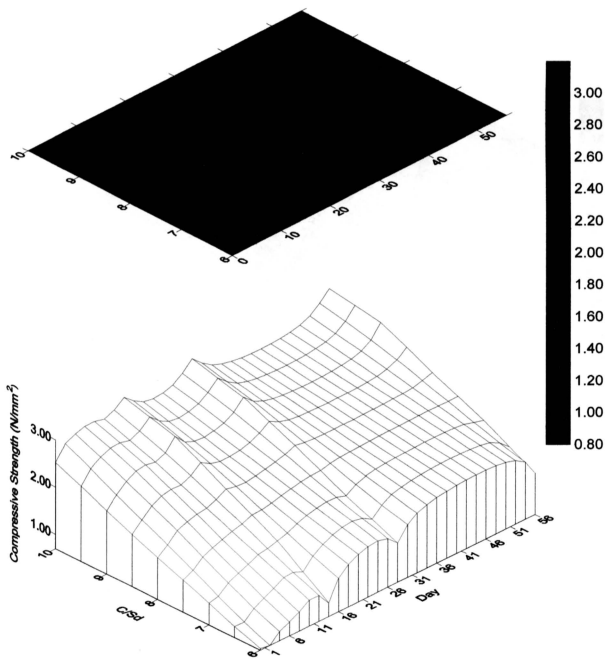


Figure 5.25 Development of UCS on Various Concentration of Copper

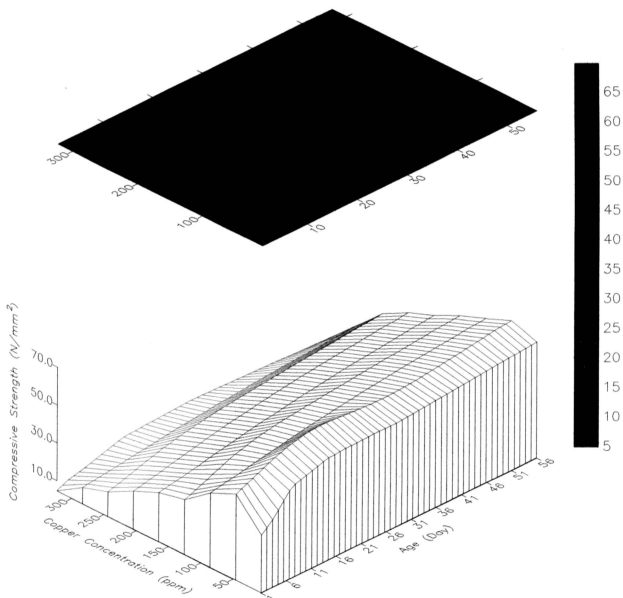


Figure 5. 26 Development of UCS on Various Concentration of Zinc

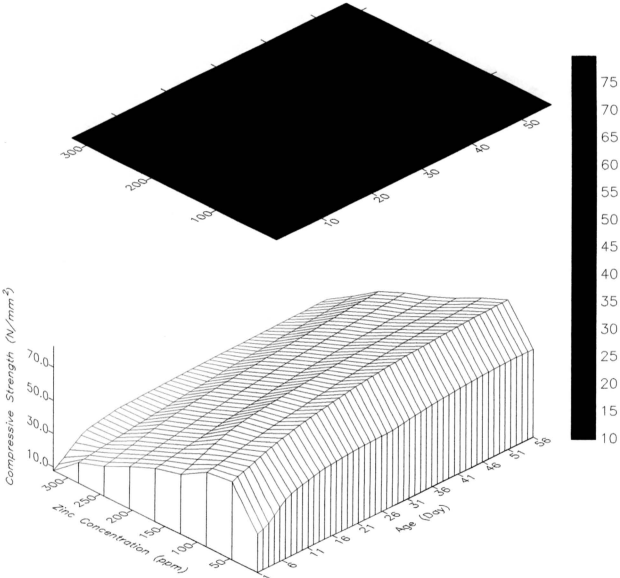
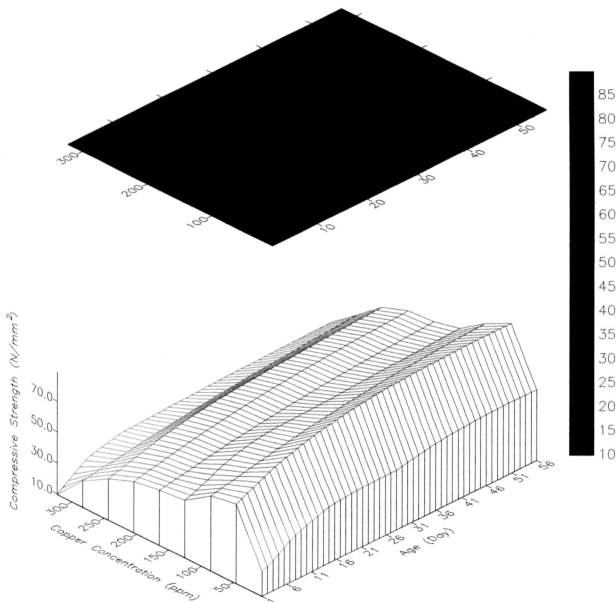


Figure 5.27 Development of UCS on Various Concentration of Iron



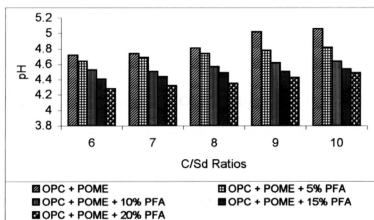


Figure 5.29 pH of HAC extracts of TCLP for various C/S_d ratio

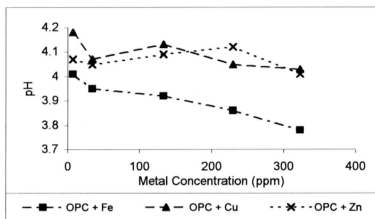


Figure 5.30 pH of HAC extracts of TCLP for pure model study

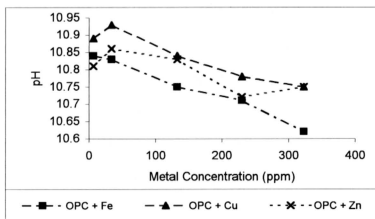


Figure 5.31 pH of DW extracts of TCLP for pure model study

The TCLP tests were carried out for all the samples after 28 days of curing. The leachate obtained after each interval was analyzed for pH prior to the determination of contaminants concentration by using ICP-OES. Referring to Figures 5.28 –5.31, all the pH of HAc extracts exceeded 3 and all the pH of DW extracts exceeded pH 10. These pH results were estimated because after the extraction, the OPC and PFA which were incorporated in the solidified wastes would neutralize the acetic acid and then yield a highly alkaline solution. pH of leachant play an important role in the leachability of heavy metals in the S/S treated sample. This, in turn is primarily dependent on the alkalinity of the cementitious materials added. In the S/S process, some previous investigations have shown that the leaching of metals was very little at higher values of pH extract. However, as the pH falls below 7, there is generally a very rapid increase in the amount of metals leached from stabilized/solidified wastes.

5.5.2 Leachate Analysis Contaminant

In this TCLP leaching, for both POME sludge and pure model study, the metals of Fe, Zn and Cu were chosen and determined using ICP-OES. From the results, the metals released in the TCLP extracts were very low. This indicated that the concentration of Fe, Cu, Zn in both the HAc and DW extracts were substantially reduced by using S/S technique. The leaching was found to decrease when the addition of PFA was increased. However, leaching reduced as the C/S_d increased. This is because when the quantity of PFA increased in the cement-sludge paste, it reduced the pH of the TCLP extracts. The lower pH extracts would reduce the capability of fixing the metals.

In case of copper in HAc leachant, it ranged from 0.076 – 0.235 ppm and in DW leachant it varied from 0.04 - 0.186 ppm (see Figures 5.32 and 5.33). In the copper/cement system, in the presence of OH⁻, SO₄²⁻ and NO₃⁻, mixed salts were precipitated and retarded the cement hydration by forming an impervious coating around the cement

clinker grains. As pH of the cement pore water fluctuates during hydration, lead salts will be present on the surfaces of cement and easily leached (Zaiton *et al*, 1997).

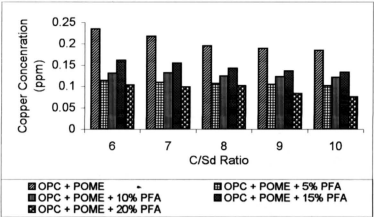


Figure 5.32 Leaching of copper in HAc leachant

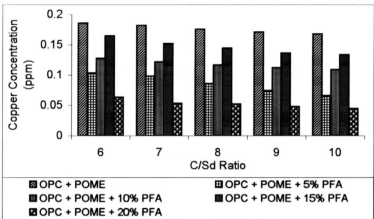


Figure 5.33 Leaching of copper in DW leachant

Figures 5.34 and 5.35 show the leaching of iron in the leachants were found to decrease with increasing C/S_d ratio. When the quantity of PFA is increased in the cement-sludge paste, it reduced the pH of the TCLP extracts. The lower pH extracts would reduce the capability of fixing the metals. Iron in HAc leachant ranged from 3.13 - 4.27 mg/L and DW leachant varied from 2.08 - 2.87 mg/L, implying that continuous water curing is needed to prevent more leachants from moving out of the solidified samples. For zinc, HAc leachants ranged from 0.035 - 0.156 mg/L and DW leachants varied from 0.012 - 0.132 ppm (see Figures 5.36 and 5.37). In all cases, the leachants were well below the

regulatory limit as given in Table 4.2. These results imply that OPC and OPC-PFA systems are capable of preventing the leaching of toxic materials to well below their regulatory levels (Hilmi, 1998).

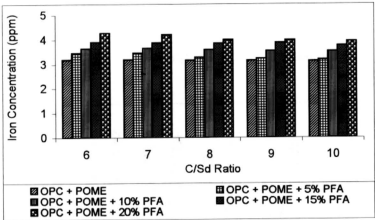


Figure 5.34 Leaching of iron in HAC leachant

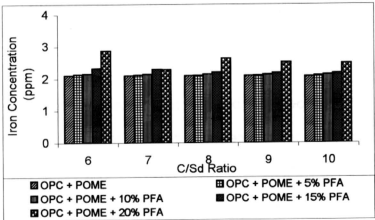


Figure 5.35 Leaching of iron in DW leachant

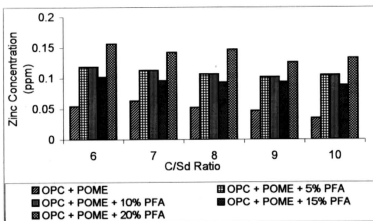


Figure 5.36 Leaching of zinc in HAc leachant

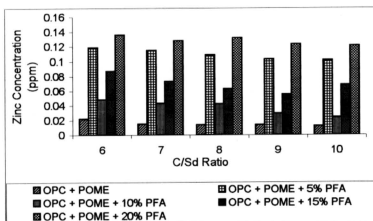


Figure 5.37 Leaching of zinc in DW leachant

For pure model study, it was observed that the solidified specimen of OPC + 323 ppm of Fe gave the highest iron released and the solidified cement paste indicated the lowest iron released (refer Figures 5.38 – 5.39). Figures 5.40 – 5.41 show that the highest zinc released was at the OPC + 327 ppm of Zn and the cement paste showed the lowest zinc released. The figures also indicate that much higher iron concentrations were detected in HAc leachants when compared to the DW leachant.

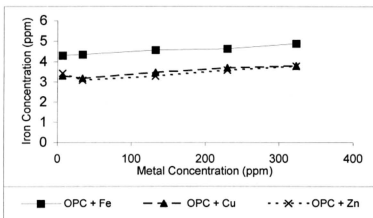


Figure 5.38 Leaching of iron in HAc leachant for various simulated metals

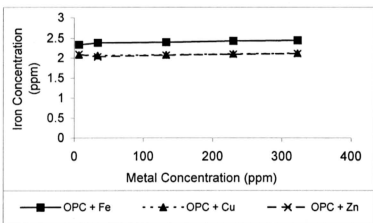


Figure 5.39 Leaching of iron in DW leachant for various simulated metals

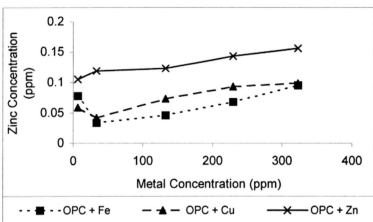


Figure 5.40 Leaching of zinc in HAc leachant for various simulated metals

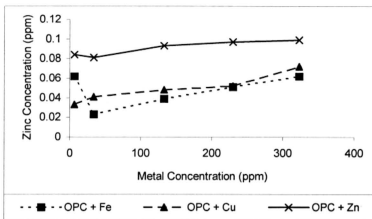


Figure 5.41 Leaching of zinc in DW leachant for various simulated metals

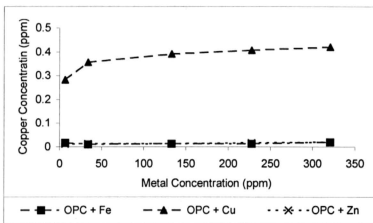


Figure 5.42 Leaching of copper in HAc leachant for various simulated metals

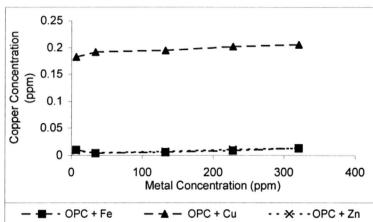


Figure 5.43 Leaching of copper in DW leachant for various simulated metals

Some previous investigations have showed that the leaching of metals was very little at higher values of pH extract (Shively *et al.*, 1986). Besides, metals that can be fixed and encapsulated in the structure of stabilized/solidified samples are primarily due to cement paste. Cement paste is highly alkaline with silica and oxyhydroxide surface that provide an environment for amphoteric metal precipitation and complex sorption reaction (Sollars & Perry, 1988). This explained that higher C/S_d ratio will effectively reduce the metals release from the treated wastes. Detail results of metals release from TCLP extracts are shown in Appendices P, Q, R and S.

5.5.3 Summary of the Results of Leachability

1. pH of the TCLP extracts generally decrease with PFA addition.
2. The stabilized/solidified wastes showed improved metals retention when compared to the untreated wastes.
3. Higher TCLP extracts pH would cause lower metals concentration released in the leachate.
4. Leaching of metals depends on C/S_d ratio and PFA addition. Leaching decreases when C/S_d ratio increase and the percentage of PFA added decreased.
5. Leaching of metals also depends on the inorganic constituents contained in the samples. Higher concentration of metals will increase the metals being leached.
6. Metals released in HAc leachant are higher than in DW leachant for all the samples.

5.5.4 Relationship Between Compressive Strength and Leachability

The strength development and leachability are the two main aspects in these studies. Thus, the correlation of strength development and the leachability was also investigated. The results of the leachability tests (see Appendix R) show that the metals concentration in TCLP extracts were very low therefore Fe was chosen in the studies of relationships between strength development and leachability. This is because it has the highest

leachability. The C/S_d , compressive strength at 28 days and the leachability of Fe were plotted as surface and contour graphs according to the different percentages of PFA used (0 %, 5 %, 10 %, 15 %, 20 %). The surface and contour plots are shown in figures 5.44-5.53. The surface plots with different percentages of PFA used show similar shape. The leaching showed little variation with increase in C/S_d ratio but the increase in UCS was almost proportional to increase in C/S_d ratio.

Figure 5.44 Relationship Between 28-Days UCS and Iron Leachability for 0 % PFA in HAc Leachant

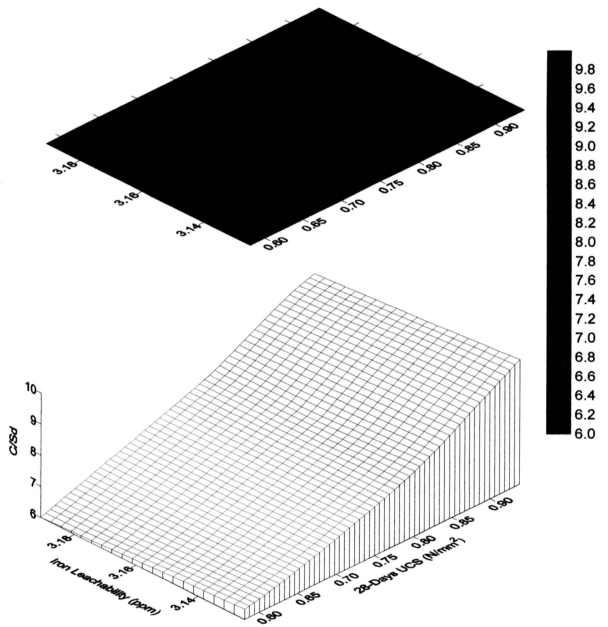


Figure 5.45 Relationship Between 28-Days UCS and Iron Leachability for 0 % PFA in DW Leachant

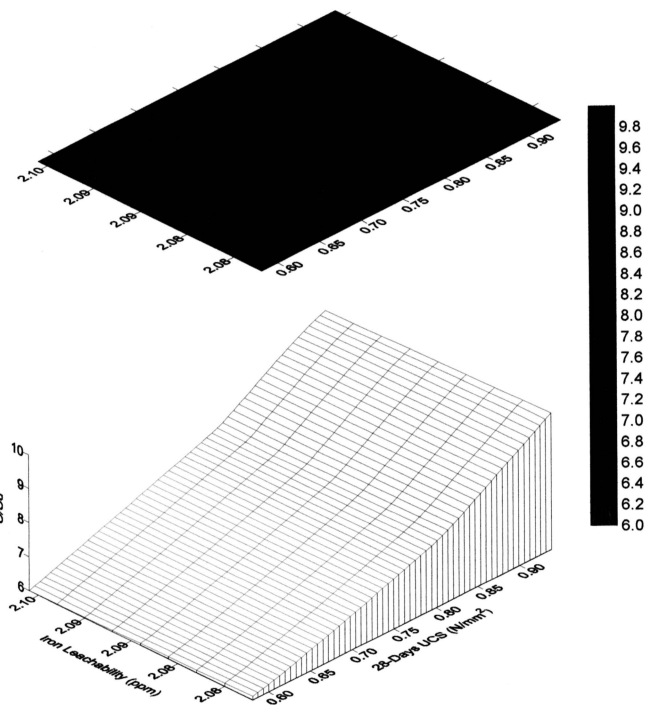


Figure 5.46 Relationship Between 28-Days UCS and Iron Leachability for 5 % PFA in HAc Leachant

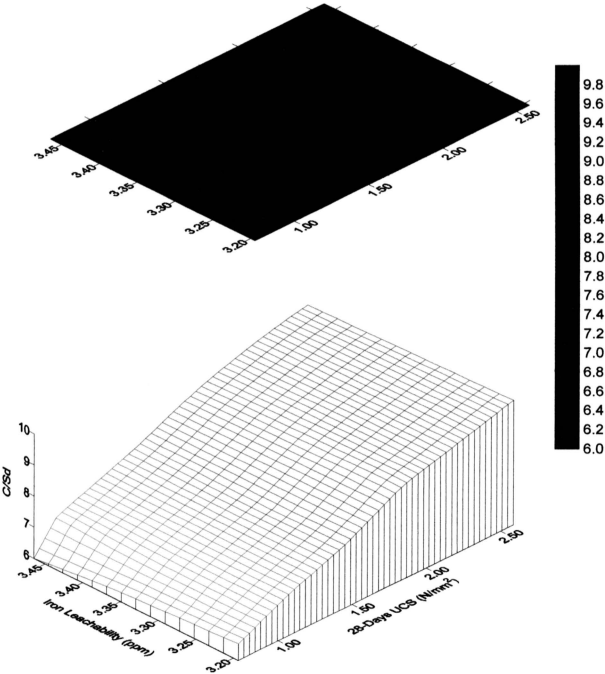


Figure 5.47 Relationship Between 28-Days UCS and Iron Leachability for 5 % PFA in DW Leachant

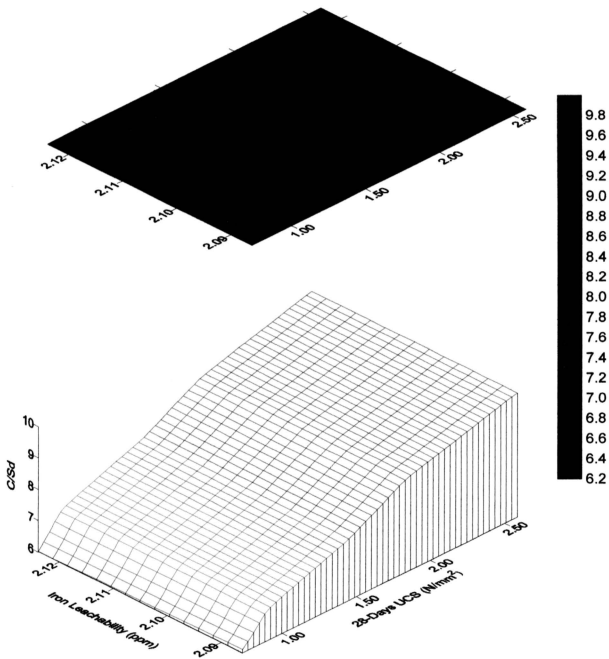


Figure 5.48 Relationship Between 28-Days UCS and Iron Leachability for 10 % PFA in HAc Leachant

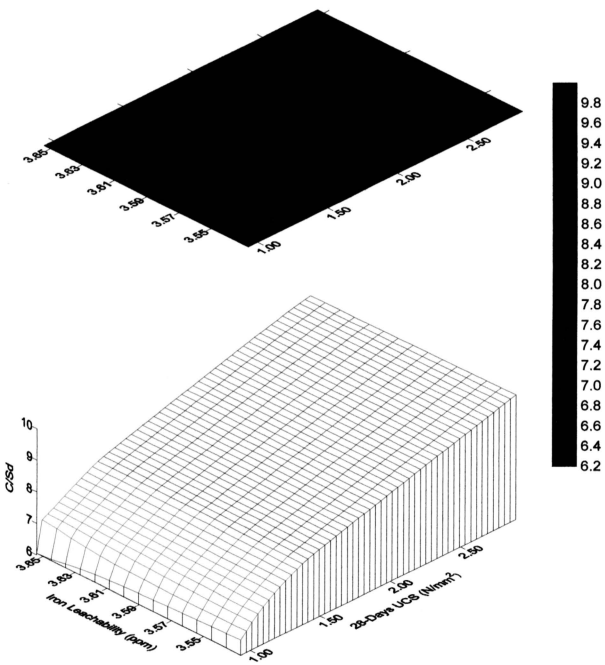


Figure 5.49 Relationship Between 28-Days UCS and Iron Leachability for 10 % PFA in DW Leachant

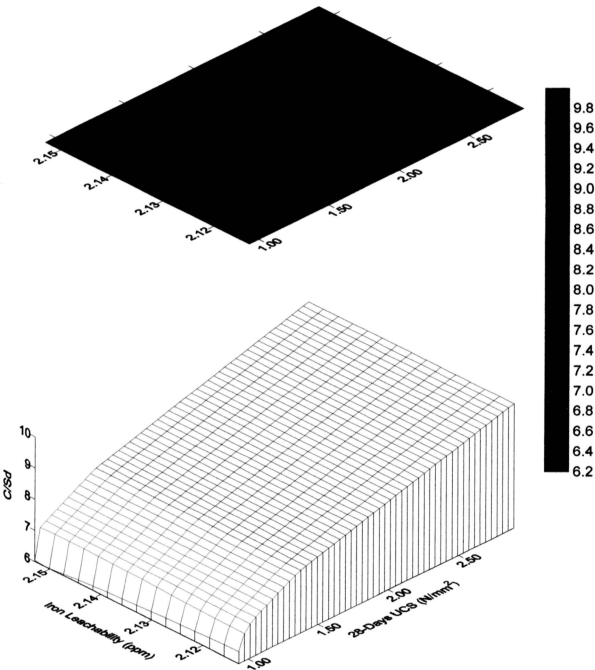


Figure 5.50 Relationship Between 28-Days UCS and Iron Leachability for 15 % PFA in HAc Leachant

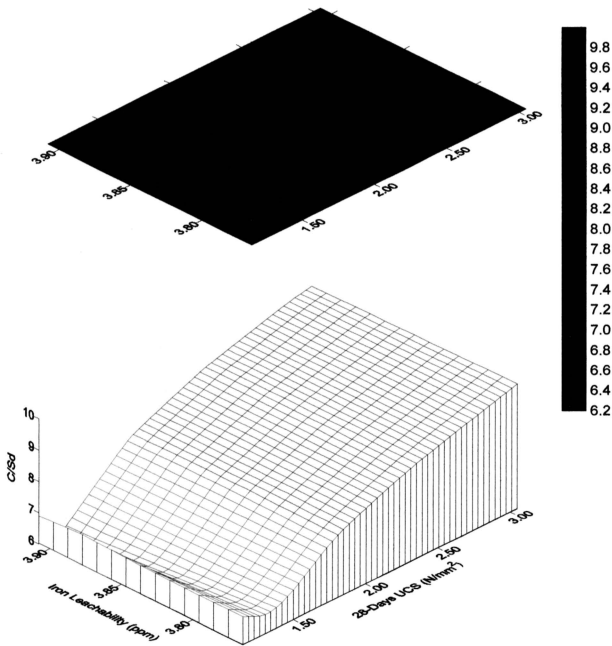


Figure 5.51 Relationship Between 28-Days UCS and Iron Leachability for 15 % PFA in DW Leachant

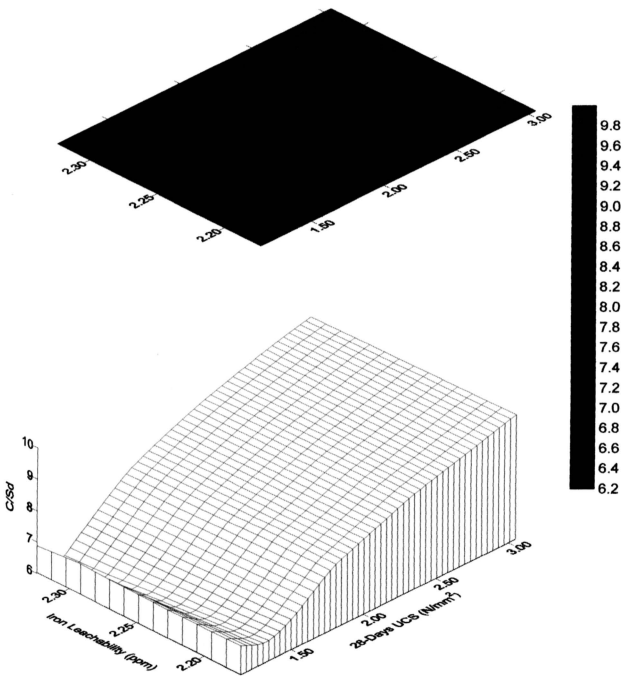


Figure 5.52 Relationship Between 28-Days UCS and Iron Leachability for 20 % PFA in HAc Leachant

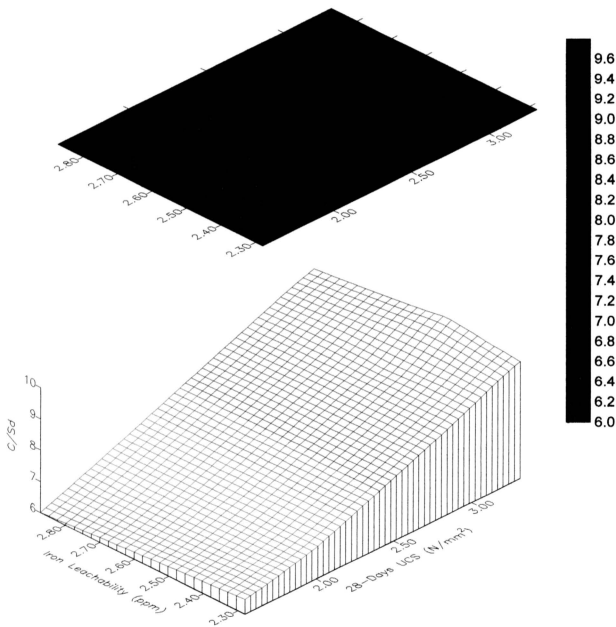


Figure 5.53 Relationship Between 28-Days UCS and Iron Leachability for 20 % PFA in DW Leachant

