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Strength and Microstructure of Sustainable High Performance Concrete

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Abstract: ***Concrete has an amalgamated microstructure which would be very difficult to study its microstructure due to high level of heterogeneity This research intends to produce a Sustainable High performance concrete (SHPC) by replacing conventional concrete materials with sustainable materials. The vital elements of concrete were replaced with sustainable materials which has the ability to improve the mechanical property of concrete and to make the concrete sustainable. Cement was partially substituted with Fly ash (30% and 35%) and Silica fume (7.5 % and 10%) and fine aggregate was wholly substituted with manufactured sand. Coarse aggregate was partially replaced with recycled aggregate taken from the Construction Demolished Waste (CDW) (30% and 40%).Five trial mixes were prepared and casted into cubes. Compressive strength and quantitative analysis of concrete by using XRD Analysis were studied and the obtained results were interrelated with each other based on their composition of minerals elements and strength of SHPC. The comparative study showed a promising result on the SHPC 3 in which the sustainable materials binds to produce a well-built C-S-H gel. The influence of the sustainable materials at optimal range could help to accomplish sustainability in High Performance Concrete.***

Keywords: ***Concrete, High Performance Concrete, Sustainability, CSH gel***

I. INTRODUCTION

The behavior of any material is usually related to its microstructure of the material. The understanding of bond between microstructure and properties of materials forms the material science. In terms of concrete microstructure, it has an amalgamated microstructure which would be very difficult to study its microstructure due to its high level of heterogeneity but, through X Ray Diffraction technique the crystal structure of minerals compounds exist in the microstructure of hydrated cement matrix can be indexed effectively which will helps in microstructural investigation of the microstructure of concrete.

Based on the references, it was found that concrete has diverse microstructure which depend on the formation of CSH gel during the hydration process and byproducts such as cement, sand and other miscellaneous materials in the mixture. Ref [1] notifies that the development of CSH gel improves the structural strength of the concrete for long time. In order to improve the CSH gel formation in the microstructure of concrete, recycled materials are included in the concrete mix.

[2] Illustrates that fly ash has the capability to make the concrete more sustainable and also able to yield huge amount of $Ca(OH)_2$ and $CaCO_3$.[4] indicated that the C–S–H gel structure was somewhat less monolithic than that of conventional concrete and total intensity of (ettringite) hydrous calcium aluminum sulfate was not changed with the inclusion of coal bottom ash in concrete. Ref [5] explains that mechanical properties, complete replacement of coarse aggregate would be possible when recycled coarse aggregates were produced from unique concrete with a least strength. [2], [6] clarifies the inclusion of SF can decrease the content of Calcium Hydroxide (CH) due to its pozzolanic response.[13] illustrates that denser formation of CSH gel will influence the structural strength of concrete

In general, this research paper focuses on assessing the relationship between the structural and microstructural behavior of HPC and to attain sustainability through partial replacement of concrete ingredients with recycled waste material or cost-effective materials.

II. EXPERIMENTAL PROGRAM

A. Materials and Mixtures

The materials used in this tentative program were

- OPC (43 grade) conforming IS 1489 -1991 was used for this research
- Fly Ash and Silica Fume used as pozzolanic agent
- Manufactured Sand and Conventional river sand was used as Fine Aggregate
- Normal Course Aggregate and Aggregates obtained from Construction Demolition Waste (CDW)
- Superplasticiers (Conplast SP430)

Table.1 shown below displays the various properties of fine aggregate whereas Table .2 shows the properties of Coarse aggregate used in the research

Table 1 Properties of Fine Aggregate

S.No	*Properties*	*Natural Sand*	*M- Sand*
1	Bulk Density	1670 kg/m^3	1728 kg/m^3
2	Water Absorption	1.2%	0.98%
3	Specific Gravity	2.74	2.68
4	Fineness Modulus	2.4	2.48

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Table 2 Properties of Coarse Aggregate

S.No	*Properties*	*Coarse Aggregate*	*CDW (RCA)*
1	Bulk Density	2.46	2.67
2	Water Absorption	0.78%	0.88%
3	Specific Gravity	2.64	2.68
4	Impact Value	24.5%	21.74%

***Note:** The Test were conducted as IS 2386

Table 3 Mix Proportion for SHPC

Mix design was done for M60 grade of concrete

S.No	*Materials*	*Proportion*	*In Kg/m^3*
1	Cement	1	580
2	Water	0.31	179
3	Coarse Aggregate	1.09	608
4	Fine Aggregate	2.55	1136
5	Admixture	0.031	1.79

Note:

*SHPC 1 Conventional Concrete Mix
*SHPC 2 (7.5 % S.F+ 30% F.A+ 30% CDW)
*SHPC 3 (10% S.F+ 35% F.A+ 30% CDW)
*SHPC 4 (7.5 % S.F+ 30% F.A+ 40% CDW)
*SHPC 5 (10 % S.F+ 35% F.A+ 40% CDW)

III. COMPRESSIVE STRENGTH

In this project, five different mixes were prepared for cube casting. The cube mould was oiled with oil which aids to remove the cube sample from the mould with ease. Fresh concrete was poured into the 100 x 100 x 100 mm cube in three layers and tamped 25 times with the help of tamping rod. The mould was placed in the vibrating table for final compaction. Then, the concrete filled cube mould is fined at the top surface.

After the compaction process, the concrete filled cube mould was kept sin open surface for 24hrs for setting process at room temperature. The cube samples are removed from the mould and immersed in water bath for 28 days curing process. After the curing process, the test cube was placed on the platform of compression testing machine. Then, the load is applied smooth surface of the test cubes until the failure occurs as shown in **Fig.1**

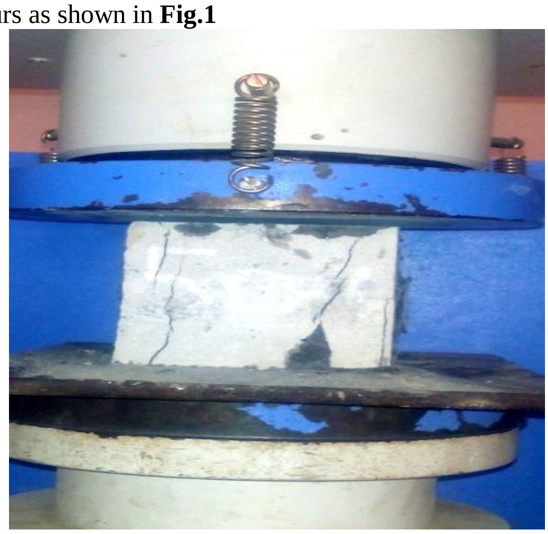

Fig.1 Compressive Strength Test

IV. MICROSTRUCTURAL ANALYSIS

A. Preparation of Samples

This sample preparation was conducted for the micro structural analysis of hardened cement paste obtained from the test cubes. In general, a little quantity of powder samples is enough (about 30 to 50 gms) for microstructure examinations such as XRD, SEM and EDS.

The sample preparation technique was used based on the theoretical study on the micro structural analysis. The process of sample preparation in the project is described as follows.

a. Crushing and Sieving

After Compressive testing was finished, the cube samples are crushed and the hardened cement was collected from the innermost core of the concrete cube sample. The collected samples are sieved through 300µ sieve. From the sieved samples, 30gms of powdered samples of hardened cement paste was collected. The cursing and sieving process of samples are pictured below which displays the procedure accomplished for preparation of samples for microstructural analysis. Seven specimens are arranged by the same method for microanalysis. The samples attained from crushing and sieving process are shown below in the **Fig.1**

Fig.1 Crushing and Sieving of samples

b. Cone and Quartering

The samples were prepared by means of cone and quartering method for optimal sample size. The sample was distributed on flat surface so that it takes on a conical shape. The top of the conical shape is flattened and the cone is divided into quarters. Two opposite quarters was discarded; the other two are combined. The process was repeated until the suitable sample size was reached. The cone and quartering process is pictured below in the **Fig. 2**

Fig 2 Cone and Quartering

B. X-Ray Diffraction Analysis

The target used in the X ray tube was copper (Cu) with the voltage 40kV and 30mA current. Scanning of sample was done at the drive axis of 2Theta with the scan range 10 to 90 degree.

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The mineral identification through XRD pattern was performed with the help of a XRD Pattern Analysis Software Package called Match! Version 2. The indexing of peaks are automatically done by the software which also shows the percentage of existence of mineral elements in the sample.

C. Scanning Electron Microscopy

The electron beam incident on the sample placed above the secondary electron detector. The SEM image was obtained for several resolution for analysis. .

These magnification of hardened cement paste helps to identify the crystal and mineral particles smaller than 5µm In this research, four resoultions were taken to observe the microstructural change in the concrete

D. Energy Dispersive Spectroscopy

SEM and EDS Analysis allows us to authenticate the firmness of the Concrete microstructure structure [9]. In EDS analysis, the elemental analysis was done in all the five samples to determine the mass percentage of the mineral elements present in the concrete. The mass percentage will give a general idea about the characteristics of each sample and also helps in modification of concrete microstructure.

V. RESULT AND DISCUSSION

A. Compressive Strength

The test was done for all the four mixes and the average value of compressive strength of concrete samples were pictured below in the **Fig.3**.

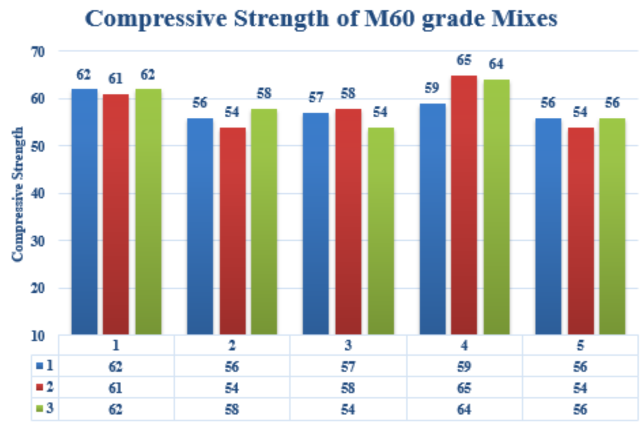

Fig.3 Result from Compressive strength Test

B. Microstructural Analysis

Microstructure of Conventional Concrete Mix (SHPC 1)

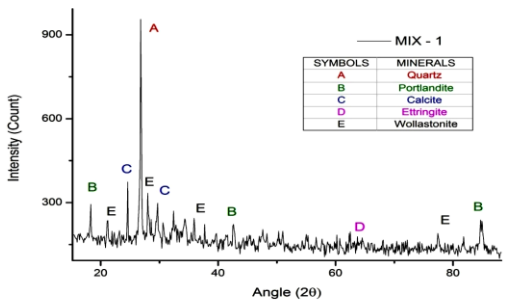

Fig.4 Peak Identifation of SHPC 1

The XRD pattern **Fig.4** highlights the presence of major hydration products of concrete such as Quartz (SiO2), Portlandite (Ca(OH)2), Calicite (CaCO3), Ettringite and Wollastonite (CaSiO3) are tagged in the Fig . The highest peak values of Quartz, Portlandite (Ca(OH)2) and Calicite (CaCO3) shown in the diffraction pattern are the major mineral elements involved in the hydration process of the concrete mix, Wollastonite (CaSiO3) present in the mix reacts with the Portlandite (Ca(OH)2) and leads to production of Calcium Silicate Hydroxide (C-S-H) which can be visualized in the SEM micrograph of Mix-1.Decomposition of C-S-H leads to development of Calcite crystals on the exterior surface of the hydrated cement paste. Some small needles like structures of Ettringite are also found on the microstructure of SHPC 1. The optimized level of development and distribution of mineral elements helps to gain the designed target strength.

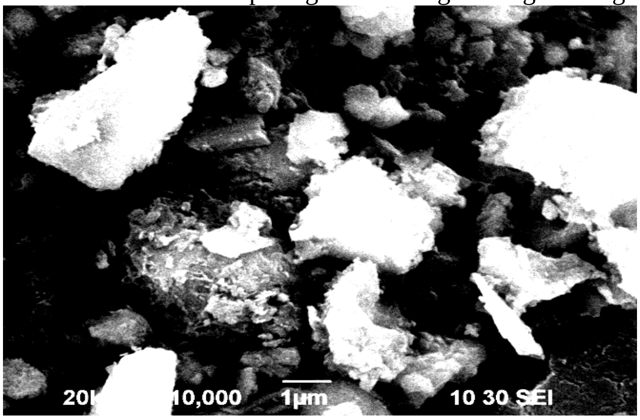

Fig.5 SEM Micrograph of SHPC 1

From this SEM Micrograph of CCM **Fig 5**, it was observed that C-S-H gel was vastly spread on the mixture of hydrated cement paste which was the main cause for the effective strength. Formation of Portlandite Ca $(OH)_2$ and Calcite $(CaCO_3)$ was visualized all over the exterior surface of hydrated cement paste. These expansion and distribution of mineral elements was one of the reasons for the effective strength of the mix. Replacement of fine aggregate with manufactured sand did not exposed any flaw in strength but, the range of distribution of minerals was changed due to replacement of fine aggregate with manufactured sand.

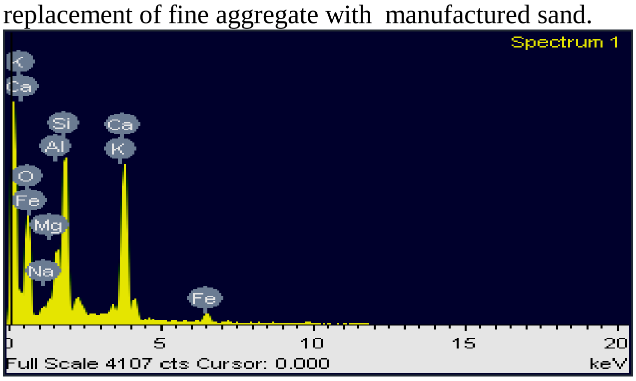

Fig.6 Elemental Analysis of SHPC 1

The elemental composition of SHPC 1 was analyzed by SEM+EDS Analysis. The chemical composition of CCM was taken from the selected target of the SEM micrograph. The spectral diagram **Fig.6** exhibits the high intensity of Silicon (Si), Calcium (Ca) and Oxygen (O) representing the presence of C-S-H gel in the mix. The weight percentage of chemical components present in the spectral diagram was shown in the

Table 4 Mineral Elements in SHPC 1

Element	*Wt (%)*
O K	52.15
Na K	0.82
Mg K	..
Al K	6.77
Si K	21.83
K K	0.89
Ca K	14.48
Fe K	3.06

Microstructure of SHPC 2

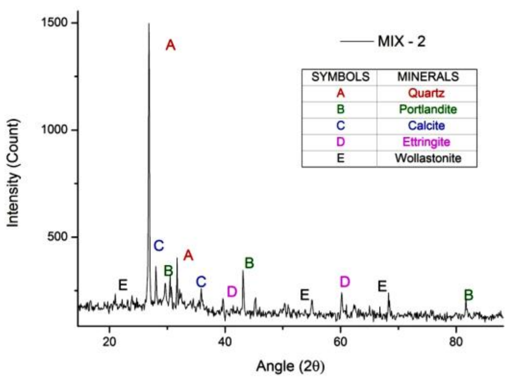

Fig 7 Peak Identifation of SHPC 2

The diffraction pattern **Fig.7** shows the development of numerous hydrated products which mainly consists of Quartz (SiO2), Portlandite (Ca(OH)2), Ettringite and Wollastonite. The highly distributed minerals in the mix were Quartz (SiO2) and Wollastonite. Other minerals are fairly dispersed in the mix which has small peaks denoted in the XRD pattern.

The silica fume and fly ash in the mix remains unreacted due to the lack of hydration of grain particles in the mix at the age of 28 days. The reaction between the wollastonite and silica phase in the mix was not performed due to the early disintegration of C-S-H as shown in the SEM micrograph.

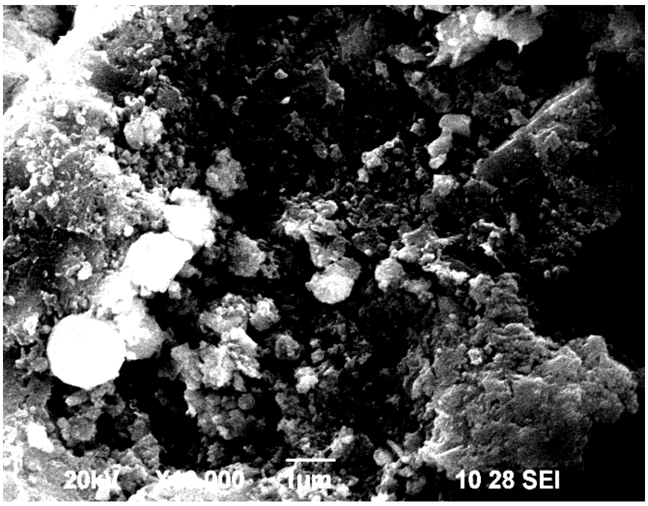

Fig.8 SEM Micrograph of SHPC 2

From the SEM micrograph **Fig.8**.of the hardened cement paste, the distribution of C-S-H was decreased at stage of 28 days due to replacement of cement with fly ash and silica fume. In this mix, the range of development of C-S-H was less which may be due to unreacted particles present in the mix. The accumulation of other major mineral elements such as Portlandite (Ca (OH) 2) and Calcite (CaCO3) crystals are minimal in the microstructure of the mix. The main reason for the decrease in strength was the lack of hydration of particles present in the hardened cement matrix.

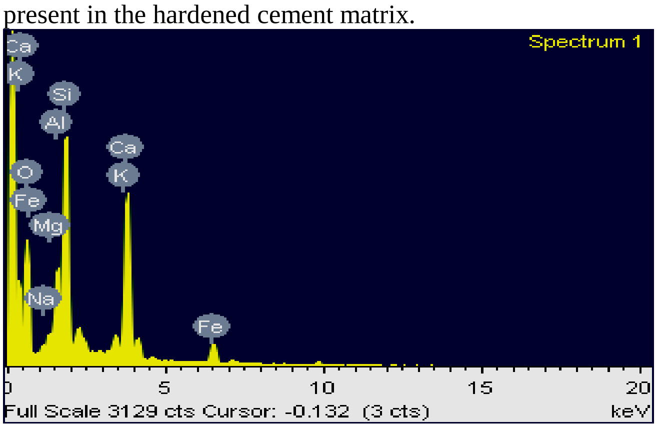

Fig.9 Elemental Analysis of SHPC 2

The spectral diagram shown in the **Fig.9** illustrates the weight percentage of minerals elements present in the blended cement matrix. In this spectral image, the range of Silicon, Calcium and Oxygen was different from the normal concrete mix which creates the complexity in developing C-S-H gel in the mix. In this mix, a small quantity of Sodium (Na), Potassium (k) and Magnesium (Mg) are also formed during the hydration process which also affects the development of C-S-H gel in the mix.

Table 5 Mineral Elements in SHPC 2

Element	*Wt (%)*
O K	**52.07**
Na K	**0.86**
Mg K	**1.56**
Al K	**5.82**
Si K	**16.9**
K K	**1.19**
Ca K	**17.29**
Fe K	**4.3**

Microstructure of SHPC 3

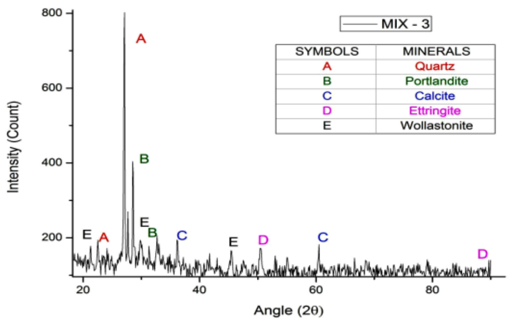

Fig.10 Peak Identifation of SHPC 3

From the interpretation of XRD pattern of SHPC 3, The diffraction pattern **Fig 10** shows the growth of major hydrated products which mainly consists of Quartz (SiO2), Portlandite (Ca(OH)2), Ettringite and Wollastonite.

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The presence of wollastonite in the mix was confirmed from the diffraction pattern which was the major mineral element helps in production of C-S-H gel. From the compressive strength test, the strength of SHPC 3 was low because of presence of amalgamated particles of aggregates and other supplementary materials such as Fly ash and Silica fume. After 28 days, the unreacted grains developed into amorphous microstructure which was indicated in the curves in the XRD pattern.

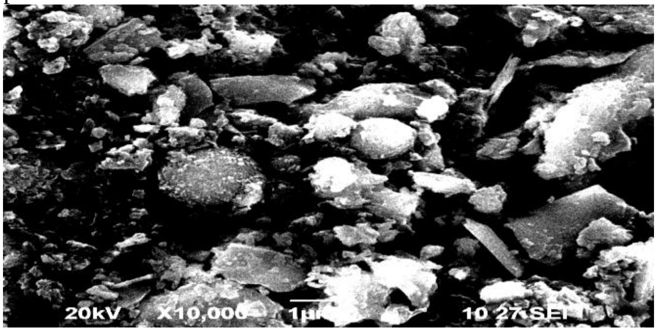

Fig.11 SEM Micrograph of SHPC 3

From the SEM micrograph of the hardened cement paste **Fig. 11**, the distribution of C-S-H was decreased at stage of 28 days due to replacement of cement with fly ash and silica fume. In this mix, the range of development of C-S-H was less which may be due to unreacted particles present in the mix.
The accumulation of other major mineral elements such as Portlandite (Ca (OH) 2) and Calcite (CaCO3) crystals are minimal in the microstructure of the mix. The main reason for the decrease in strength was the lack of hydration of particles present in the hardened cement matrix.

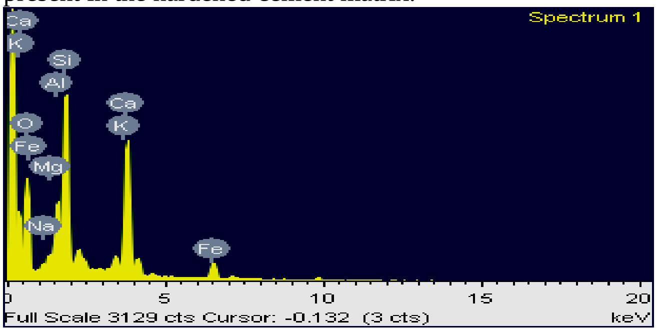

Fig.12 Elemental Analysis of SHPC 3

The spectral diagram shown in the **Fig.12** illustrates the weight percentage of minerals elements present in the blended cement matrix. In this spectral image, the range of Silicon, Calcium and Oxygen was different from the normal concrete mix which creates the complexity in developing C-S-H gel in the mix. In this mix, a small quantity of Sodium (Na), Potassium (k) and Magnesium (Mg) are also formed during the hydration process which also affects the development of C-S-H gel in the mix

Table 6 Mineral Elements in SHPC 3

Element	*Wt (%)*
O K	**52.07**
Na K	**0.86**
Mg K	**1.56**
Al K	**5.82**
Si K	**16.9**
K K	**1.19**
Ca K	**17.29**
Fe K	**4.3**

Microstructure of SHPC 4

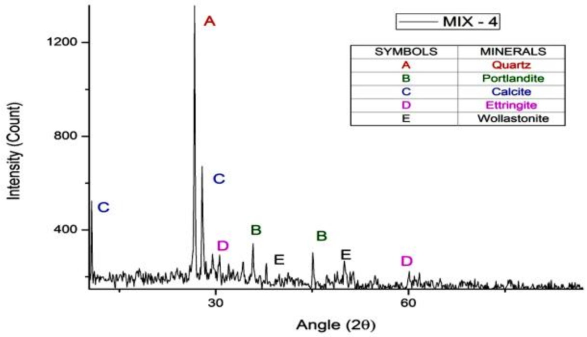

Fig.13 Peak Identification of SHPC 4

The diffraction pattern of SHPC 4 was indexed with the major hydration products such as Quartz (SiO2),Portlandite (Ca(OH)2) and Calcite (CaCO3).other minor products are Wollastonite and Ettringite. Wollastonite present in the mixture chemically reacts with Portlandite leads to development of dense C-S-H gel in the mix as shown in the **Fig.13** The additional silica content in the mix assisted the growth of substantial C-S-H production in the microstructure of SHPC 3

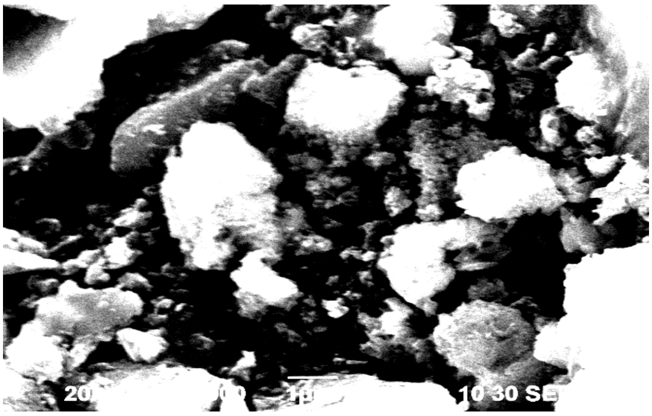
Fig.14 SEM Micrograph of SHPC 4

The SEM micrograph of SHPC 4 was shown in the **Fig.14** Considerable strength obtained in this mix was due to the pozzolanic activity of silica fume and fly ash. The reaction of silica fume and fly ash with the Portlandite (Ca (OH) 2) leads to production of surplus C-S-H gel which was the main reason for the strength of this mix. Even though the strength of concrete mix was not up the anticipated level, it reached to a considerable strength which can also be used as a replacement for the normal concrete mix in certain concreting works.

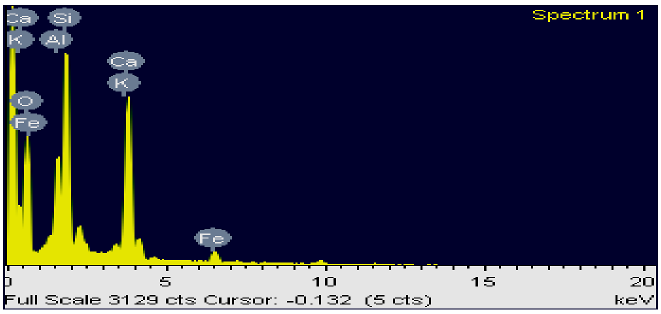

Fig.15 Elemental Analysis of SHPC 4

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The spectral graph shows the presence of high amount of Silicon (Si) and Calcium (Ca) which leads formation of huge cluster of C-S-H gel in the mix. In SHPC 4, the presence of other small hydrated products such as Magnesium (Mg) and Sodium (Na) are not evidenced in the spectral image of Mix-4.Iron (Fe) and Potassium (K) contents are minimal in quantity which did showed some effect on the strength and microstructure of SHPC 4.

Due to mild consumption silica content in the mix, the microstructure behavior of the mix gets distorted and leads to development in strength of mix. The elemental analysis showed that the presence of chemical elements in the mix undergoes exothermic reaction and results in development of hydration products such as Portlandite, Quartz, Calcite and Ettringite.

Table 7 Mineral Elements in SHPC 4

Element	*Wt (%)*
O K	**55.82**
Na K	**..**
Mg K	**..**
Al K	**6.81**
i K	**16.43**
K K	**0.59**
Ca K	**17.78**
Fe K	**2.57**

Microstructure of SHPC 5

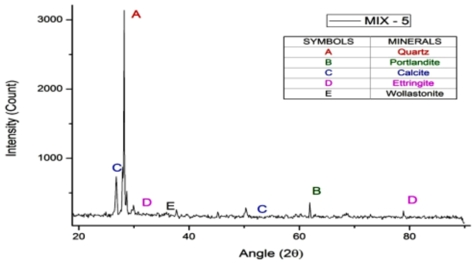

Fig.16 Peak Identifation of SHPC 5

The diffraction pattern of SHPC 4 shown in the **Fig.16** indicates the presence of major hydration products in the mix. In this mix, Quartz and Calcite are two major minerals elements present in the mix. The other small peaks labeled in the figure are Portlandite and Wollastonite. The existence of ettringite was found and visually conformed through the SEM micrograph shown in **Fig.17** The small quantity of Wollanstonite leads to reduction of development of C-S-H gel in the mix.

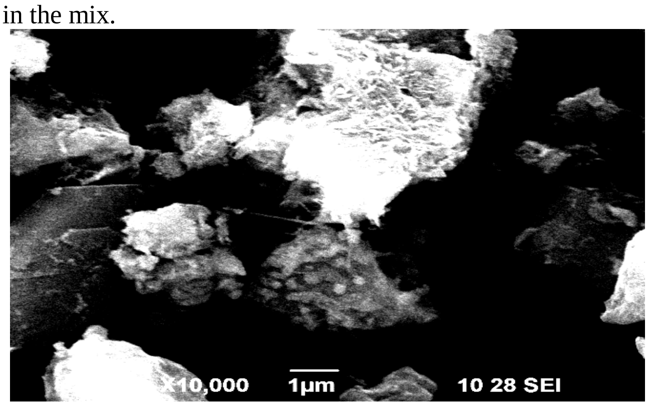

Fig.17 SEM Micrograph of SHPC 5

In SHPC 5, the rate of hydration was insufficient to achieve the strength of concrete due to the unreacted grains present in the hydrated cement paste. Excessive addition of Recycled aggregates in the mix makes the mix vulnerable. C-S-H formation was incomplete and lack of chemical reaction between the Portlandite (Ca (OH) 2) and silica in the silica fume and fly ash results in the inadequate strength in concrete. In the SEM micrograph, the presence of Ettringite was clearly evidenced in the micrograph which leads to reduction of development and distribution of C-S-H gel in the hardened cement paste

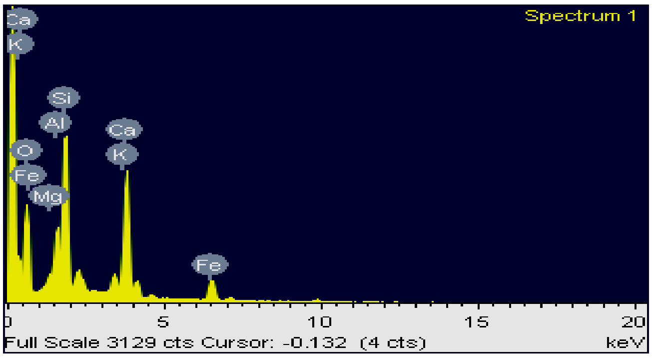

Fig.18 Elemental Analysis of SHPC 5

The Spectral diagram shown in the **Fig.18** was obtained from the particular point on the SEM image. Unlike the mixes, the presence of Calcium (Ca) ,Silicon (Si) and Oxygen (O) are quiet less. The shortage of these elements stopped the decomposition process of C-S-H gel in the mix which leads to lack of bond between the cement and aggregate interfaces. The spectral diagram also shows existence of Magnesium (Mg) and Potassium (K) which also influence the strength of the concrete mix

Table 8 Mineral Elements in SHPC 5

Element	*Wt (%)*
O K	**51.86**
Na K	**..**
Mg K	**1.42**
Al K	**5.83**
Si K	**15.97**
K K	**1.77**
Ca K	**17.02**
Fe K	**6.13**

VI. CONCLUSION

From the overall investigation,

- It was clear that the addition of cost-effective materials such as silica fume, fly ash, Recycled coarse aggregate and M-sand improved the microstructure of concrete and structural strength of concrete mixes.
- From the test results of compressive strength, it was witnessed that replacement of concrete ingredients has improved the Compressive strength on SHPC 4mix.
- Based on the comparison of the microstructure of concrete mixes, it is obvious that the formation of CSH gel was quite denser due to the reaction between CaOH and Silicon in SHPC 4 mix

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