# CHAPTER - 04

# POND ASH-GGBFS GEOPOLYMER

## 4.1 General

In the process of developing geopolymers using various combinations of waste materials as discussed in materials and methodology, this chapter discusses the development of Pond Ash–GGBFS geopolymer. The mutual replacement of Pond ash and GGBFS at the rate of 10% up to 100% has been followed. The geopolymer of each mixture was tested for strength and durability aspects and was compared before and after the alkali activation. The geopolymers of these mixes were also analysed using XRD, XRF, SEM and FTIR techniques to know the formation of geopolymer products during the alkali activation along with increased curing while achieving the unconfined compressive strength.

## 4.2 Specific Gravity of Pond ash-GGBFS Mixes

The specific gravity results of Pond Ash-GGBFS mixes have been reported in Table 4.1 and Fig 4.1 discussed. The specific gravity of pond ash without the addition of GGBFS is 2.041. When the Pond ash is replaced with GGBFS at the rate of 10% the specific gravity of designed mixes has been increased. 10% replacement of Pond ash with GGBFS the specific gravity of mix $P_{90}G_{10}$ is 2.155. On continuous replacement of Pond ash with GGBFS the specific gravity has been increased consistently. On 50% replacement of Pond Ash with GGBFS the specific gravity of mix $P_{50}G_{50}$ has been reached to the value 2.450. 80% Pond ash replacement with GGBFS in the mix leads to a specific gravity of 2.604. While 100% GGBFS with 0% Pond ash shows a specific gravity of 2.75.

**Table: 4.1 Specific Gravity Analysis of All Pond ash-GGBFS Mixes**

| Mixtures | Specific Gravity |
|---|---|
| $P_{100}G_0$ | 2.041 |
| $P_{90}G_{10}$ | 2.155 |
| $P_{80}G_{20}$ | 2.192 |
| $P_{70}G_{30}$ | 2.293 |
| $P_{60}G_{40}$ | 2.33 |
| $P_{50}G_{50}$ | 2.450 |
| $P_{40}G_{60}$ | 2.577 |
| $P_{30}G_{70}$ | 2.551 |
| $P_{20}G_{80}$ | 2.604 |
| $P_{10}G_{90}$ | 2.747 |
| $P_0G_{100}$ | 2.75 |

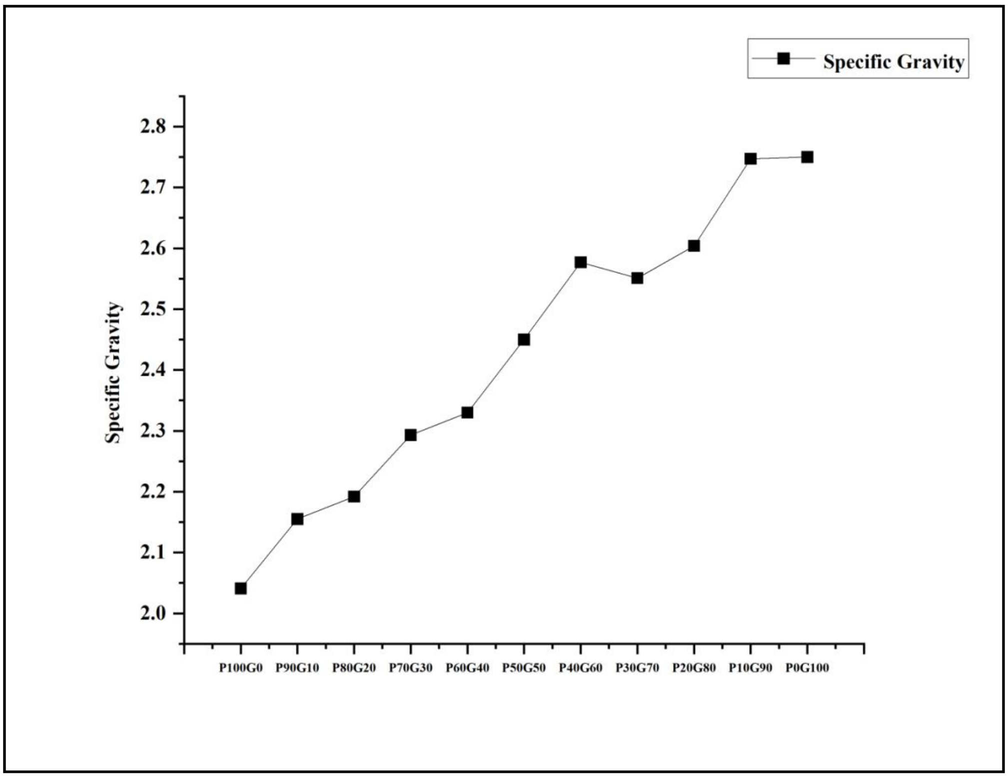



**Fig: 4.1 Specific Gravity Graph of Pond ash-GGBFS Mixes**

### 4.3 Grain Size Distribution of Pond ash-GGBFS Mixes

A detailed study of grain size analysis of Pond ash-GGBFS mixtures has been conducted and reported in Fig. 4.2 and Table 4.2 for analyzing the effect of GGBFS on the Pond ash in the grain size distribution. From Table 4.2 Pond ash without GGBFS $P_{100}G_0$ did not show sand percentage but 22% sand, 78% silt and 0.0% clay exist in the unmixed mix $P_{100}G_0$. When pond ash was replaced with GGBFS in the mix, changes were noticed in the grain size distribution of mixes. In the replacement of Pond ash up to 20% with GGBFS, a minor increase in clay percentages increased. The mixes with more than 30% GGBFS, increases the percentage of clay from 12 to 17% in the grain size distribution. The increase in clay size percentage in mixes has made the mixes dense and also decreased permeability as discussed in forth coming sections of the chapter.

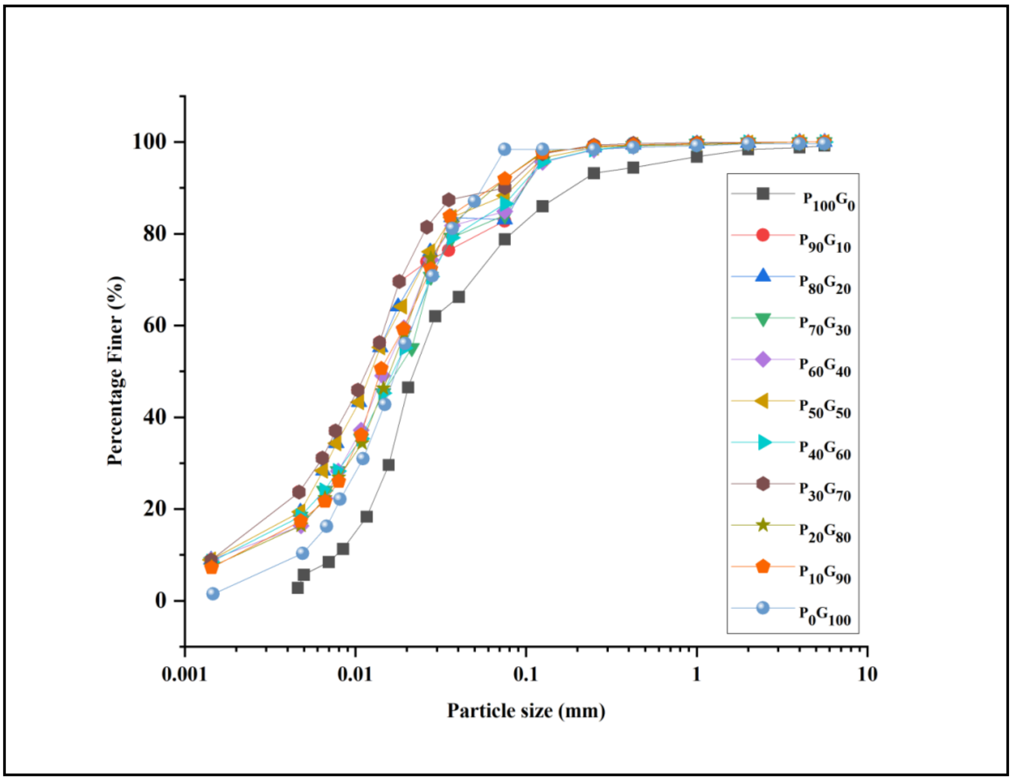



**Fig: 4.2 Grain size Distribution of All Pond ash-GGBFS Mixes**

**Table: 4.2 Grain Size Distribution of All Pond ash-GGBFS Mixes**

| **Designed mixture** | **Sand (%)** | **Silt (%)** | **Clay (%)** |
|---|---|---|---|
| $P_{100}G_0$ | 22.0 | 78.0 | 0.0 |
| $P_{90}G_{10}$ | 18.0 | 74.0 | 8.0 |
| $P_{80}G_{20}$ | 17.0 | 75.0 | 8.0 |
| $P_{70}G_{30}$ | 16.0 | 72.0 | 12.0 |
| $P_{60}G_{40}$ | 16.0 | 70.0 | 14.0 |
| $P_{50}G_{50}$ | 12.0 | 72.0 | 16.0 |
| $P_{40}G_{60}$ | 14.0 | 73.0 | 13.0 |
| $P_{30}G_{70}$ | 10.0 | 73.0 | 17.0 |
| $P_{20}G_{80}$ | 8.0 | 80.0 | 12.0 |
| $P_{10}G_{90}$ | 8.0 | 80.0 | 12.0 |
| $P_0G_{100}$ | 1.0 | 95.0 | 4.0 |

## 4.4 Compaction Characteristics of Pond ash-GGBFS Mixes

The compaction tests have been performed on Pond ash-GGBFS mixes and presented in Fig. 4.3 (a) & (b). From the compaction analysis of Pond ash-GGBFS mixes it can be concluded that maximum dry density (MDD) has been increased and optimum moisture content has been decreased continuously on increasing the replacement percentage of GGBFS. The maximum dry density of raw Pond ash $P_{100}G_0$ is 1.18 g/cc and the optimum moisture content is 29.1%. When 10% GGBFS replaces the Pond ash the MDD of the mix $P_{90}G_{10}$ is 1.23 g/cc and the OMC of the mix is 27.9%. Further, increase in GGBFS replacement of 30% in Pond ash-GGBFS mix the MDD of the mix $P_{70}G_{30}$ is 1.29 g/cc the OMC of the mix is 26.8% and then onwards observed a continuous increase in MDD in a gradual manner up to 70% replacement of Pond ash with GGBFS ($P_{30}G_{70}$). When 80% Pond ash in the mix is replaced with GGBFS there is a sudden increase in MDD (1.47g/cc) of the mix $P_{20}G_{80}$. MDD increased to the value of 1.57g/cc on 100% replacement of Pond ash $P_0G_{100}$. However, the OMC of all mixes has been reduced gradually.

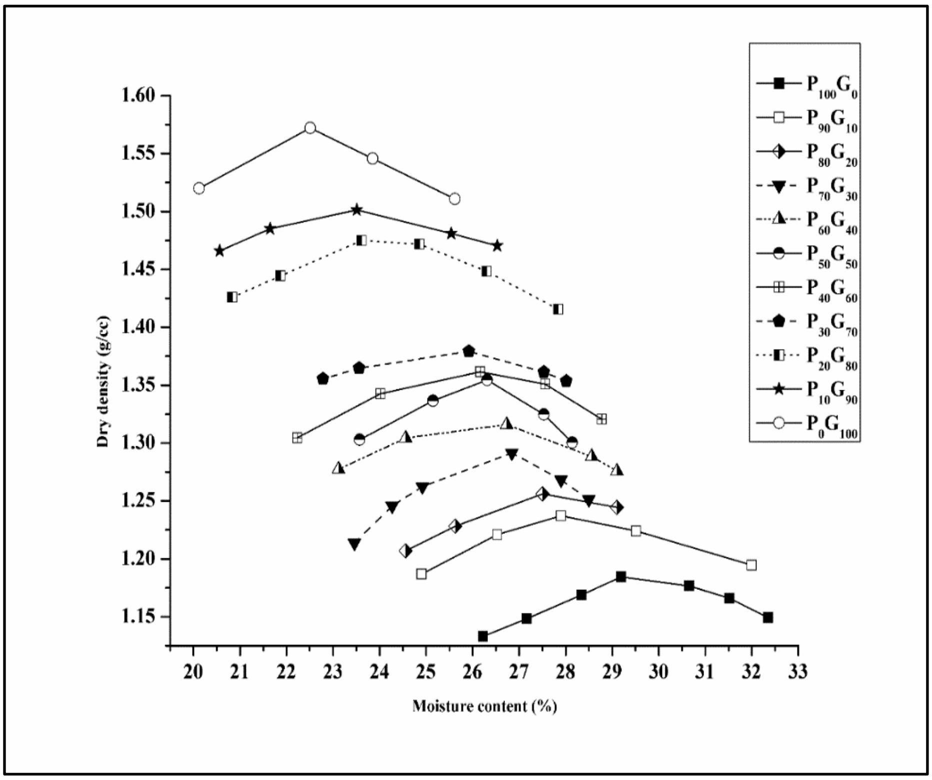



**Fig: 4.3 (a) Compaction curves of Pond Ash- GGBFS Mixes**

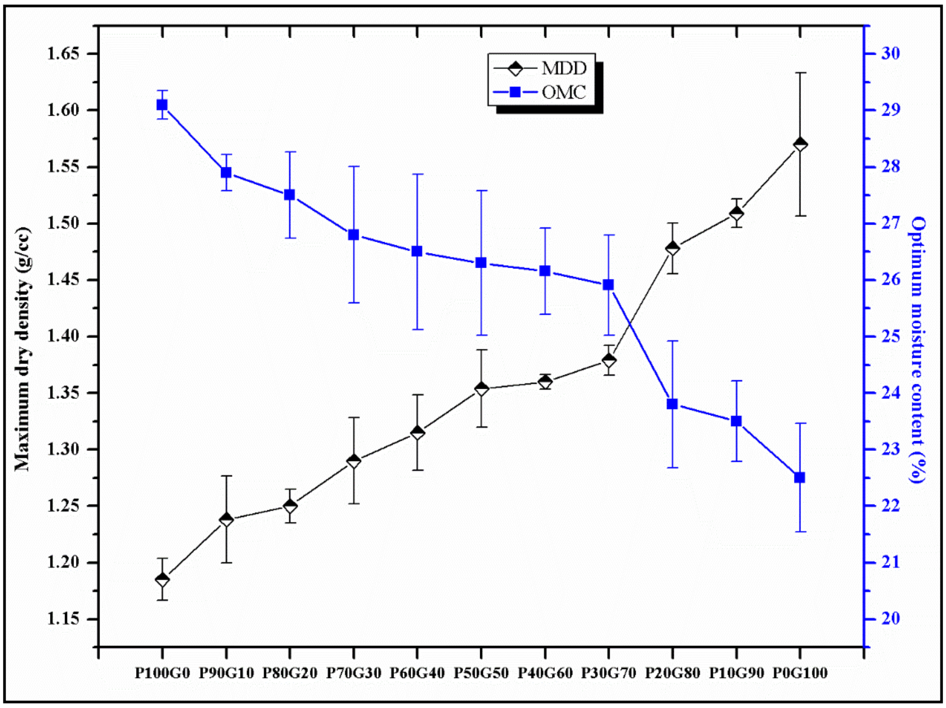



**Fig: 4.3 (b) Trends of OMC and MDD with Pond Ash – GGBFS Mixes**

### 4.5 Permeability Analysis of Pond ash-GGBFS Mixes

Based on the compaction test it was observed that with the increase in the percentage of GGBFS, the bulk density / maximum dry density has increased gradually while optimum moisture content is decreased up to mix proportion $P_{30}G_{70}$. Upon the replacement of slag at higher percentages of GGBFS i.e., 80%, 90% & 100% to the pond ash a steep increase has been observed in bulk density/permeability of all mixes with the increase in GGBFS. The permeability (k value) of unmixed pond ash and unmixed GGBFS were found $1.36 \times 10^{-4}$ cm/sec and $0.412 \times 10^{-4}$ cm/sec respectively. The pore fluid used while performing the permeability test was potable water. Fig. 4.4 shows the variation of permeability with reference to Pond ash-GGBFS mixes. The permeability of the mixes was found to be increased when increasing the GGBFS to Pond ash. The trend of coefficient of permeability values is supported by the trend of MDD of Pond ash-GGFS mixes.

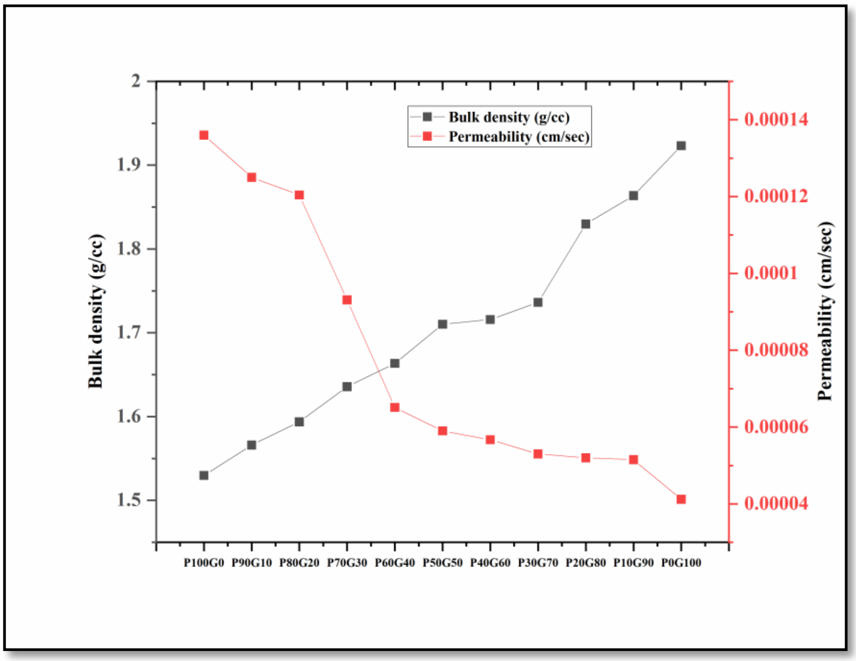



**Fig: 4.4 Bulk density and Permeability Analysis of All Pond ash –GGBFS Mixes**

## 4.6 UCS of Pond ash-GGBFS Mixes Activated with NaOH and cured in Polythene bags

**Fig: 4.5 Polythene curing of Pond ash-GGBFS Mixes for different curing period**


**Fig: 4.6 UCS Testing of Pond ash-GGBFS Mixes**

Fig. 4.5 and 4.6 show the photographs of UCS testing on Pond ash-GGBFS mixes. The unconfined compressive strength is measured according to the IS:2720 part-10 (BIS1991) using different proving ring capacities such as 5 kN, 10 kN, 20 kN and 50 kN and presented in Fig. 4.7 to 4.10. The UCS samples of mixes of Pond ash – GGBFS compacted to their respective OMC and MDD using water (without NaOH) as pore fluid, and kept in polythene bags the UCS values are found low. The UCS values of $P_{100}G_0$ and $P_0G_{100}$ with water are 50 kPa and 157 kPa respectively at one day of the curing. However, the increase in the duration of the curing period i.e., 7, 28 and 56 days pond ash-GGBFS mix samples prepared with water as pore fluid did have not yielded any significant strength. Even in the case of unmixed GGBFS ($P_0G_{100}$) samples cured after 56 days, yielded a very insignificant increase in strength i.e., 180 kPa.

An excellent improvement has been observed in the UCS of the mixes of Pond ash-GGBFS when samples were compacted and activated with alkali concentrations (2, 4, 6, 8 and 10M) at their respective MDD and OMC and kept in polythene bags for interaction. On day one curing, mix $P_{100}G_0$ activated with low concentrated (2M NaOH) did not show any significant strength (0.048 MPa). Further, the increasing concentration of sodium hydroxide (4M NaOH) mix $P_{100}G_0$ did not represent a considerable value of UCS (0.0453 MPa). Even with the high concentration of sodium hydroxide 10M NaOH, there is no considerable improvement in the UCS (0.112 MPa) of the mix $P_{100}G_0$. On replacement of Pond ash with the GGBFS in the mixes, the samples activated with 2M NaOH did not yield any significant strength (0.216 MPa) up to 60% replacement of Pond ash with GGBFS. When 70% GGBFS replaces the pond ash i.e., mix $P_{30}G_{70}$ possesses a considerable strength of 2.06 MPa. With further replacement of GGBFS in the Pond ash mix $P_{20}G_{80}$ yielded the UCS strength of 4.66 MPa. When 100 per cent replacement of Pond ash with GGBFS the mix $P_0G_{100}$ i.e., unmixed GGBFS activated with the same concentration gives the improved value of the UCS 10.93

MPa. When the concentration of NaOH and replacement percentage of Pond ash with GGBFS was increased, a great improvement was observed in the UCS strength of the pond ash - GGBFS mixes. At a 4M concentration of sodium hydroxide, the mix $P_{70}G_{30}$ has found a UCS of 1.93 MPa. Yielding of high strength has been perceived in the samples with the addition of the GGBFS to Pond ash. With the increase of sodium hydroxide, a noticeable value of strength is attained even at low dosages of GGBFS in the mixes. The mix $P_{90}G_{10}$ containing 10% replacement of Pond ash with GGBFS activated with 6M NaOH reported a marked value of UCS 1.5 MPa. The same trend of continuous improvement is observed in increasing the amount of GGBFS in the mix. For 8M NaOH the strength of the mix $P_{90}G_{10}$ slightly declined (0.52 MPa) due to excessive concentration of OH- ions. At a maximum concentration of 10M NaOH, the mix $P_{90}G_{10}$ shows a slightly improved value (0.59 MPa) of UCS compared to 8M NaOH-activated mix. Strength increases with the increment in the activator concentration as well as the increment in the dosage of GGBFS. However, at higher concentrations (10 M), the same mix shows a marginal decrease in UCS value.

As the curing period of the mixes extended to 7 days, the rate of the increment of the UCS became high and a significant improvement was observed in the strength of the mixes. At 7 days of the curing period mix $P_{100}G_0$ without any GGBFS amount possesses a considerable value of UCS with the concentration 6, 8 and 10 M NaOH. Mix $P_{100}G_0$ activated with 2M and 4M NaOH did not represent a meaningful value of UCS even at 7 days of the curing period. On replacing 10% Pond ash with GGBFS mix $P_{90}G_{10}$ did not possess a significant value of UCS (0.112 MPa) activated with 2M NaOH concentration. With the same concentration on 7 days of the curing period, a significant strength did not achieve up to 30% addition of GGBFS in the mixtures. On 40% replacement with GGBFS in the mixes, the mix $P_{60}G_{40}$ displayed a meaningful value (8.8 MPa) of UCS with the same concentration.

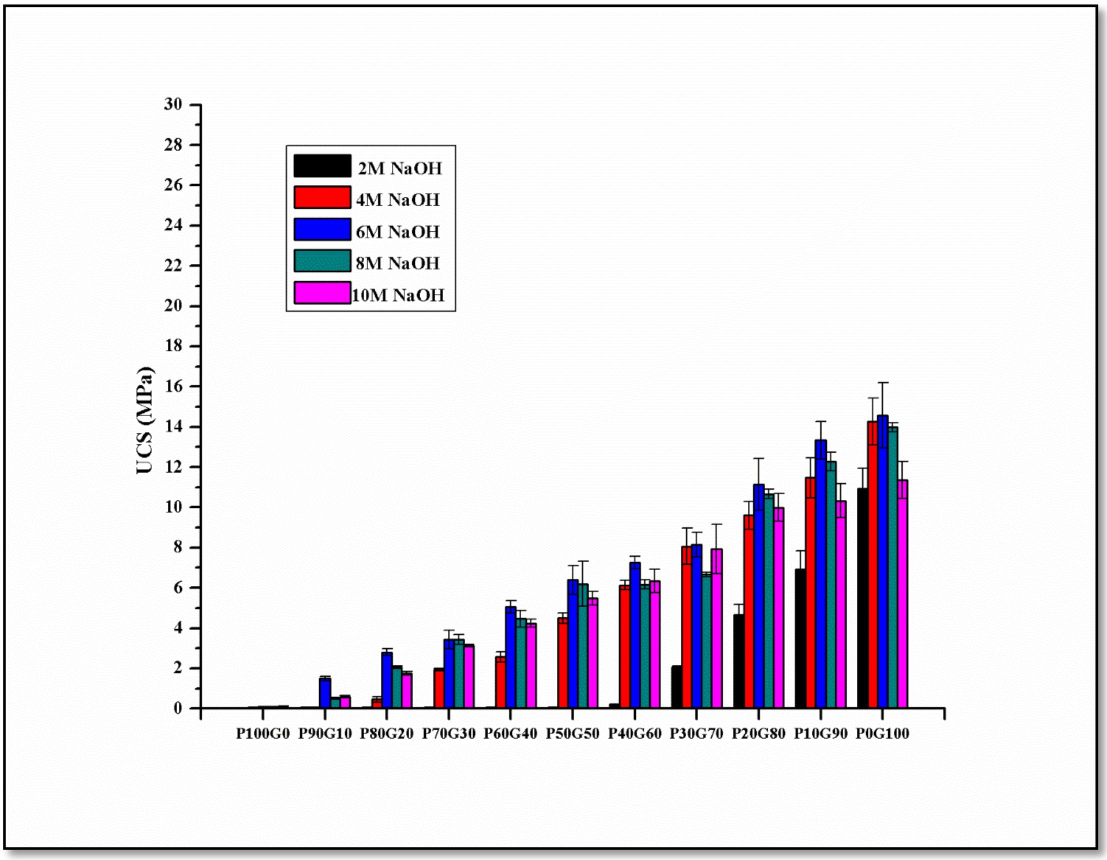



**Fig: 4.7 UCS of All Pond ash-GGBFS Mixes Activated with NaOH at 1 day**

While on increasing the concentration to 4M NaOH, a low dosage GGBFS mix $P_{90}G_{10}$ represented a value of 4.66 MPa of UCS. As the dosage of GGBFS increases in the mixes the immense improvement in strength has been recognized activated with the same concentration. On increasing the concentration to 6M NaOH a minute decrement in UCS of all mixtures has been detected in comparison with 4M NaOH-activated mixes. On further increasing the concentration to 8M NaOH and 10M NaOH the strength of all designed mixtures has been decreased continuously on a marginal scale. But the mixes $P_{30}G_{70}$, $P_{20}G_{80}$, $P_{10}G_{90}$, and $P_0G_{100}$ showed the increased value of UCS activated with 8M NaOH.

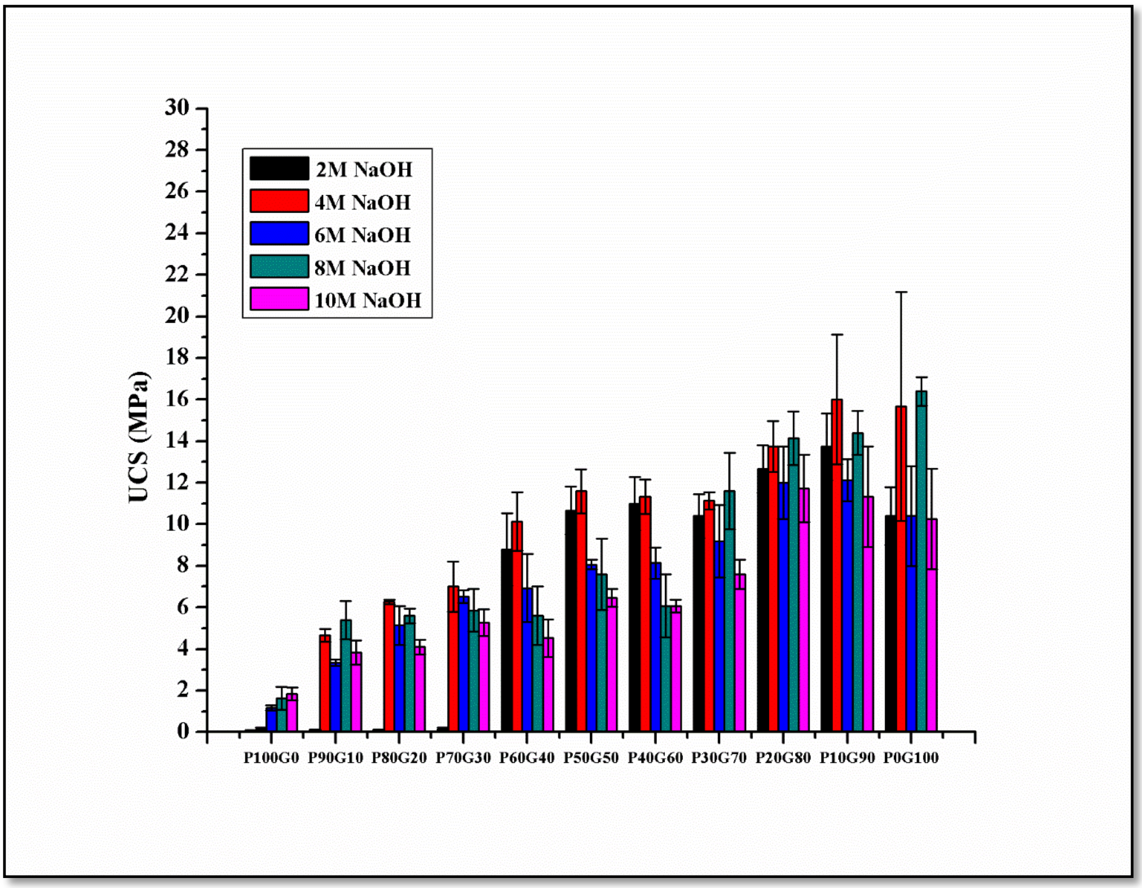



**Fig: 4.8 UCS of All Pond ash-GGBFS Mixes Activated with NaOH at 7 days**

At 28 days of curing period, the rate of attaining the UCS is very high. Increasing the period of curing time to 28 days the mix $P_{100}G_0$ without any GGBFS content possess a considerable strength activated with increased concentration of NaOH i.e., 8M NaOH (3.13 MPa) and 10M NaOH (2.63 MPa). With the low dosage of NaOH concentration (2M NaOH) mix P70G30 having 30% GGBFS possesses an admirable value of UCS (7.4 MPa). By extending the curing period, the Pond ash with more GGBFS in the mix the strength achieved a good value. The maximum value of UCS reached 17.33 MPa activated with 2M NaOH. The effect of increasing the curing time to 28 days is that a favorable value is attained even at the low percentage of GGBFS in the mixes. With the addition of 10% GGBFS in the mix, the mix $P_{90}G_{10}$ provides valuable strength when activated with 4M NaOH (1.56 MPa), and 6M NaOH

(2.5 MPa), 8M NaOH (4.86 MPa) and with 10M NaOH (4.93 MPa). Mix $P_{90}G_{10}$ shows exceptional trend.

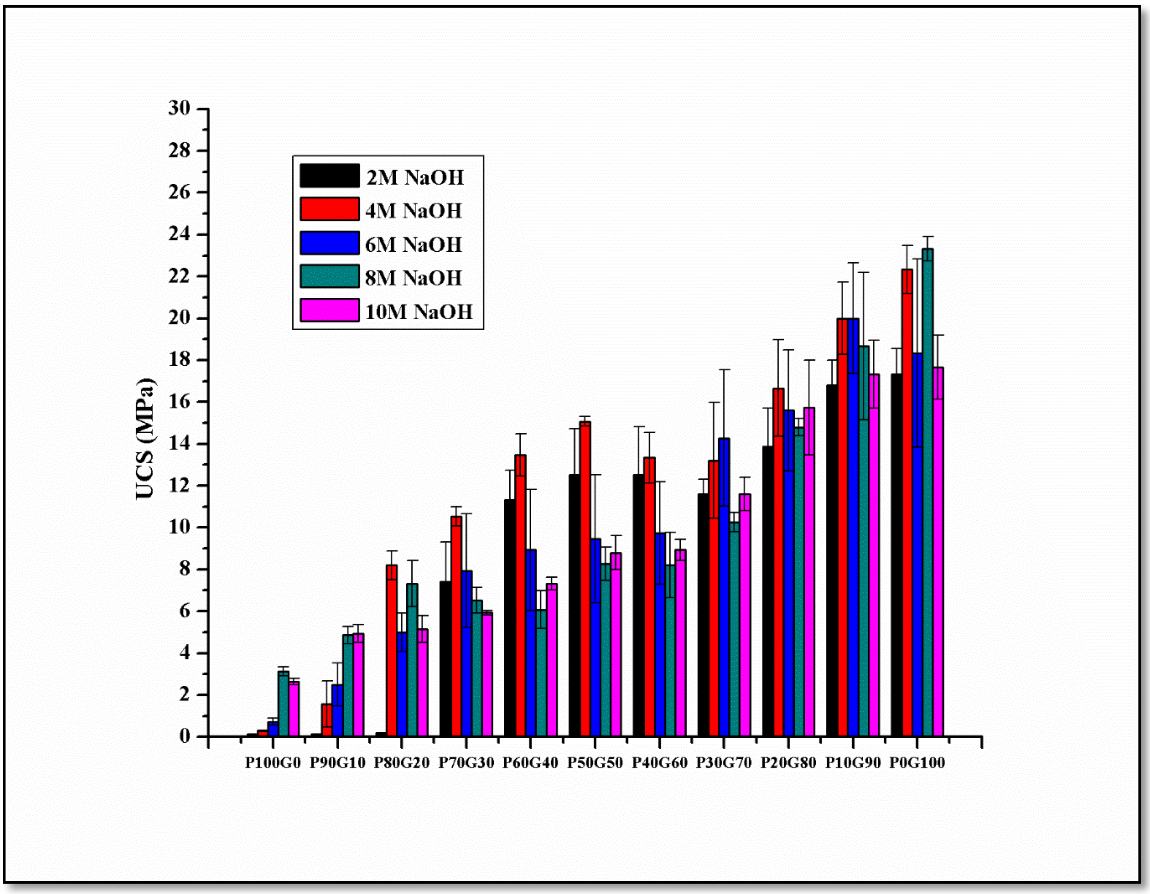



**Fig: 4.9 UCS of All Pond ash-GGBFS Mixes activated with NaOH at 28 days**

In this study primarily the strength increases with increment in the concentration of NaOH, but on adding the heavy dosage of sodium hydroxide the strength slightly decreases. But in some mixes the same trend did not follow. As the amount of ground granulated blast furnace slag in all mixes increases, the rate of increasing the strength also becomes high. On increasing the concentration from 2M to 4M NaOH the strength of all mixes has been increased. But further increase in the concentration the strength of all mixes has been decreased except for the mix $P_{90}G_{10}$. Overall, the 4M NaOH-activated samples show the highest strength.

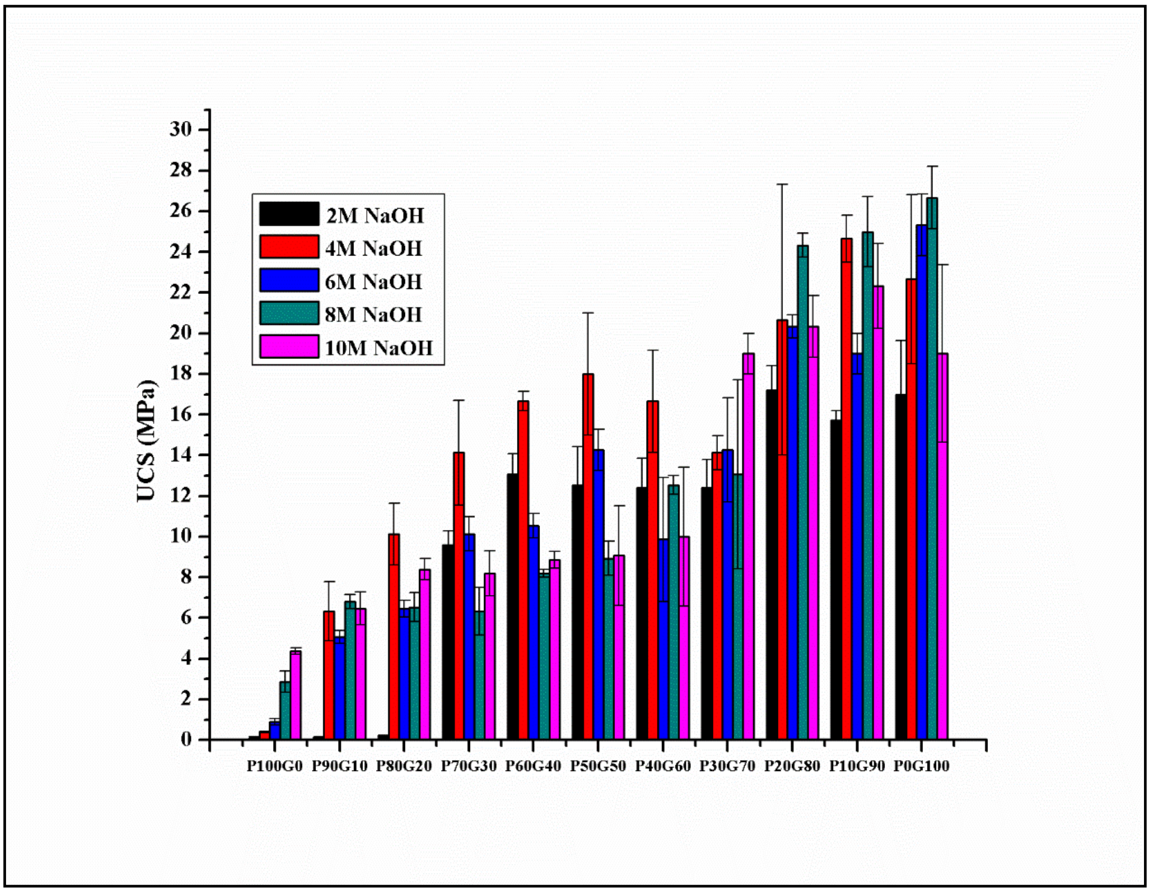



**Fig: 4.10 UCS of All Pond ash-GGBFS Mixes Activated with NaOH at 56 days**

Mix $P_{100}G_0$ activated with 2M (0.10 MPa), 4M (0.39 MPa) and 6M NaOH (0.89 MPa) did not possess any considerable strength even at an increased curing period of 56 days. But on increasing the concentration the significant strength (2.86 MPa- 8M NaOH and 4.36 MPa- 10M NaOH) has been observed. There is no huge increment in strength after increasing the curing period to 56 days. The reason behind for low strength is the maximum involvement of Na, Si reaction with NaOH without any presence of calcium. Thus, even though the gain in strength appears to be low this is the best example of geopolymer synthesis without any carbon footprint. The mix $P_{80}G_{20}$ activated with 2M NaOH still did not yield a considerable UCS value (0.21 MPa) even at an increasing period of 56 days. The same mix displayed a 0.16 MPa value of UCS at 28 days of period. Strength increased on the marginal scale but the rate of increment of strength was not as high as in the 7 days and 28 days of curing period. At

56 days of the curing period, the 4M NaOH-activated sample presented the maximum strength. On increasing the concentration of NaOH to 6M the strength started decreasing due to the high concentration of $OH^-$ ions. On further increasing the concentration of NaOH to 8M the strength of some mixes has been decreased and the strength of some mixes slightly increases. The strength of mixes slightly increases when the concentration of mixes has been increased to 10M NaOH.

### 4.7 Effect of water and acid curing on the UCS of the Pond ash-GGBFS Mixes

**Fig: 4.11 Samples immersed in the water and acid for Durability**

To understand the effect of water curing on the strength and durability of compacted mixes of Pond ash-GGBFS activated with 4, 6, 8 and 10 M NaOH specimens were cured in water and evaluated for strength by conducting a UCS test. The curing process followed in the present study is shown in the Fig. 4.11. The UCS values observed in the case of the water-cured and acid-immersed samples are shown in Fig. 4.12 to Fig. 4.15. After immersing in water, the mix $P_{100}G_0$ got dispersed in the water and did not give any strength even on activating at a high concentration (10M NaOH). On replacing 10% Pond ash with GGBFS the mix $P_{90}G_{10}$ possesses significant value activated with 4M NaOH (0.85 MPa), 6M NaOH (1.88 MPa), 8M NaOH (4.3 MPa) and 10M NaOH (2.2 MPa). As above mentioned, strength slightly decreases on increasing the concentration of the NaOH due to an excessive quantity of OH- ions. Mixtures perform excellent strength even at immersing the samples in water for 7 days. On average 4M and 6M NaOH-activated samples reported the highest value in water curing of 7 days. At 7 days of water curing mix, $P_{50}G_{50}$ possesses a good strength activated with 4M NaOH (9.6 MPa), 6M NaOH (12.4 MPa), 8M NaOH (12 MPa) and 10M NaOH (8.8 MPa). It means that by adding 50 % GGBFS to the Pond ash, Pond ash can be used in construction work. Mix with 70% slag ($P_{30}G_{70}$) provides the UCS 13.6 MPa (4M), 14 MPa (6M), 10.4 MPa (8M) and 11.1 MPa (10M) at 7 days. Further on increasing the percentage of replacement of Pond ash with GGBFS the compressive strength also increases. With 100% replacement of Pond ash with GGBFS in the mix $P_0G_{100}$ provides the UCS 22 MPa (4M), 22 MPa (6M), 19.9 MPa (8M) and 18 MPa (10 M).

On increasing the curing period (28 days) in the water, the Pond Ash-GGBFS geopolymer exhibited significant strength in water except for the mix $P_{100}G_0$. At 28 days in water, mix P90G10 reported the UCS with 4M NaOH (1.16 MPa), with 6M NaOH (2.2 MPa), with 8M NaOH (2.8 MPa) and with 10M NaOH (4.7 MPa). On 50% replacement of Pond ash with GGBFS in the mixture $P_{50}G_{50}$ recorded almost equal or slightly higher values of compressive strength 9.6 MPa (4M NaOH), 13.2 MPa (6M NaOH), 12 MPa (8M NaOH) and 12.4 MPa (10M NaOH). A slight improvement in the value of compressive strength 17.2 MPa (4M NaOH), 21 MPa ( 6M NaOH), 20MPa (8M NaOH) and 14.8 MPa (10M NaOH) has also occurred in the mix $P_{20}G_{80}$.

On further increasing the curing days (56 days) of Pond ash-GGBFS geopolymer, no major loss has been observed in the value of compressive strength. A slight decrement has been observed in the value of compressive strength (0.92 MPa) of the mix P90G10 activated with 4 M NaOH at 56 days. As the concentration rises, the improvement has also been seen in the mix $P_{90}G_{10}$. Mix $P_{90}G_{10}$ activated with 6M NaOH recorded the value of compressive strength 3.1 MPa, with 8M NaOH (4.5 MPa) and with 10 M NaOH (5.6 MPa). On 50% replacement of Pond ash with GGBFS the mix $P_{50}G_{50}$ reported the compressive strength 12.4 MPa (4M NaOH), 14 MPa (6M NaOH), 12.4 MPa (8M NaOH) and 11.6 MPa (10 M NaOH). On further replacement of 80% Pond ash with GGBFS, the mix $P_{20}G_{80}$ exhibited the compressive strength 15.2 MPa (4M NaOH), 21 MPa (6M NaOH), 20 MPa (8M NaOH) and 17.6 MPa (10 M NaOH).

To study the effect of the acidic environment on the Pond Ash-GGBFS geopolymer samples has been dipped in the acidic solution of 1% $H_2SO_4$ of pH 0.24. The UCS test has been on the dipped samples in acidic solution for 28 and 56 days. Fig 4.15 represented the UCS analysis of Pond Ash-GGBFS geopolymer in acidic environment. Samples made from Pond Ash – GGBFS showing significant strength in the acidic environment. There is slight decrement after increasing the curing period to 56 days.

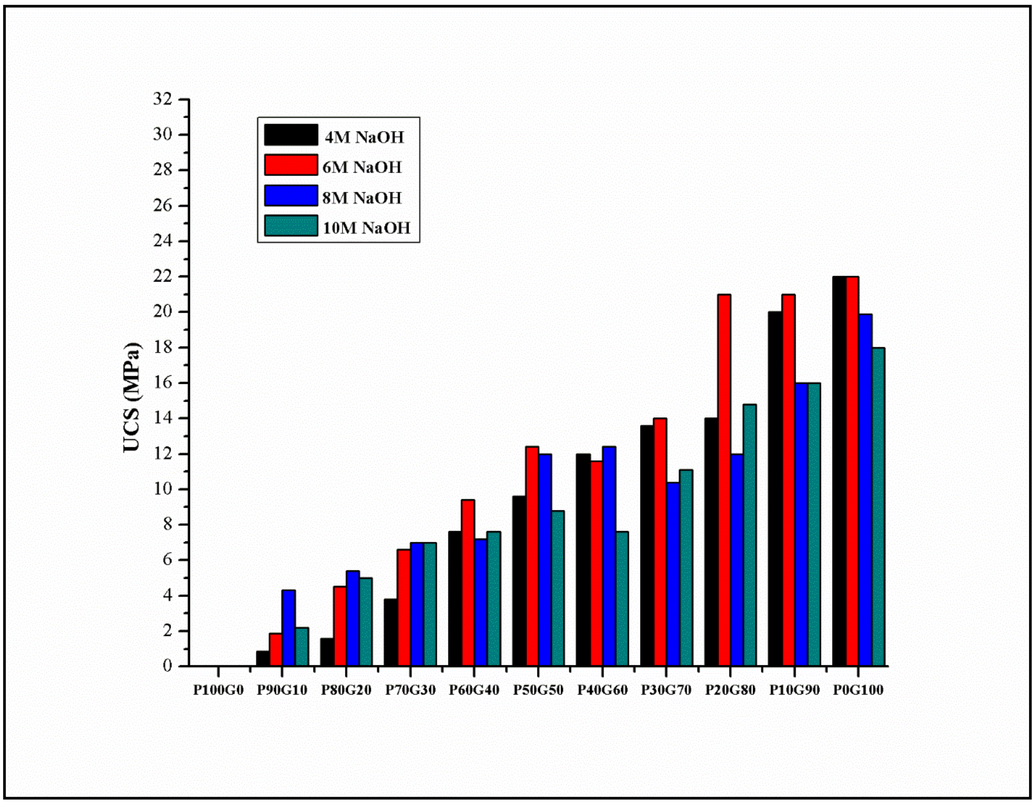



**Fig: 4.12 UCS of All Pond ash-GGBFS Mixes activated with NaOH at 7 days in water**

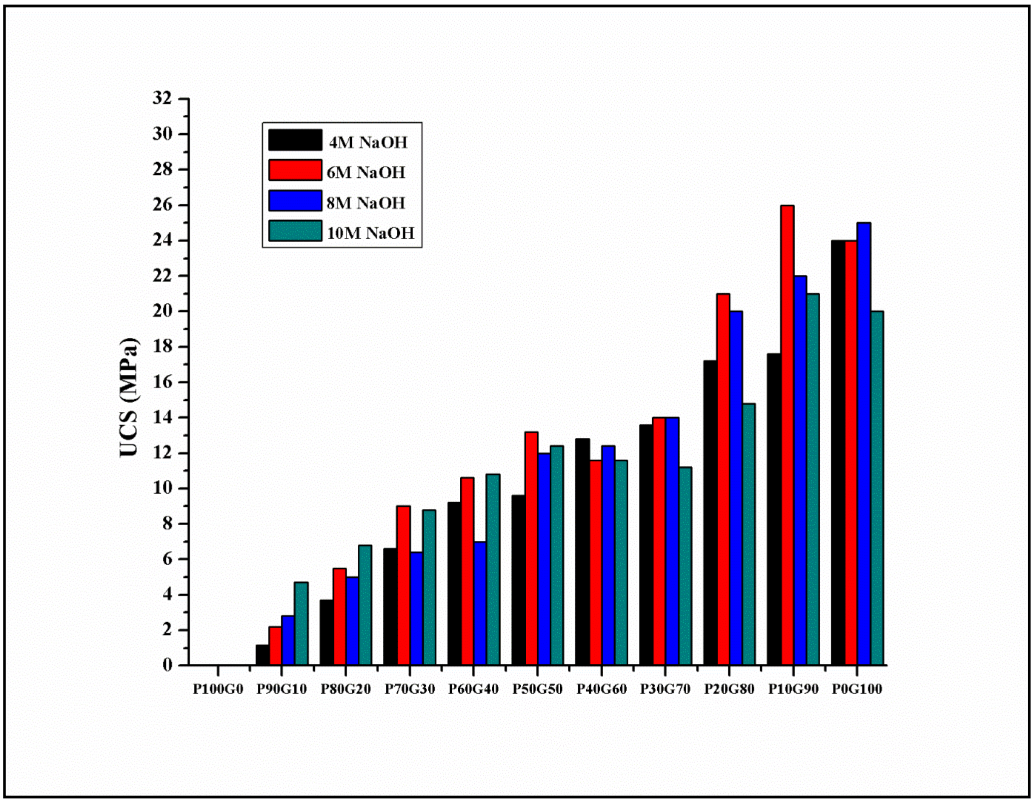



**Fig: 4.13 UCS of All Pond ash-GGBFS Mixes activated with NaOH at 28 days in water**

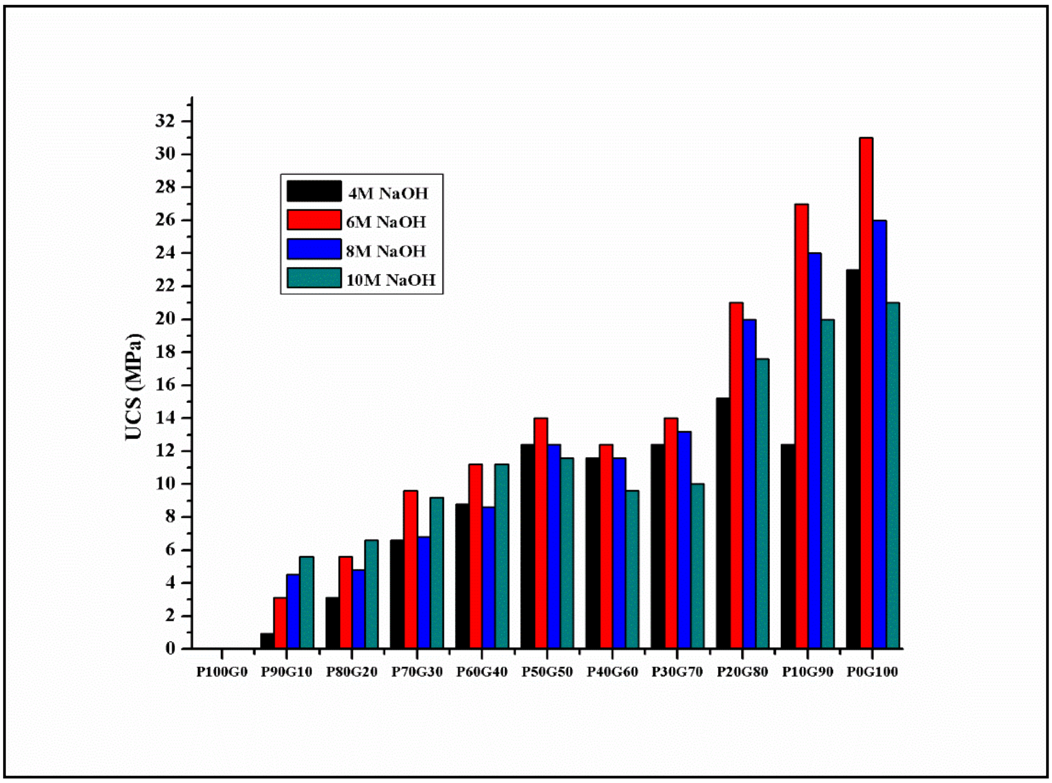



**Fig: 4.14 UCS of All Pond ash-GGBFS Mixes activated with NaOH at 56 days in water**

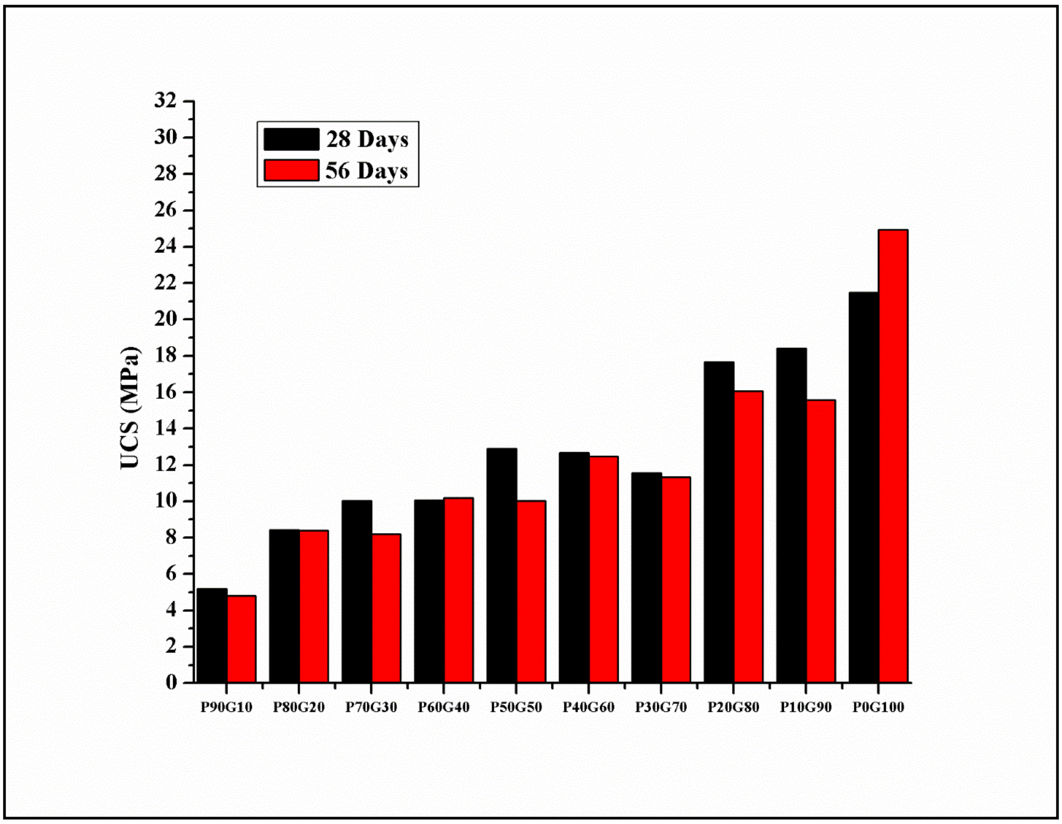



**Fig: 4.15 UCS of All Pond ash-GGBFS Mixes activated with 4M NaOH in the acidic environment**

### 4.8 XRD Pattern of All Pond ash-GGBFS Mixes Activated with NaOH

The optimized results of unconfined compressive strength have been recorded with 4M NaOH activated mixes of Pond ash-GGBFS. Hence the XRD study has been conducted on the broken pieces of 4M NaOH activated Pond ash-GGBFS mix after conducting the UCS at the curing period of 56 days. XRD analysis characterized the mineralogical/ microstructural analysis of the developed geopolymer shown in Fig. 4.16 (a) and (b). After doing activation with 4M NaOH of mix $P_{100}G_0$, there is no significant change observed except the detection of NASH geopolymeric gel identified at the 2θ value $33.49^0$ & $36.80^0$ ( PDF#84-0528) because of low Ca/Si ratio shown in Fig.4.17. Peak of quartz ($SiO_2$) has been observed in the same intensity in the XRD analysis of mix before activation or after activation. This peak of quartz has been observed in all mixes at 2θ value $26.53^0$, $20.74^0$ & $50.08^0$ (PDF# 89-8934) but with the increasing percentage of replacement of Pond ash with GGBFS, the intensity of this peak has been decreased. When 10% Pond ash replaced with GGBFS, the improvement in the UCS of the mix $P_{90}G_{10}$ has been justified with peak of geopolymeric gel NASH($33.49^0$) ( PDF#84-0528), CSH($36.80^0$ & $60.40^0$)(PDF#89-7639), CASH ($39.71^0$ & $68.57^0$)(PDF#88-1135, PDF#86-2218) and NCASH ($42.86^0$)(PDF#75-0743) has been observed. Up to 30% addition of GGBFS the same peaks has been detected. On 40% replacement of Pond ash with GGBFS one more of CSH gel has been detected at $29.86^0$ and the intensity of this peak increased with the increment of the percentage of GGBFS which is clear indication of improved unconfined compressive strength. As the percentage of GGBFS increases in the mix beyond 40%, the peak of NASH replaced with peak CASH due to the high calcium matrix. In high calcium mix $P_{30}G_{70}$ a hump is identified at specific range of 2θ values $25.8^0$ to $34.44^0$ which assign of the amorphous state of the material. This hump widened at to 2θ value of $16.9^0$ to $37.5^0$ the high calcium (GGBFS) addition in the mix $P_0G_{100}$. It is clearly reported

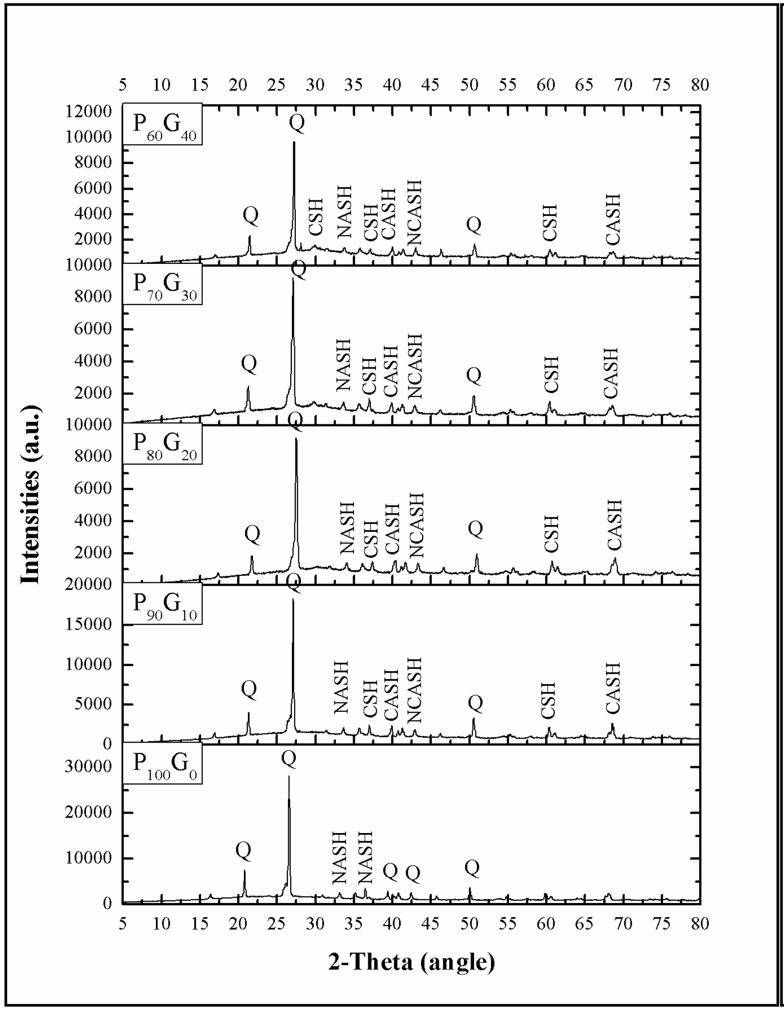



**Fig: 4.16(a)**

**XRD Pattern of 4M NaOH Activated Mixes at 56 Days ( $P_{100}G_0$ to $P_{60}G_{40}$)**

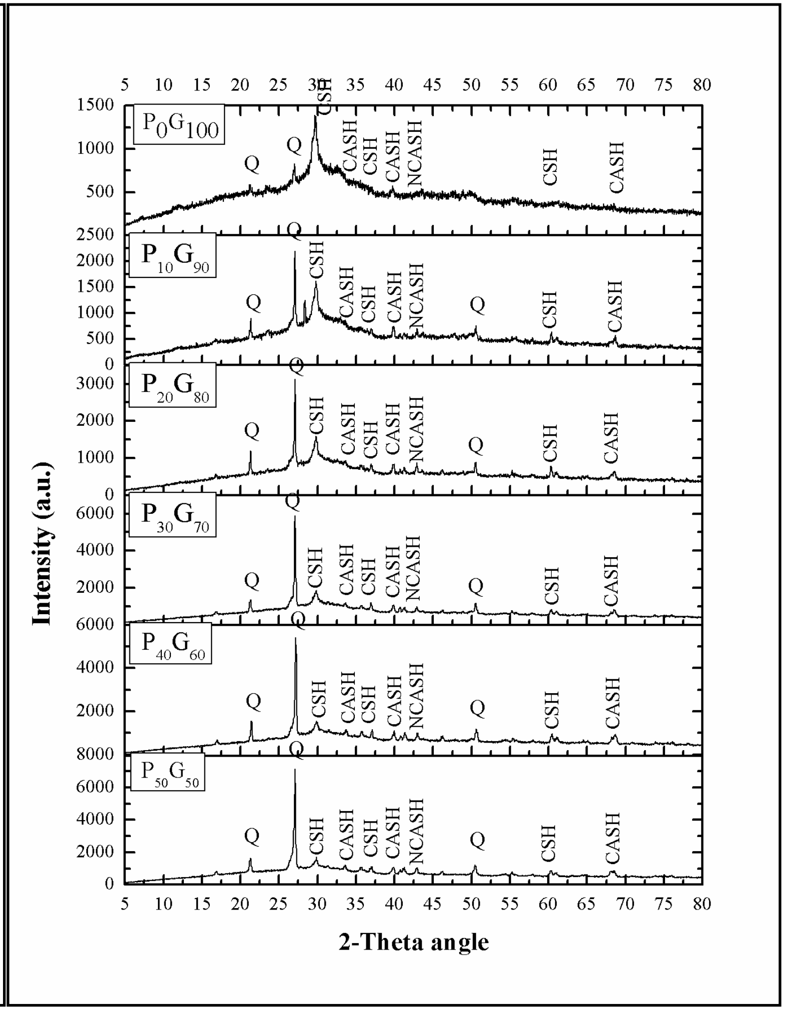



**Fig: 4.16(b)**

**XRD Pattern of 4M NaOH Activated Mixes 56 Days ( $P_{50}G_{50}$ to $P_0G_{100}$)**

That with low percentage of GGBFS mix possesses less dense structure in comparison to high percentage GGBFS mix because of increasing Ca/Si ratio

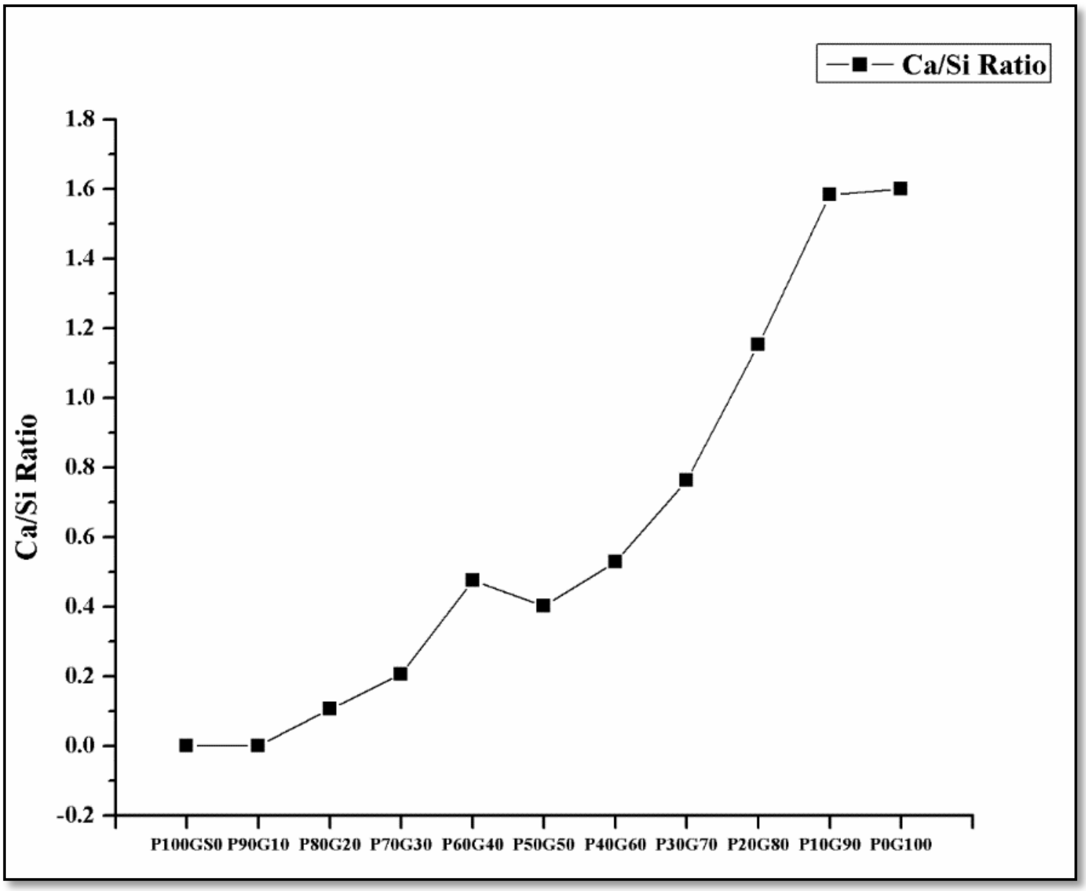



**Fig: 4.17 Ca/Si ratio of Pond ash-GGBFS mixes geopolymers**

### 4.9 FTIR of Pond ash-GGBFS Mixes Activated with NaOH

Fig. 4.18 (a) & (b) showing detailed FTIR analysis of Pond ash-GGBFS geopolymers. FTIR study was done on mix proportions activated with 4M NaOH which is the optimum alkaline concentration yielded the highest compressive strength at a curing period of 56 days. The shifting of peaks in the FTIR spectra of activated mix proportions was compared with raw waste material indicating the structural changes in the geopolymer. The first peak of all geopolymer mixtures at band 453 $cm^{-1}$ referred to the bending vibration of the bond Si-O-Si (Ranjbhar et al., 2014)**.** The spectrum of alkaline mixtures up to $P_{50}G_{50}$ is linked to the vibration of Si-O-Si symmetric stretching at band 785 $cm^{-1}$ (Salih et al., 2014). In the case of

GGBFS-rich mixes the same band at 785 $cm^{-1}$ is slightly shifted to a lower wavelength and centred at 725 $cm^{-1}$, and 736 $cm^{-1}$ which established the Al-O bending vibration **(**Part et al. 2015). Vibrations of bond Si-O-Si and Al-Si-O identified near at 740 $cm^{-1}$ are connected to symmetric stretching (Ismail et al., 2014)**.** Asymmetric stretching vibration modes of Si-O-T (T: tetrahedral Si or Al) is related to the band between 1200-950 $cm^{-1}$ (Ismail et al., 2014) and 950-1222 $cm^{-1}$ (Salih et al., 2014**)**. This band is located in the range of 1043-957 $cm^{-1}$ and is attributed to the development of CSH and CASH gels. These asymmetric stretching of Si-O and T-O-Si at this main band is associated with the development of the alumino-silicate phase as well. Due to the rise in the location and amount of Al atom tetrahedral in the developed geopolymer gels with the increased percentage of GGBFS caused the shifting of the main band from 1043 $cm^{-1}$ to 957 $cm^{-1}$ in the FTIR spectrum (Part et al., 2015)**.** For substitution of GGBFS 40% and below CASH, NASH and CSH are dominant phases supported by the shifting of this band from 1043 $cm^{-1}$ to 1006 $cm^{-1}$. In the case of GGBFS-rich mixes activated with alkali caused the stretching vibration of O-C-O between band range of 1413-1437 $cm^{-1}$ which confirms the carbonation reaction (Bernal et al., 2013; Panias et al., 2007; Nath and Kumar, 2013; Fernandez-Jimenez and Palomo, 2005**).** The formation of hydrated reaction products identified by the improved intensity of peak around 1647$cm^{-1}$ associated with the stretching vibration of –OH and modification of band form 3430 $cm^{-1}$ to the 3468 $cm^{-1}$ recognized the shifting of bending vibration of O-H-O (Somna et al., 2011). The presence of these leading bands of activated mixes as discussed confirmed the development of gels such as CASH, CSH, NASH and NCASH (Zawrah et al., 2016).

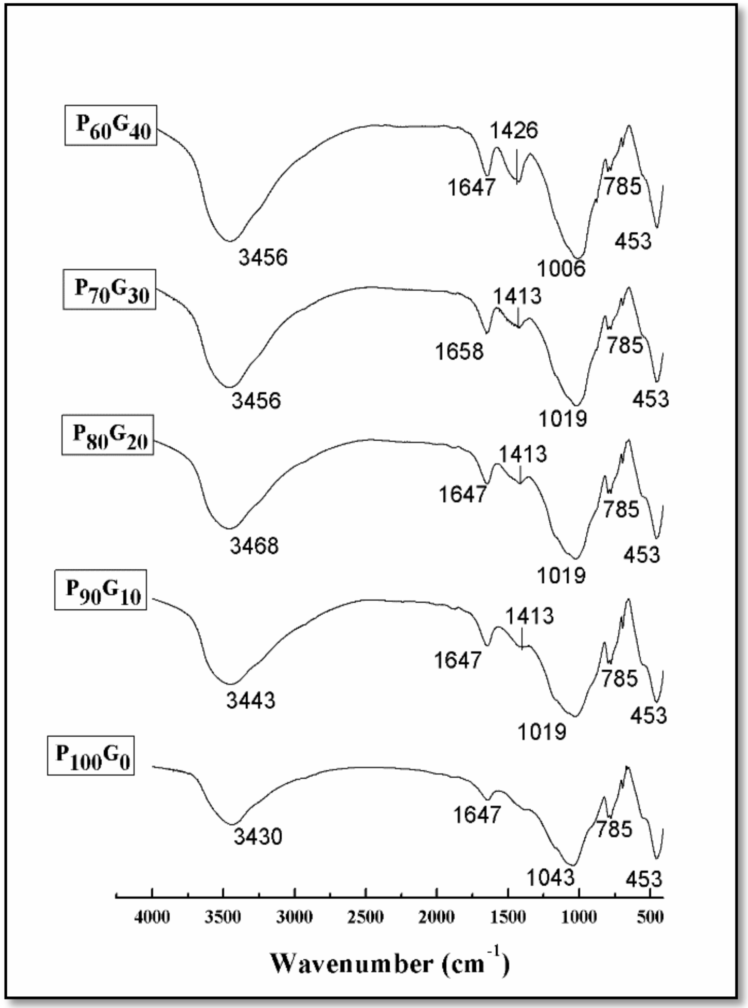



**Fig: 4.18(a)**

**FTIR Pattern of 4M NaOH Activated Mixes at 56 Days ( $P_{100}G_0$ to $P_{60}G_{40}$)**

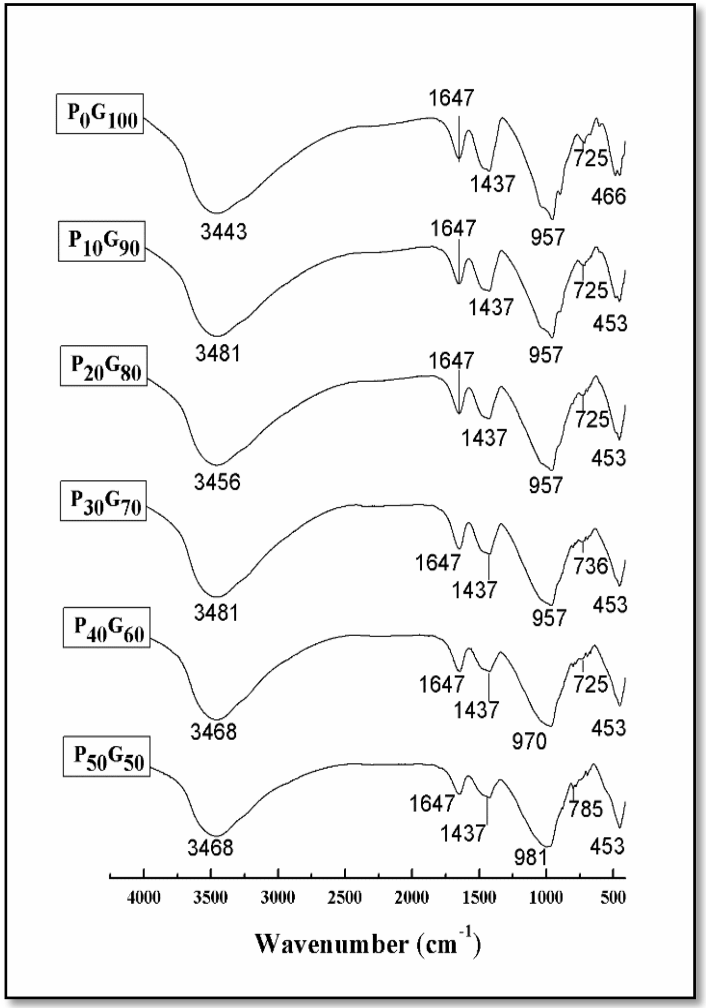
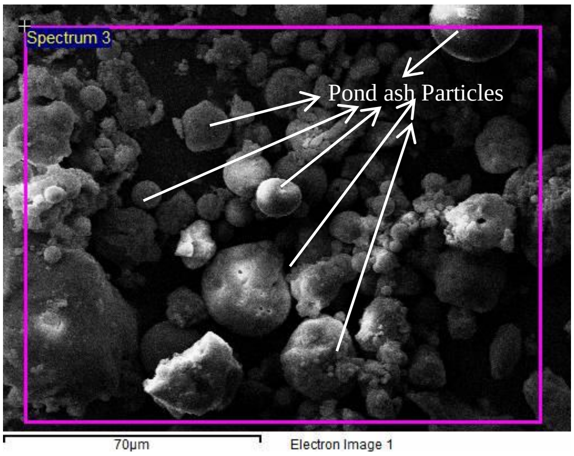



**Fig: 4.18(b)**

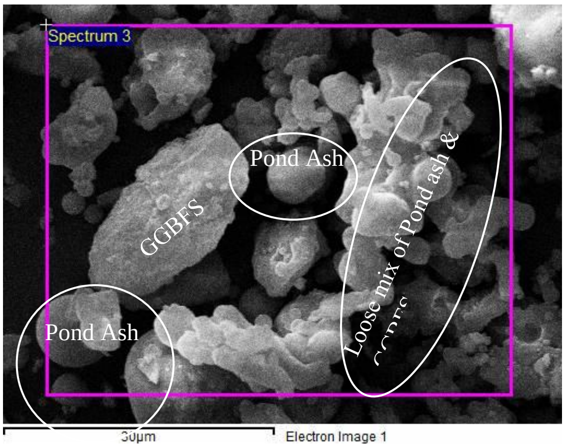
**FTIR Pattern of 4M NaOH Activated Mixes at 56 Days ( $P_{50}G_{50}$ to $P_0G_{100}$)**

### 4.10 SEM Analysis on Pond ash-GGBFS Mixes Geopolymers

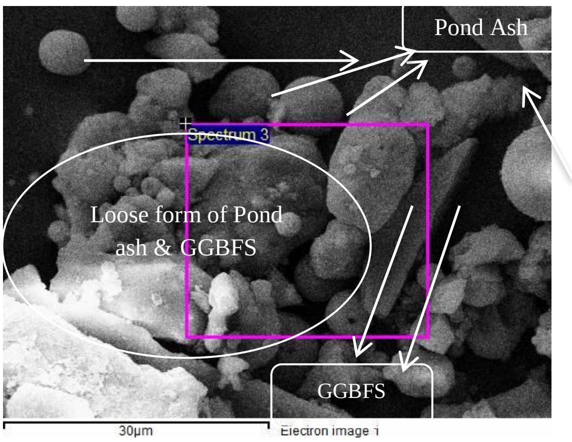
SEM Analysis has been done to observe the microstructure of the developed geopolymer of mixes that are activated with 4M NaOH concentration at 56 days curing period and the mixes activated without alkali (water). Fig. 4.19 (a) & (b) and Table 3 show the detailed SEM and EDX analysis of pond ash-GGBFS mixes without alkali activation. From the images, it is observed that no reaction has been developed in mixes activated with water. When mixes were activated with sodium hydroxide the geopolymeric gel was developed to create the denseness in the mix. It is observed that without sodium hydroxide the particles of pond ash and GGBFS do not develop any bond between them and they are looking separated in the mixes.



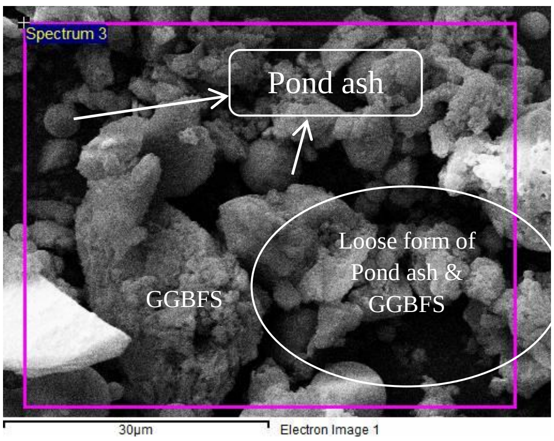

**$P_{100}G_0$**



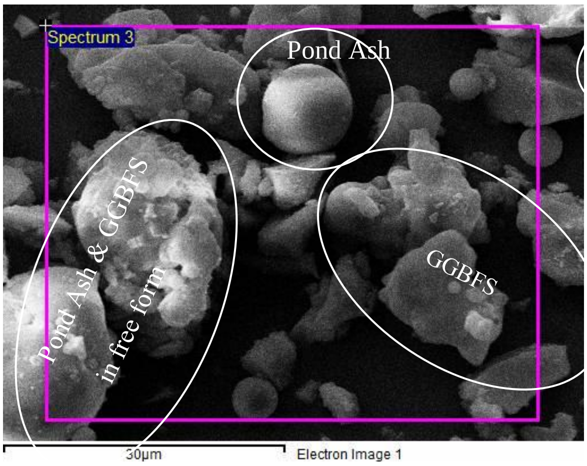

**$P_{90}G_{10}$**



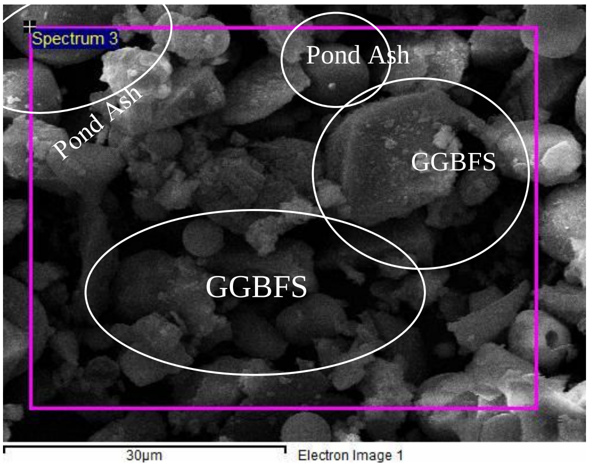

**$P_{80}G_{20}$**



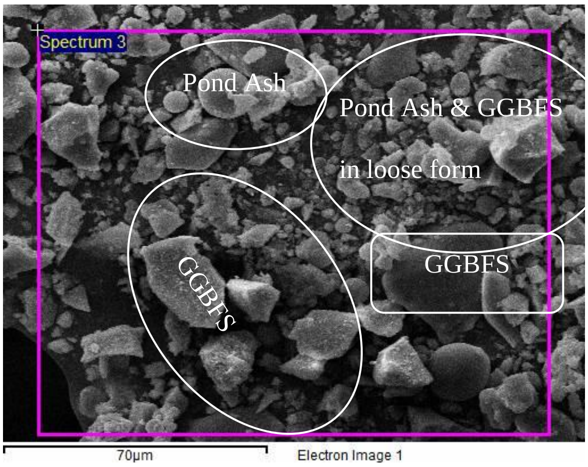

**$P_{70}G_{30}$**



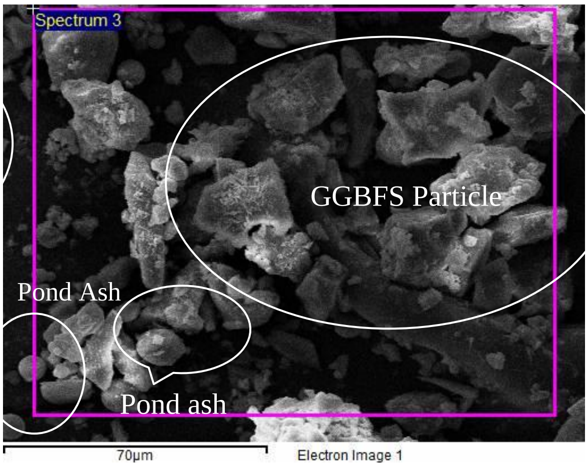

**$P_{60}G_{40}$**



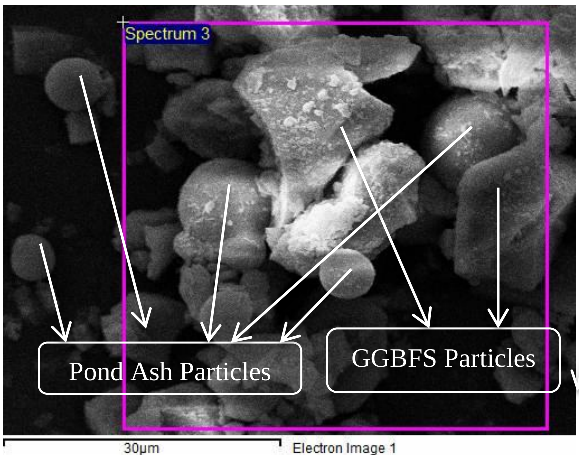

**$P_{50}G_{50}$**



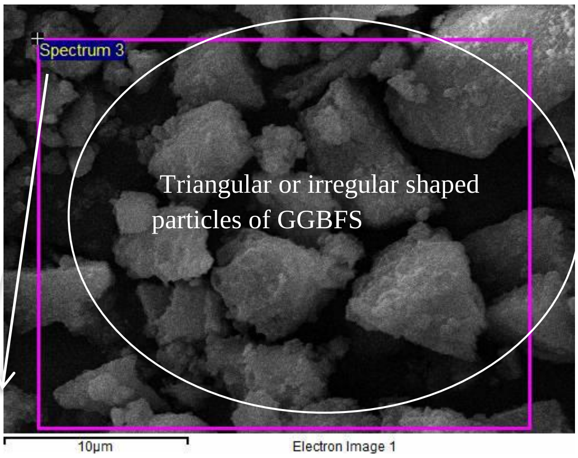

**$P_{40}G_{60}$**



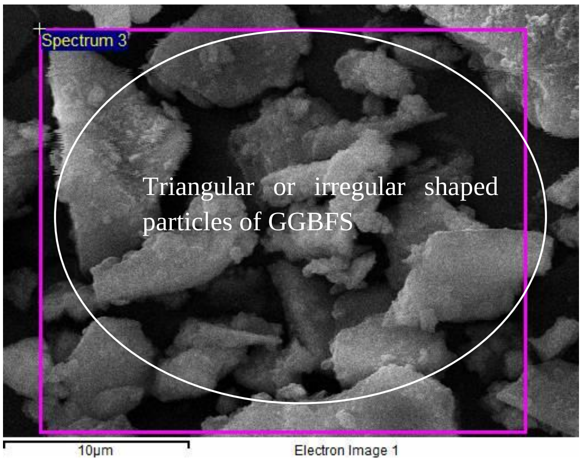

**$P_{30}G_{70}$**




**$P_{20}G_{80}$**

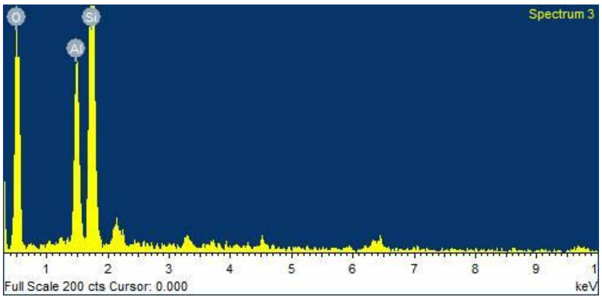



**$P_{10}G_{90}$**

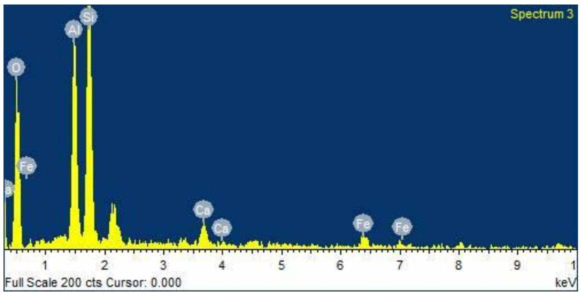



**$P_0G_{100}$**

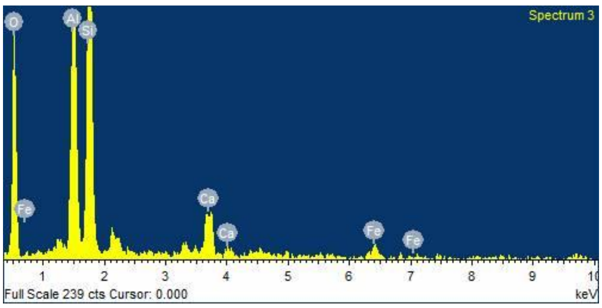
**Fig: 4.19(a) SEM Images of Pond Ash-GGBFS Mixes without Alkali Activation.**



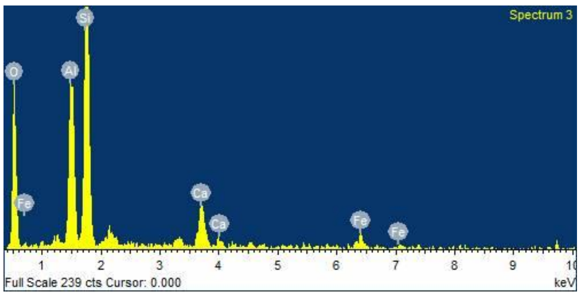

**$P_{100}G_0$**



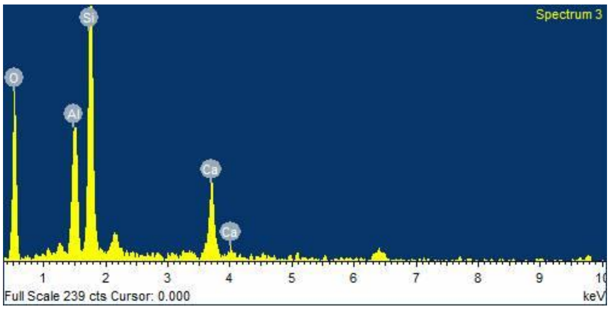

**$P_{90}G_{10}$**



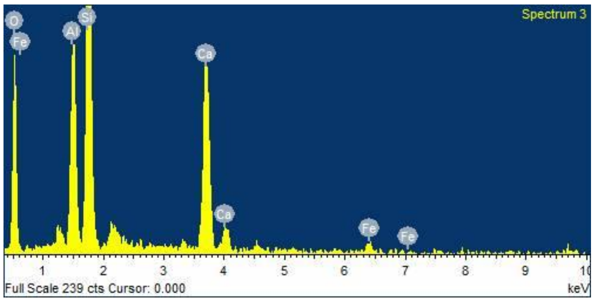

**$P_{80}G_{20}$**



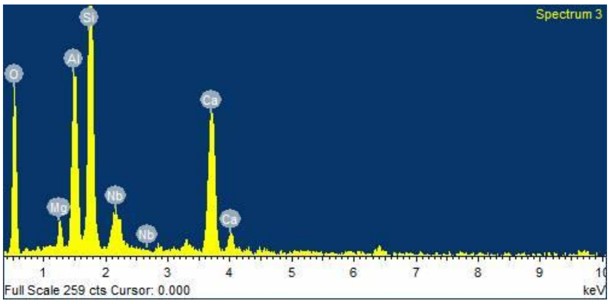

**$P_{70}G_{30}$**



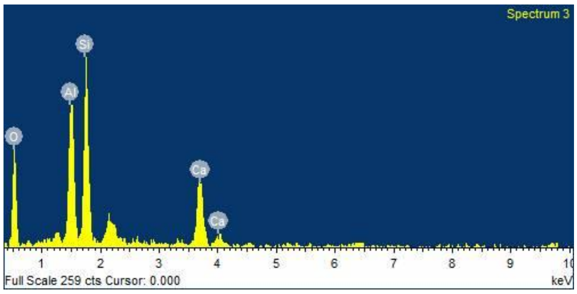

$P_{60}G_{40}$



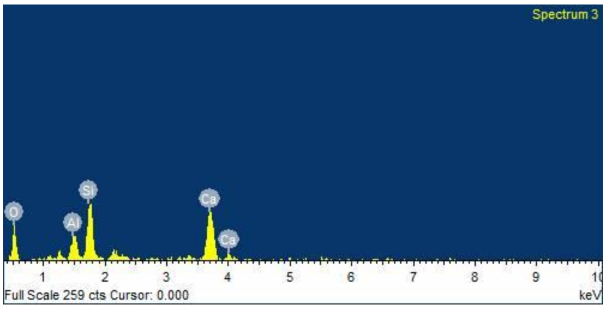

$P_{50}G_{50}$



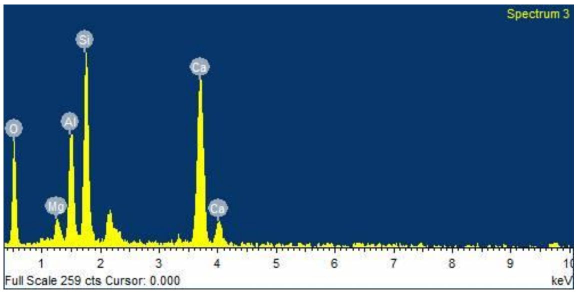

$P_{40}G_{60}$



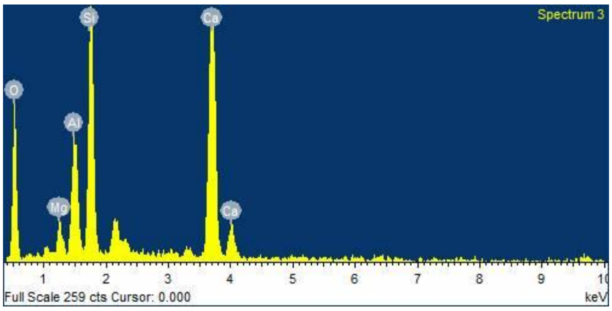

$P_{30}G_{70}$




$P_{20}G_{80}$




$P_{10}G_{90}$




$P_{0}G_{100}$

**Fig: 4.19(b) EDX Analysis of Pond ash-GGBFS mixes without alkali activation.**

**Table: 4.3 Si/Al & Ca/Si ratio for without alkali activation of Pond ash-GGBFS mixes**

| Mixtures | Si% | Al% | Ca% | Si/Al | Ca/Si |
|---|---|---|---|---|---|
| $P_{100}G_0$ | 9.28 | 3.95 | - | 2.349 | - |
| $P_{90}G_{10}$ | 8.60 | 5.76 | 0.91 | 1.493 | 0.105 |
| $P_{80}G_{20}$ | 10.01 | 5.66 | 2.05 | 1.768 | 0.204 |
| $P_{70}G_{30}$ | 13.37 | 6.47 | 2.73 | 2.066 | 0.204 |
| $P_{60}G_{40}$ | 9.46 | 3.89 | 3.24 | 2.431 | 0.342 |
| $P_{50}G_{50}$ | 14.82 | 5.83 | 9.68 | 2.542 | 0.653 |
| $P_{40}G_{60}$ | 20.36 | 9.14 | 13.12 | 2.227 | 0.644 |
| $P_{30}G_{70}$ | 8.20 | 5.78 | 4.76 | 1.418 | 0.580 |
| $P_{20}G_{80}$ | 6.82 | 2.69 | 9.69 | 2.535 | 1.420 |
| $P_{10}G_{90}$ | 8.73 | 4.72 | 11.99 | 1.849 | 1.373 |
| $P_0G_{100}$ | 7.66 | 3.11 | 12.26 | 2.463 | 1.600 |

From Fig. 4.20, 4.21 & 4.22 (4M and 10 M NaOH activated sample), it is observed that with the addition of sodium hydroxide, the alkali activation initiated the particles of pond ash and GGBFS show the development of the bond between them and they are visible like a dense structure. It is also clarified from the EDX analysis of alkaline activated mixes in which there is a presence of Albite which is a sodium-rich mineral of the feldspar group. This mineral is an indication of compactness in the mixes and this mineral albite is completely absent in without alkaline activated mixes. The SEM images supports the formation of Si-Al gels due to alkali activation as mentioned in XRD peaks of the mixes. Fig 4.20 showed that the inclusion of GGBFS in the mixes increases the compactness of the sample.

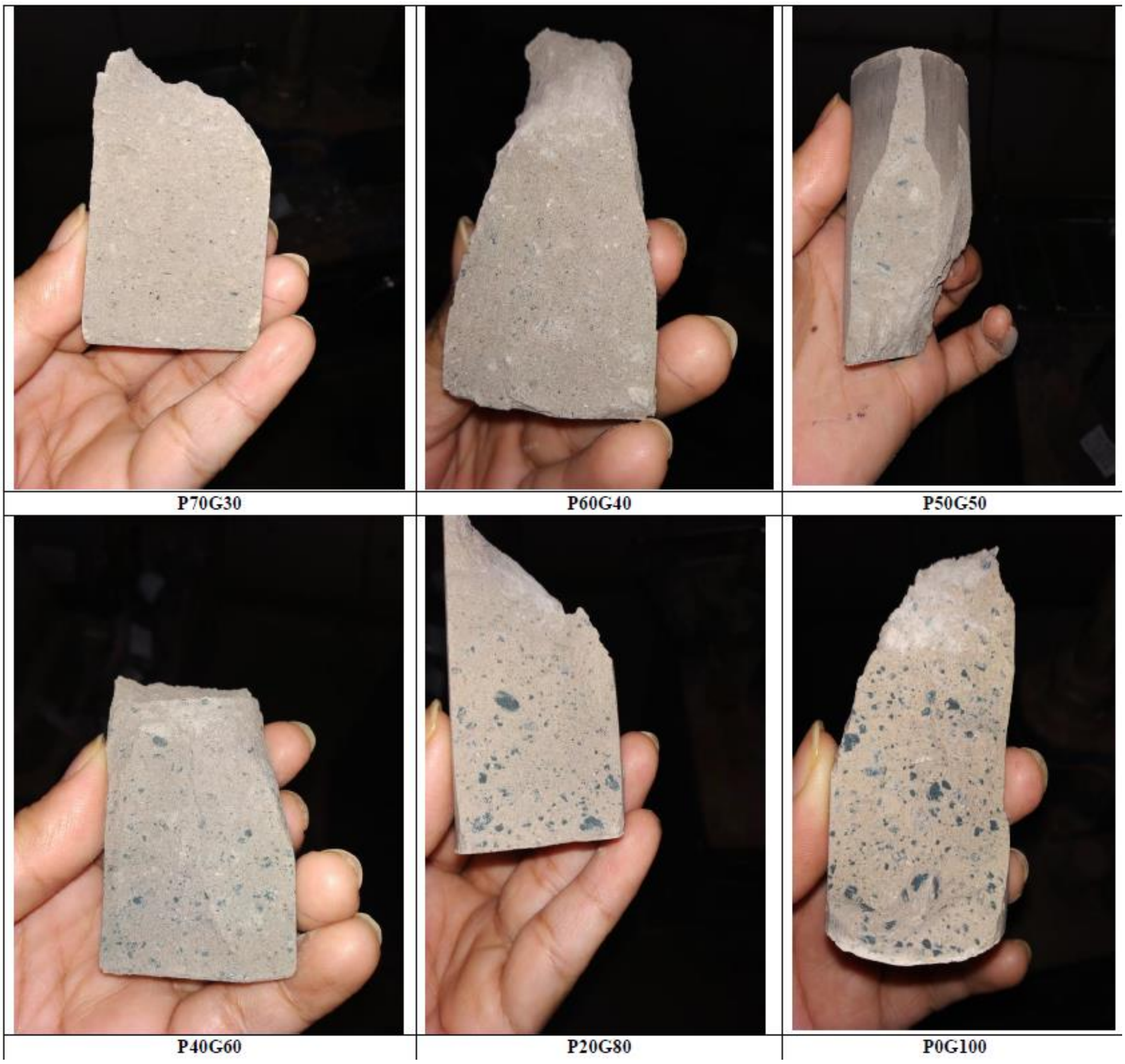
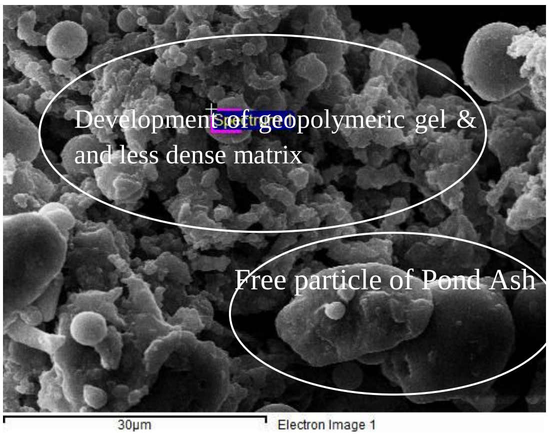
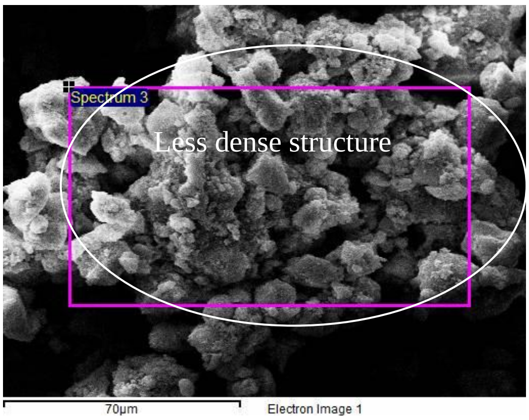


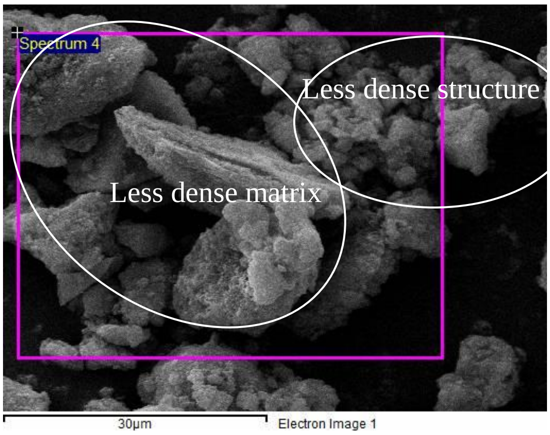

**Fig: 4.20 Image of Pond Ash-GGBFS broken samples during UCS analysis**



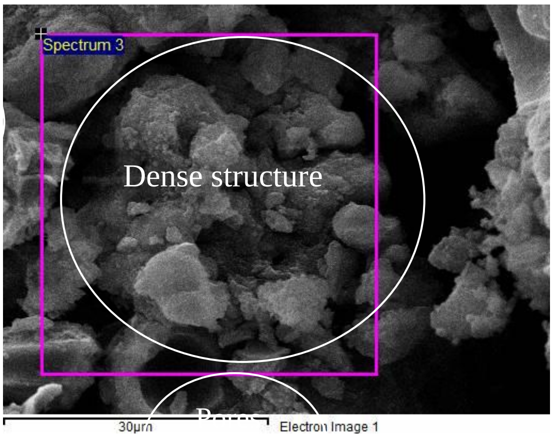

**(a) $P_{100}G_0$**



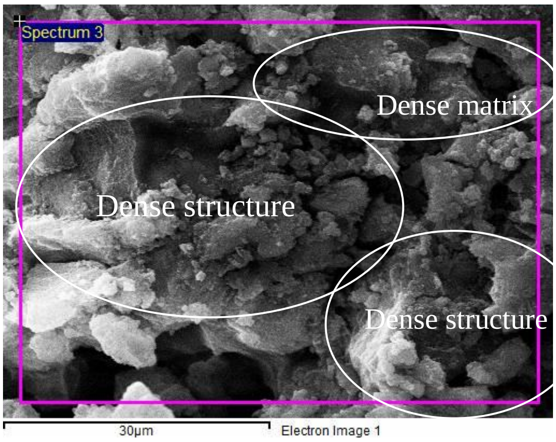

**(b) $P_{90}G_{10}$**



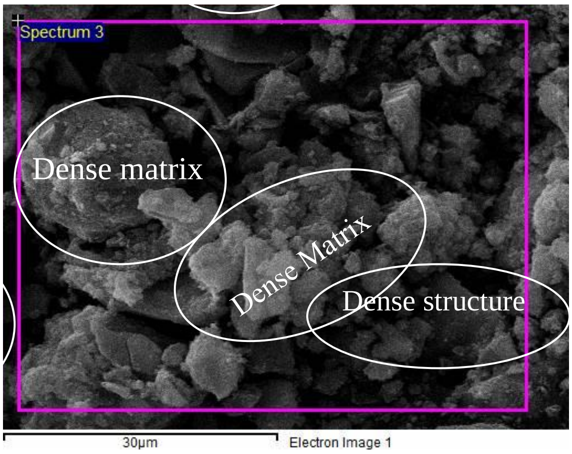

**(c) $P_{80}G_{20}$**



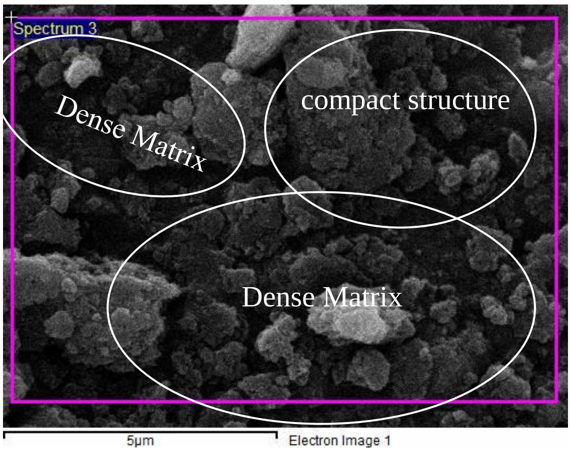

**(d) $P_{70}G_{30}$**



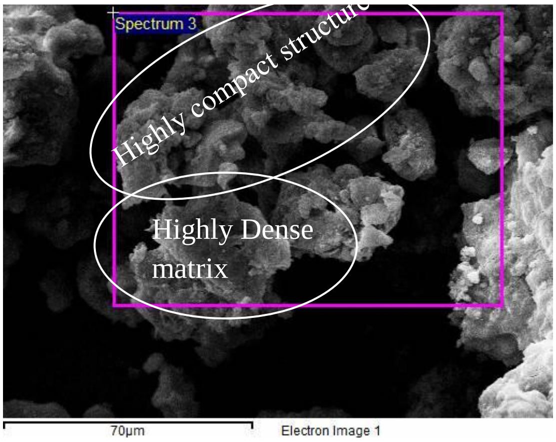

**(e) $P_{60}G_{40}$**



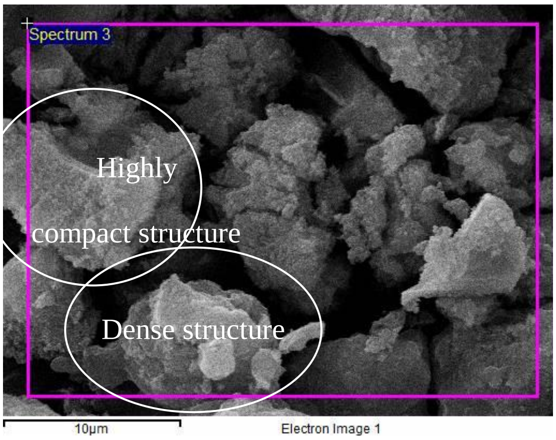

**(f) $P_{50}G_{50}$**



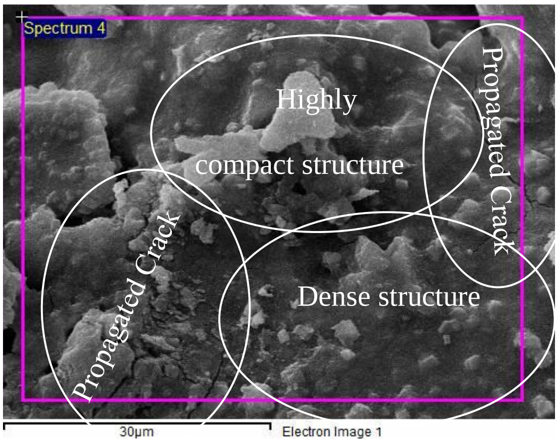

**(g) $P_{40}G_{60}$**



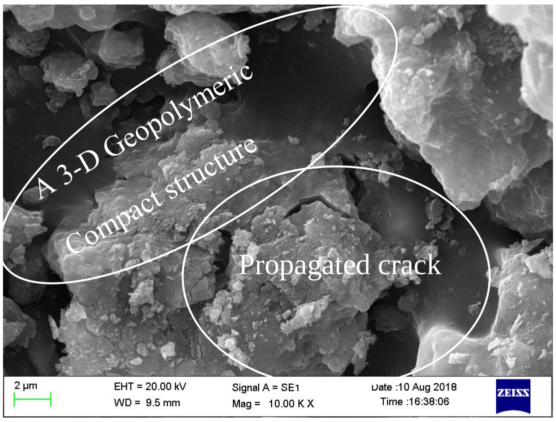

**(h) $P_{30}G_{70}$**




**(i) $P_{20}G_{80}$**

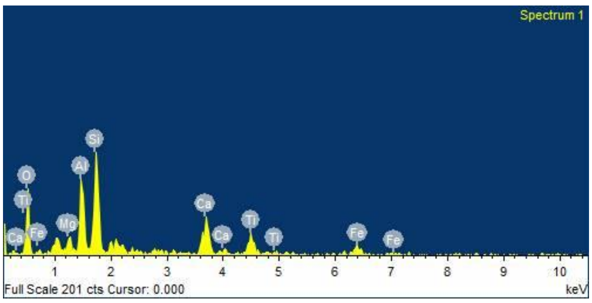



**(j) $P_{10}G_{90}$**

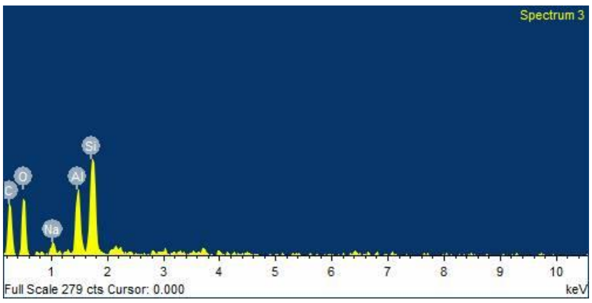



**(k)$P_0G_{100}$**

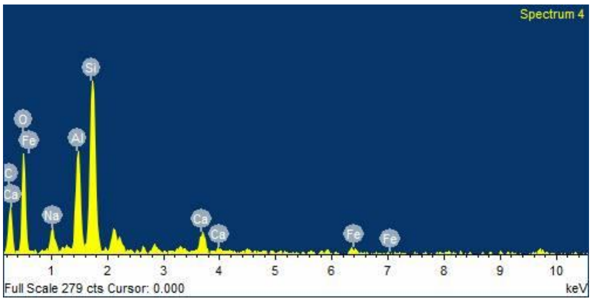
**Fig: 4.21(a) SEM Images of pond ash-GGBFS mixes activated with 4M NaOH at 56days curing period**

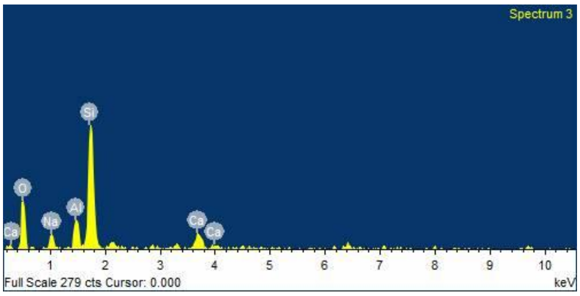



**P100G0**



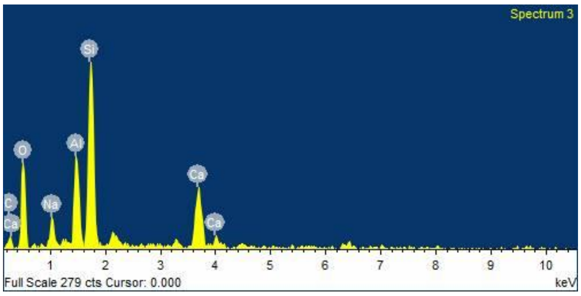

**P90G10**

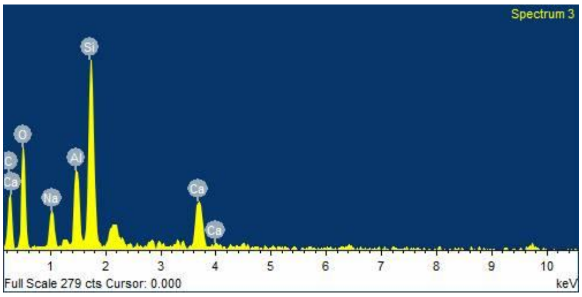



**P80G20**

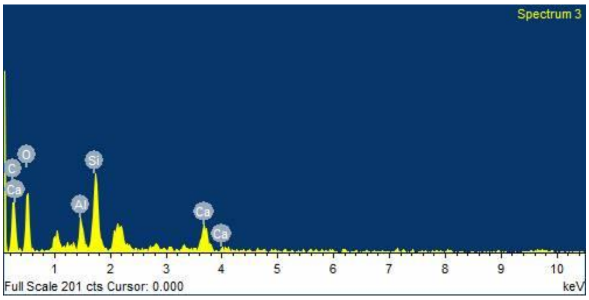
**P70G30**

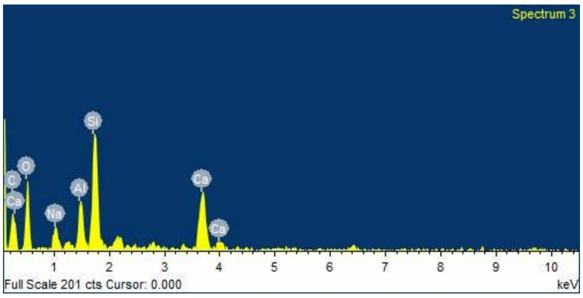



**P60G40**

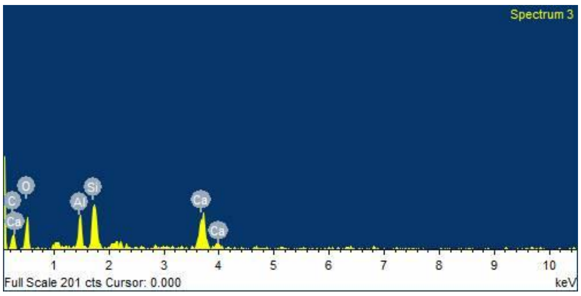
**P50G50**

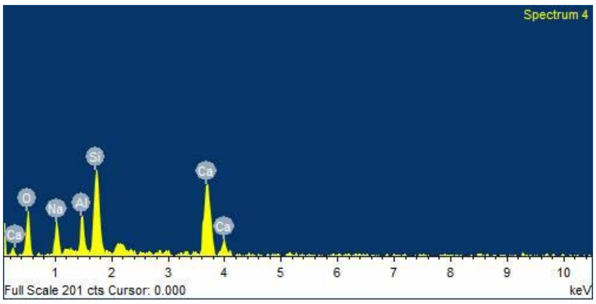



**P40G60**

**P30G70**

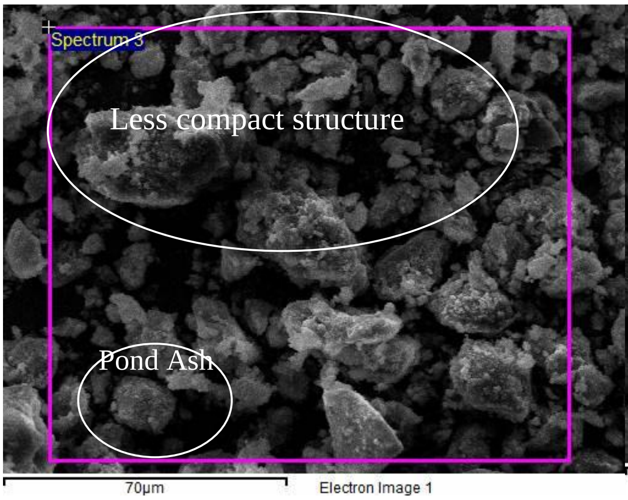


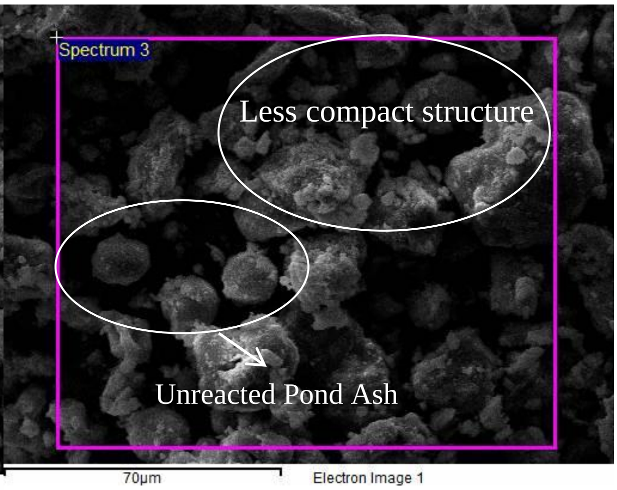

**P20G80**

**P10G90**

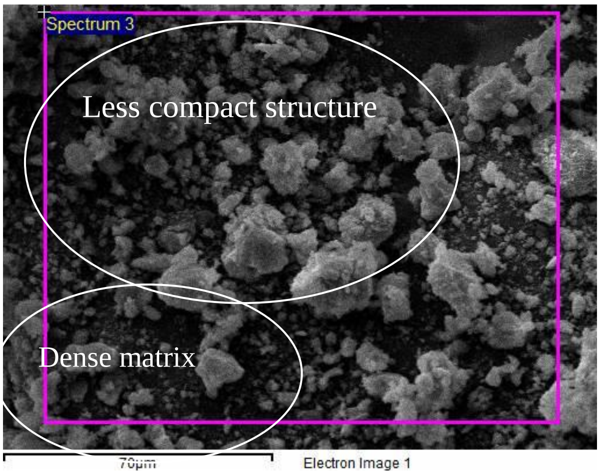
**Fig: 4.21 (b) EDX Analysis OF 4M NaOH Activated Pond Ash-GGBFS mixes at 56 days**



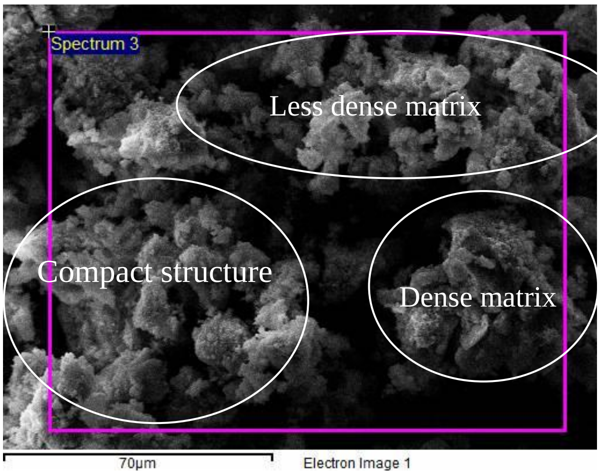

**P100G0**



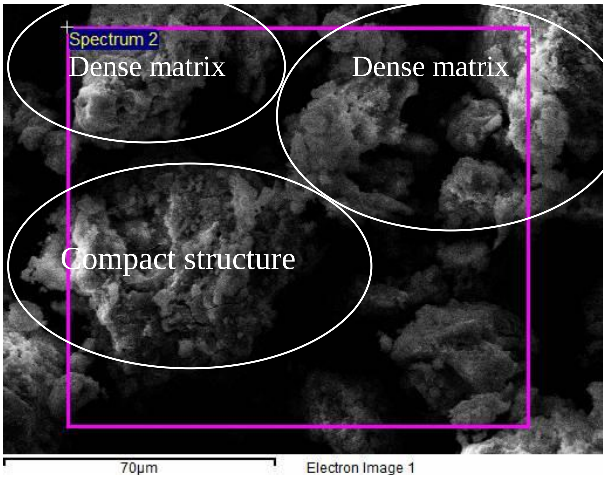

**P90G10**



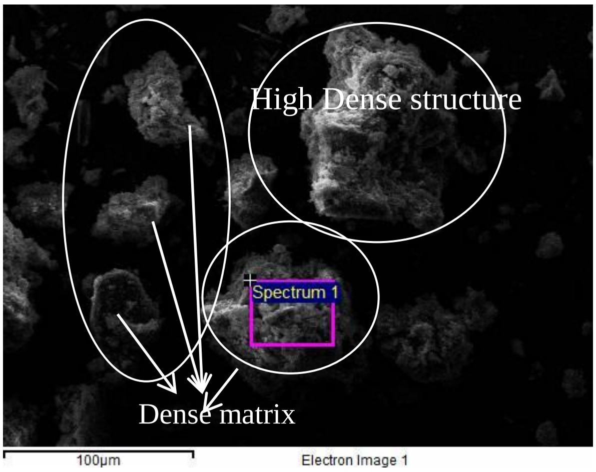

**P80G20**



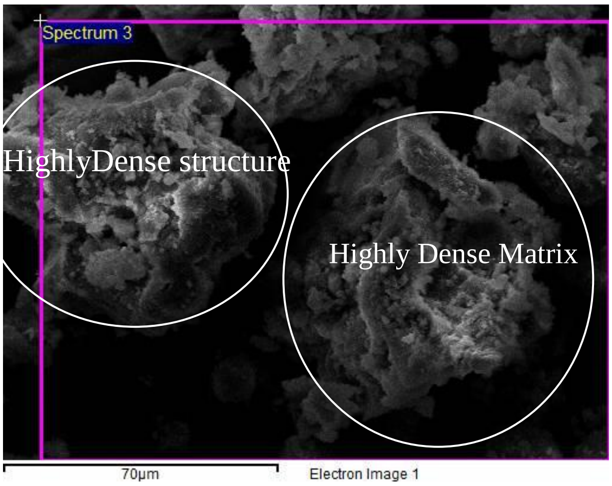

**P70G30**



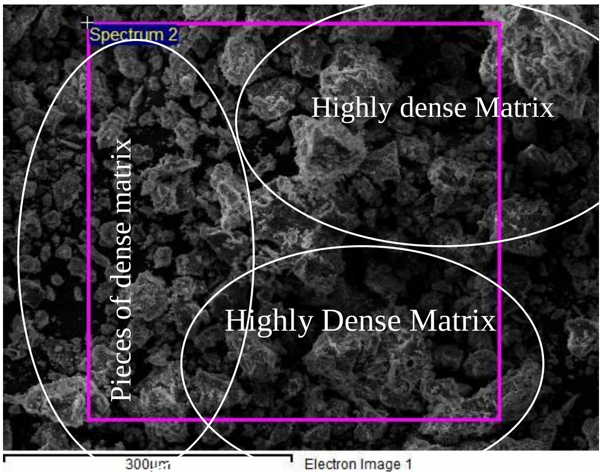

**P60G40**



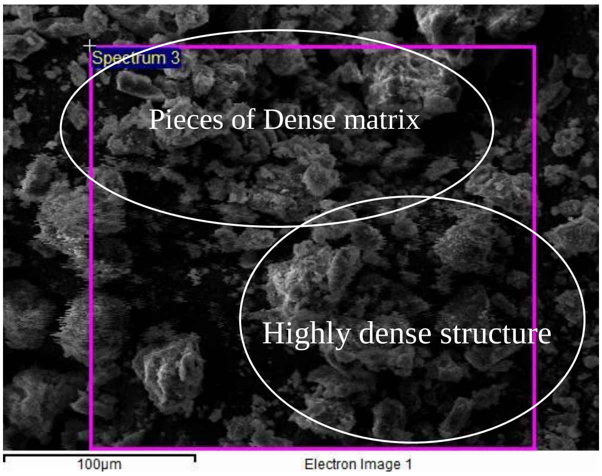

**P50G50**



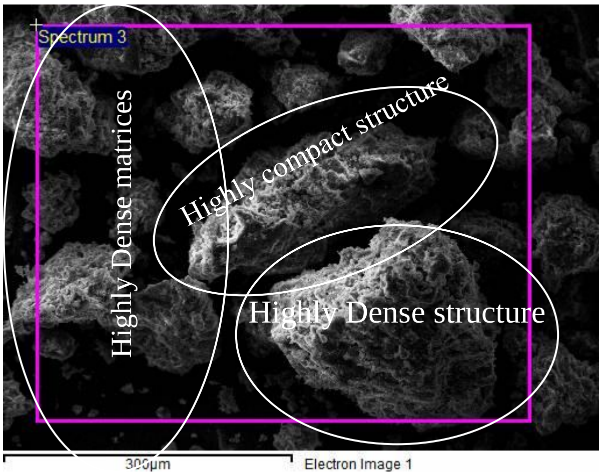

**P40G60**



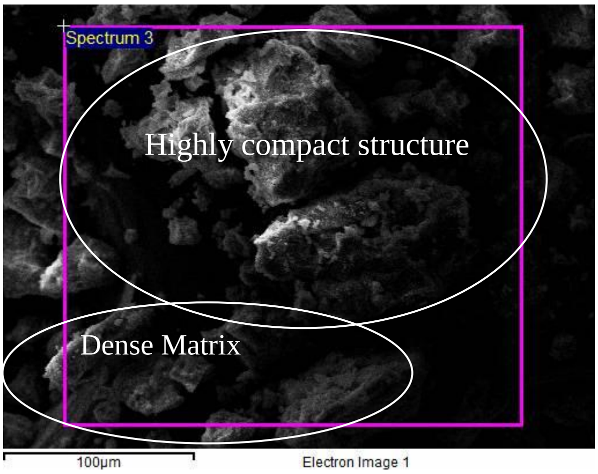

**P30G70**




**P20G80**

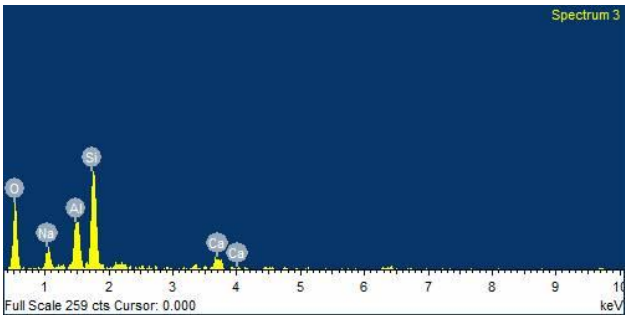



**P10G90**

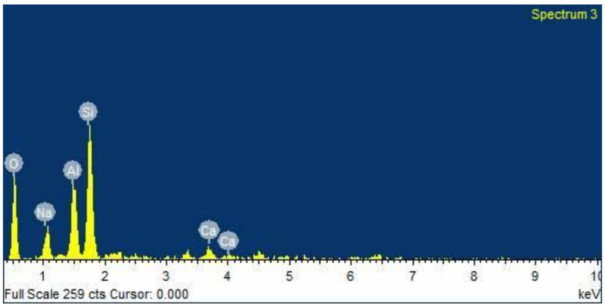



**P0G100**

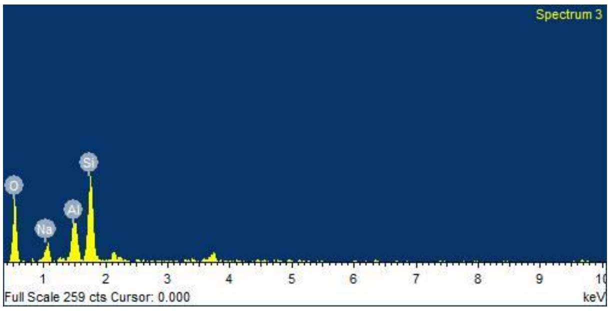
**Fig: 4.22(a) SEM Analysis of 10M NaOH activated Pond Ash-GGBFS Mixes**



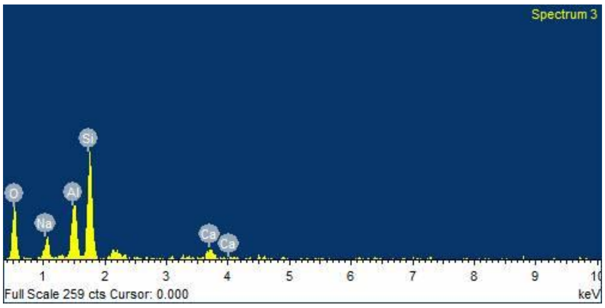

**P100G0**



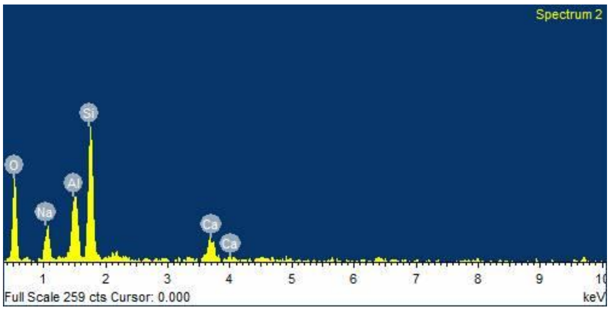

**P90G10**



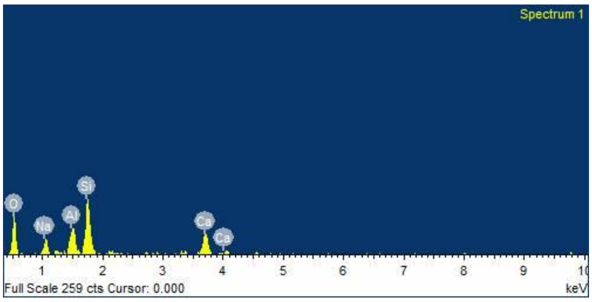

**P80G20**



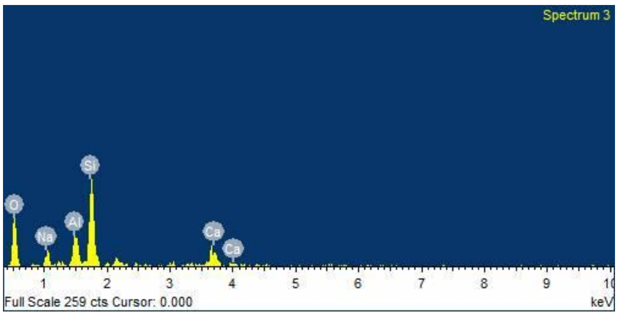

**P70G30**



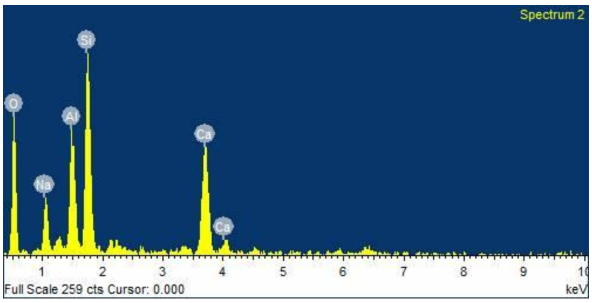

**P60G40**



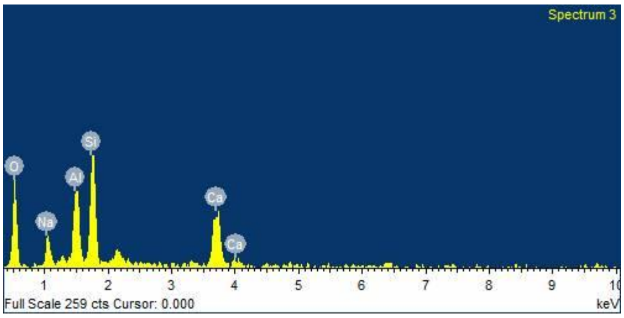

**P50G50**



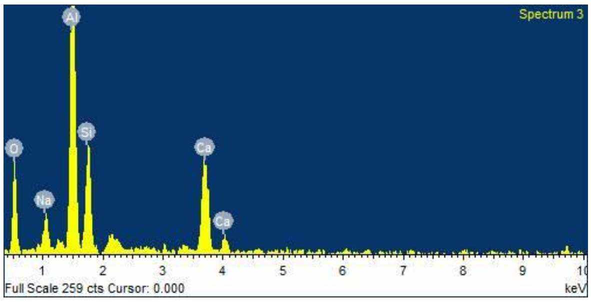

**P40G60**



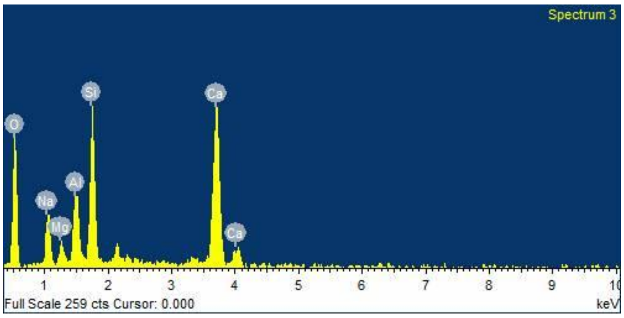

**P30G70**




**P20G80**




**P10G90**




**P0G100**

**Fig: 4.22(b) EDX Analysis of 10 M NaOH Activated Pond Ash-GGBFS Mixes**

## 4.11 Rock Triaxial Tests and Pulse Wave Velocity Tests on Pond Ash – GGBFS Mix Geopolymers.

The rock tri-axial tests as per IS:13047 (1991) and Pulse-wave velocity tests as per ASTM C597 were conducted on pond ash-GGBFS mixes activated with 4M NaOH for ensuring the denseness and stiffness of the synthesised geopolymers and cured for a period of 56 days and data has been presented in the following Fig. 4.23 & 4.24 and Table 4.4. Also these tests results are found to know the suitability of the geopolymers as a construction materials. From Table 4.4 it can be reported the shear wave velocity of the Pond ash-GGBFS mixes calculated using the pulse wave velocity from the Castagna { $V_S = -0.05509(V_P)^2 + 1.0168V_P - 1.0305$}, Brocher { $V_S = 0.7858 - 1.2344V_P + 0.7949(V_P)^2 - 0.1238(V_P)^3 + 0.006(V_P)^4$ } & Carroll empirical formula{ $V_S = 1.09913326\times (V_P)^{0.9238115336}$} (Maleki et al., 2014). The shear strength of geopolymer mixes is also verified by conducting rock triaxial tests at 20 kg/cm$^2$

confining pressure on a few samples of pond ash-GGBFS mixes and results are mentioned in Fig. 22. Based on the tests conducted the shear strength of samples is verified and values are very much near to UCS values.

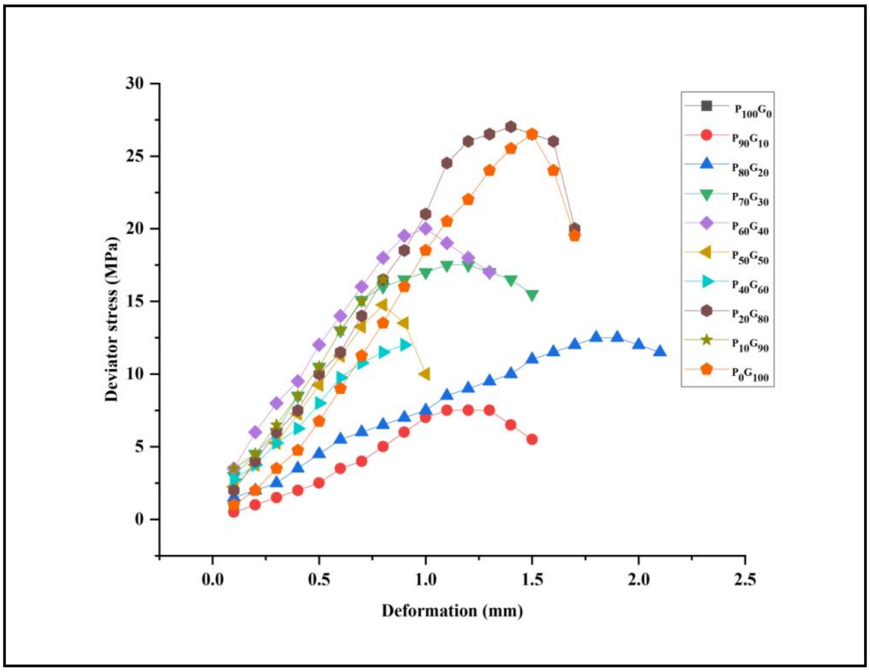



**Fig: 4.23 Rock Triaxial Testing on mixes of Pond Ash – GGBFS geopolymer**

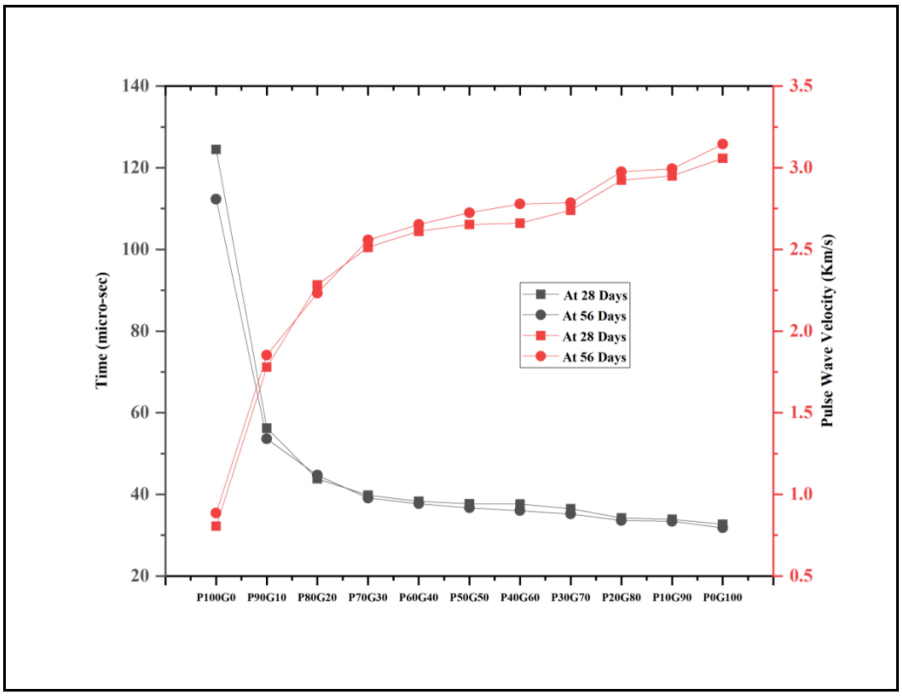



**Fig: 4.24 Pulse Wave Velocity Graph of Pond Ash-GGBFS mixes**

**Table: 4.4 Pulse wave velocity results of Pond Ash-GGBFS Geopolymer**

| Activated with 4M NaOH | Experimental values | | Maleki et al. (2014)** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Castagna equation | Brocher equation* | Carroll equation | Castagna equation | Brocher equation* | Carroll equation |
| Mix type | Vp | Vp | Vs | Vs | Vs | Vs | Vs | Vs |
| | 28 days | 56 days | 28 days | 28 days | 28 days | 56 days | 56 days | 56 days |
| | km/s | km/s | km/s | km/s | km/s | km/s | km/s | km/s |
| P100G0 | 0.805 | 0.885 | -0.247 | 0.245 | 0.899 | -0.173 | 0.233 | 0.981 |
| P90G10 | 1.779 | 1.855 | 0.604 | 0.468 | 1.871 | 0.666 | 0.512 | 1.945 |
| P80G20 | 2.283 | 2.232 | 1.003 | 0.800 | 2.356 | 0.964 | 0.763 | 2.307 |
| P70G30 | 2.513 | 2.558 | 1.176 | 0.978 | 2.574 | 1.21 | 1.014 | 2.617 |
| P60G40 | 2.611 | 2.653 | 1.248 | 1.057 | 2.667 | 1.279 | 1.091 | 2.707 |
| P50G50 | 2.653 | 2.725 | 1.279 | 1.091 | 2.707 | 1.331 | 1.150 | 2.774 |
| P40G60 | 2.66 | 2.778 | 1.284 | 1.097 | 2.713 | 1.369 | 1.194 | 2.824 |
| P30G70 | 2.74 | 2.786 | 1.341 | 1.162 | 2.789 | 1.374 | 1.200 | 2.832 |
| P20G80 | 2.924 | 2.976 | 1.471 | 1.316 | 2.961 | 1.507 | 1.359 | 3.010 |
| P10G90 | 2.95 | 2.994 | 1.489 | 1.338 | 2.985 | 1.519 | 1.375 | 3.027 |
| P100G0 | 3.058 | 3.145 | 1.563 | 1.428 | 3.086 | 1.622 | 1.501 | 3.167 |

### 4.12 Leachate Analysis

However, to assess the harmful effect due to the use of high molarity of NaOH used in the present study the pH and heavy metal concentration in the leachate sample were determined. In the present study ICP-AES (Inductively coupled plasma atomic emission spectroscopy) technique is used to determine the concentrations of trace to major elements in the leachate. In this technique a radio frequency electromagnetic field inductively coupled at atmospheric pressure which is operated by the plasma consists of argon gas. The atomic emissions produced were detected by the spectrometer, while a computer controls and monitors instrument functions to process, store and output the analysis results.

The data is presented in the following Figs. 4.25 & 4.26 and Table 4.5 & 4.6. The present study has identified the optimised strength achieved at NaOH concentration of 4M or 6M which is not very harmful in comparison to high molarities of NaOH used in several other studies followed in literature. The leachate of the samples that interacted with 6 and 10 molarities are found to be not harmful based on pH and heavy metal concentration data as mentioned in Fig. 4.25 & 4.26.

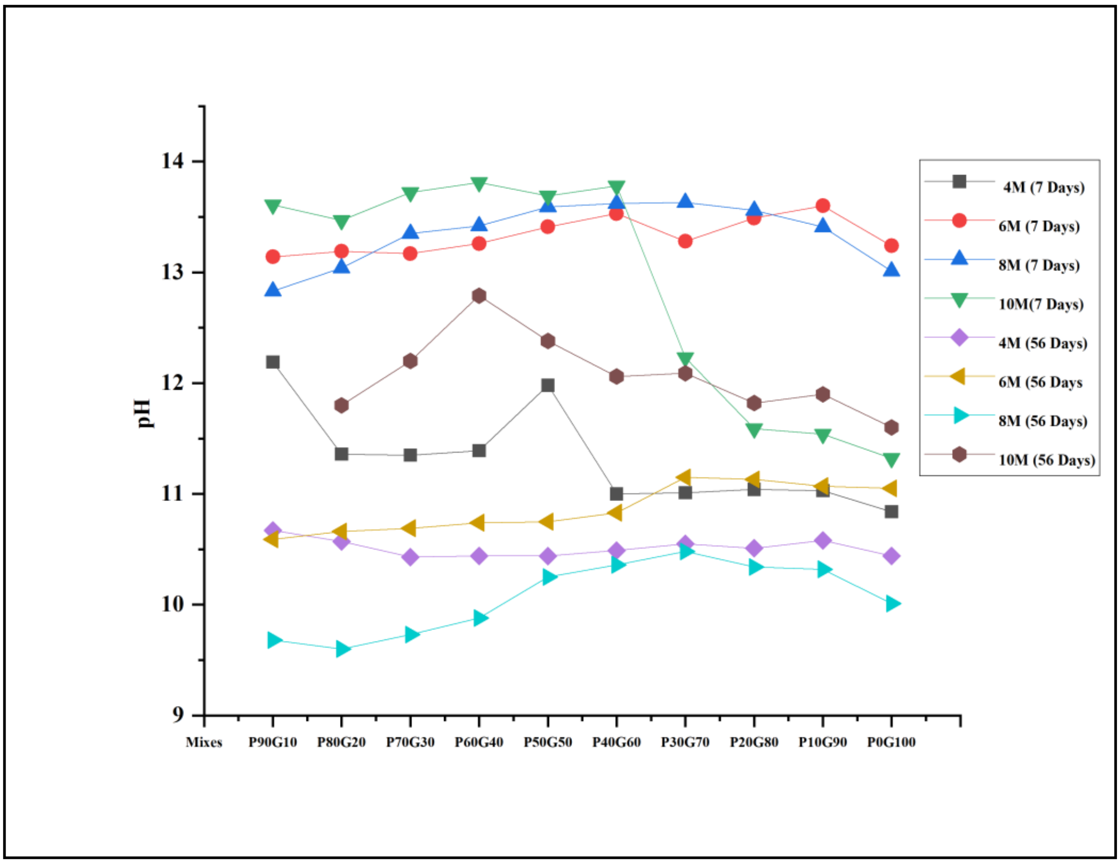



**Fig: 4.25 pH value of Pond ash-GGBFS mixes at 7 days and 56 days curing period**

**Table: 4.5 pH Value at Different Molarity**

| | **7 Days** | | | | **56 Days** | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixes** | **4M** | **6M** | **8M** | **10 M** | **4M** | **6M** | **8M** | **10M** |
| $P_{90}G_{10}$ | 12.19 | 13.14 | 12.83 | 13.61 | 10.67 | 10.59 | 9.68 | - |
| $P_{80}G_{20}$ | 11.36 | 13.19 | 13.04 | 13.47 | 10.57 | 10.66 | 9.6 | 11.8 |
| $P_{70}G_{30}$ | 11.35 | 13.17 | 13.35 | 13.72 | 10.43 | 10.69 | 9.73 | 12.2 |
| $P_{60}G_{40}$ | 11.39 | 13.26 | 13.42 | 13.81 | 10.44 | 10.74 | 9.88 | 12.79 |
| $P_{50}G_{50}$ | 11.98 | 13.41 | 13.59 | 13.69 | 10.44 | 9.2 | 10.25 | 12.38 |
| $P_{40}G_{60}$ | 11 | 13.53 | 13.62 | 13.78 | 10.49 | 10.83 | 10.36 | 12.06 |
| $P_{30}G_{70}$ | 11.01 | 13.28 | 13.63 | 12.23 | 10.55 | 11.15 | 10.48 | 12.09 |
| $P_{20}G_{80}$ | 11.04 | 13.49 | 13.56 | 11.59 | 10.51 | 11.13 | 10.34 | 11.82 |
| $P_{10}G_{90}$ | 11.03 | 13.6 | 13.41 | 11.54 | 10.58 | 11.07 | 10.32 | 11.9 |
| $P_{0}G_{100}$ | 10.84 | 13.24 | 13.01 | 11.32 | 10.44 | 11.05 | 10.01 | 11.6 |

**Table: 4.6 pH of 4M NaOH Sample Immersed in 1% $H_2SO_4$**

| Mixes | 7 Days | 28 Days | 56 Days |
|---|---|---|---|
| $P_{90}G_{10}$ | 2.02 | 1.25 | 1.28 |
| $P_{80}G_{20}$ | 2.42 | 1.21 | 1.51 |
| $P_{70}G_{30}$ | 2.06 | 1.24 | 1.9 |
| $P_{60}G_{40}$ | 2.42 | 1.31 | 1.65 |
| $P_{50}G_{50}$ | 2.32 | 1.15 | 1.49 |
| $P_{40}G_{60}$ | 2.37 | 1.09 | 1.47 |
| $P_{30}G_{70}$ | 1.97 | 1.18 | 1.08 |
| $P_{20}G_{80}$ | 1.58 | 1.24 | 1.04 |
| $P_{10}G_{90}$ | 1.45 | 1.21 | 1 |
| $P_{0}G_{100}$ | 1.37 | 1.14 | 0.89 |

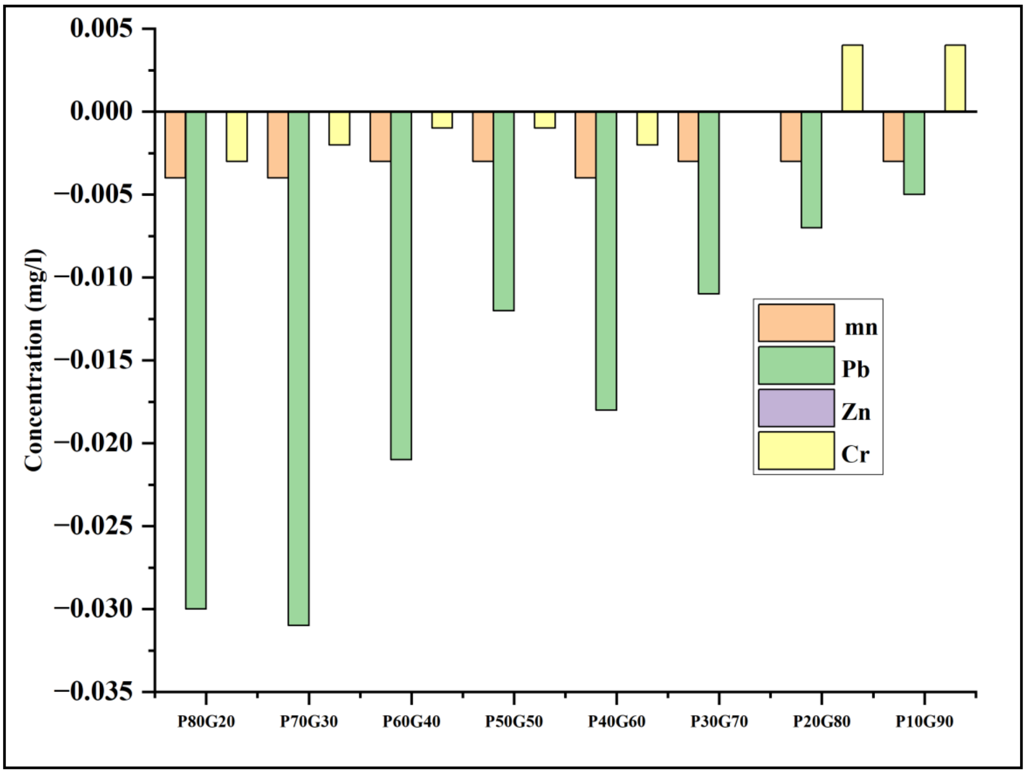



**Fig: 4.26(a) Leachate analysis of pond ash – GGBFS mixes at 6M NaOH**

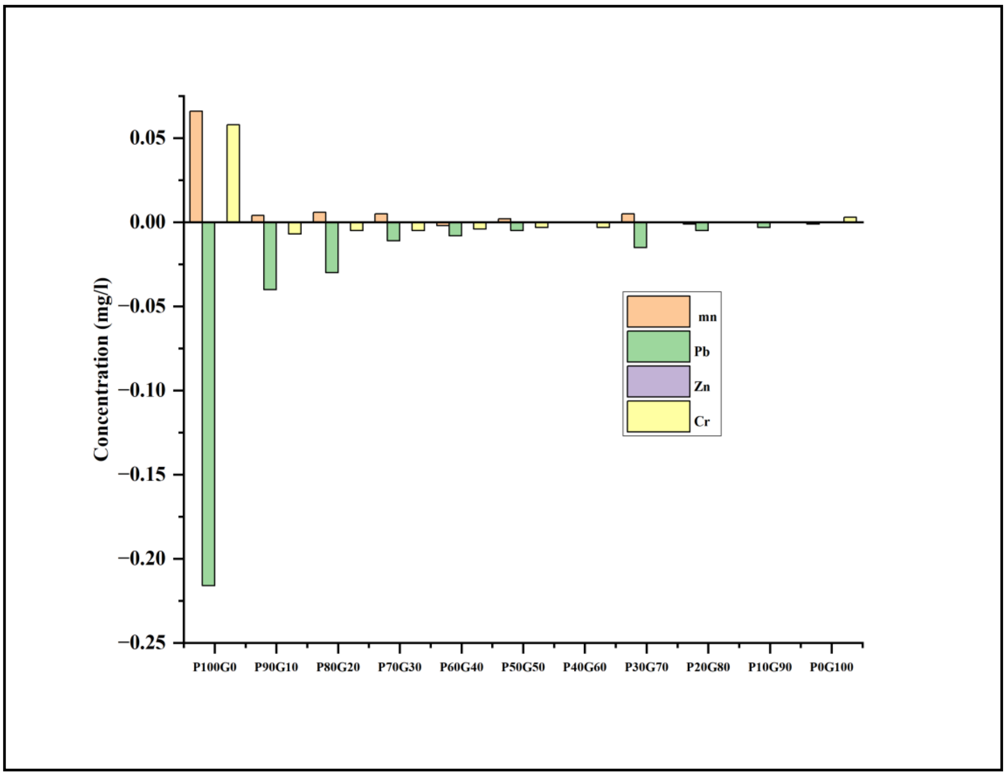



**Fig: 4.26 (b) Leachate analysis of pond ash – GGBFS mixes at 10M NaOH**

### 4.13 Summary

This study has been concluded that the designed mixtures did not possess any significant strength when mixtures activated with water. Mixtures when activating with an alkaline solution (sodium hydroxide) at different concentrations, mixtures represented significant strength. First strength increases with the increase in the concentration of sodium hydroxide. But the concentration of sodium hydroxide increases beyond 4 M, and strength slightly decreases. The reason behind this decrement is the excessive concentration of the hydroxide ions. The changes in the strength are justified with the microstructural analysis of the mixes.