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Performance of Ternary Blended Concrete and Binary Concrete Made with Perlite Powder at Elevated Temperatures

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ABSTRACT

Concrete is a widely known construction material that has been engineered to obtain certain desirable mechanical and durability properties. This research aims at studying the applicability of Perlite Powder (PP) as a partial replacement material of cement. Furthermore, this material possesses resistance to elevated temperatures. In the present study, the researchers has worked on two diferent types of concrete *viz.*, Ternary Blended Concrete (TBC) by partially replacing cement with PP and Silica Fume (SF) and a Binary Concrete (BC) made by replacing PP partially alone with cement. In addition to Normal Concrete (NC), different mixes were prepared by replacimg cement with 1%, 3%, 5% and 7% of PP, whereas SF with 10% is maintained constant in all TBC mixes and PP is varied from 1% to 7% with an increment of 2%. In addition to room temperature, the specimens were exposed to different elevated temperatures, such as 200°C, 400°C, 600°C and 800°C, respectively. Experimental studies, like compression test, XRD, SEM, EDAX and TGA-DTA analyses, were conducted. The results of these experiments concluded BC with 5% replacement of PP to possess maximum strength as well as better thermal properties.

KEYWORDS: Silica fume, Perlite powder, Elevated temperatures, XRD analysis, SEM, EDAX analysis, TG-DTA.

INTRODUCTION

Natural disasters are of different types and among them fire accidents take the top position occurring episodically all over the world. These are due to man-made and natural causes that lead to human life and property loss. Lots of changes are observed over the years, due to advancement in materials and construction technology and huge investments are being made in construction industry. Due to exposure of elevated temperatures, everything is crumbling out, which leads to heavy economic loss. Depending on the high intensity of temperatures to which structures are exposed, they result in different kinds of failure. Further, their failure types are associated with both short-term and long-term strength effects (Ruan, Z. et al., 2015).

Normally, concrete mixes can be prepared by partially replacing cement with different recycled materials, such as sugarcane bagasse ash, fly ash, metakaolin, … etc. These materials can be used as fillers, thereby resulting in reduction of porosity. Also, they have the tendency to hydrate by reacting with $Ca(OH)_2$. Apart from these, a very lightweight material; namely, PP attained from volcanic rocks (Celik et al., 2013) can also be used in making concrete. In previous research, PP has been overwhelmingly utilized as a Fine Aggregate (FA) replacement so as to make lightweight concrete, while very little work has been found in the literature regarding its utilization as cement replacement. PP holds good pozzolanic properties. Its chemical composition stands with 70-73% of SiO_2, 12-15% of Al_2O_3 and small fractions of feldspar, quartz and illite. Yet, another exceptional property of perlite is that when it gets heated to temparatures above 800˚C, it expands up to multiple times of its original volume (Chandra, 2002; Topçu, 2008).

Due to multitudes of advantages of PP, it could be

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used as a cement replacement material. Intergrinding of cement and PP is consistent and consumes less energy to convert it into a binary form (Yu, 2003; Erdem et al., 2007). PP containing countless pores with different sizes can be used for high-temperature applications, which will allow transmitting of heat and sound (Celik et al., 2013). The low thermal conductivity of PP reduces the temperature level and lets structures resist damages (Demirboğa et al., 2003; Dubé et al., 1992). The presence of voids in concrete is the basic reason for the reduction of strength properties at elevated temperatures (Tufail, 2017). The presense of porosity will also affect the thermal conductivity of concrete by encasing the pores, whereas perlite helps reduce it (Demirboğa et al., 2003). If the voids present in terms of both size and number in the concrete are reduced, strength would increase. This is because of void covering with admixtures which maintain the bonding between the aggregates and the matrices undamaged (Tjaronge, 2015).

A study of microstructue analysis is esssential to find out the minerals present in concrete and the reasons behind the behaviour of concrete. Among the various techniques used to study the microstructure of concrete are X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Thermo-gravitometric Analysis (TGA) analysis, which represent some of the tests that can be used to find out the phases present in the samples. XRD analysis has revealed minerals, like quartz, feldspar, ettringite, sodium hydroxide and aluminium tri-oxide, among others, which proves that perlite is compatible with concrete (Tufail, 2017; Barnat-Hunek, 2018; Celik et al., 2013). In SEM-analysis, we can find the glassy porous and crystal-like structures (Tufail, 2017; Demirboğa et al., 2003; Barnat-Hunek, 2018). TG-DTA analysis shows that perlite has a very minute weight loss at high temperatures, which reveals that perlite can be used even at high temperatures (Tufail, 2017; Dubé et al., 1992; Celik et al., 2013).

From the foregoing discussion, it is distinctly justified that perlite can be used as a construction material and it has a superior capability of resisting elevated temperatures. In the present research, the authors have prepared two different concrete types; namely, Binary Concrete (BC) by cement partially replaced with PP and Ternary Blended Concrete (TBC) by replacing cement with PP and Silica Fume (SF), both at different proportions. Later, they experimentally tested the mechanical properties of BC and TBC by exposing them to elevated temperatures. Various tests, like compression, porosity and microstructure analysis, were carried out so as to study the mechanical, durability and internal behaviours of concrete.

MATERIALS

According to the Indian Code of Standards, material selection has been done for the entire work. Ordinary Portland Cement (OPC) with a normal consistency of 29% and a specific gravity of 3.09 was used. River sand with a maximum size of 4.75mm, fineness modulus of 2.69 and water absorption of 4.16% was identified as FA. Coarse Aggregate (CA) with fineness modulus of 7.03 and water absorption of 0.201% was used. Tap water with a pH of 7 available in the structural laboratory was used for the research and special care has been taken to preserve all the materials in safe conditions.

PP and SF have also been used as partial replacement materials of cement. PP of white color has been used in the experiments. The physical properties of PP include thermal conductivity of 0.040 w/m^2 K at a temperature of 0°C and bulk density of 40-50 kg/m^3. Moisture content and organic content of PP were upto 0.5% and 0.1%, respectively. The chemical properties of PP are listed in Table 1.

SF with white color was obtained as a by-product of silicon and ferro-silicon production process. The physical properties of SF include specific gravity of 2.26, pH value of 6.9 and moisture content of 0.057%. The chemical properties of SF are listed in Table 2.

Table 1. Chemical properties of perlite powder

Chemical Composition	SiO_2	Al_2O_3	Na_2O	K_2O	MgO	CaO	Fe_2O_3
Content in %	71–76	12–16	2–6	2 –5	0.1–1.0	0.5–2.5	0.5–1.5

Table 2. Chemical properties of silica fume

Chemical Composition	SiO_2	Al_2O_3	Na_2O	TiO_2	CaO	Fe_2O_3	LOI
Content in %	93.04	0.043	0.003	0.001	0.001	0.44	2.240

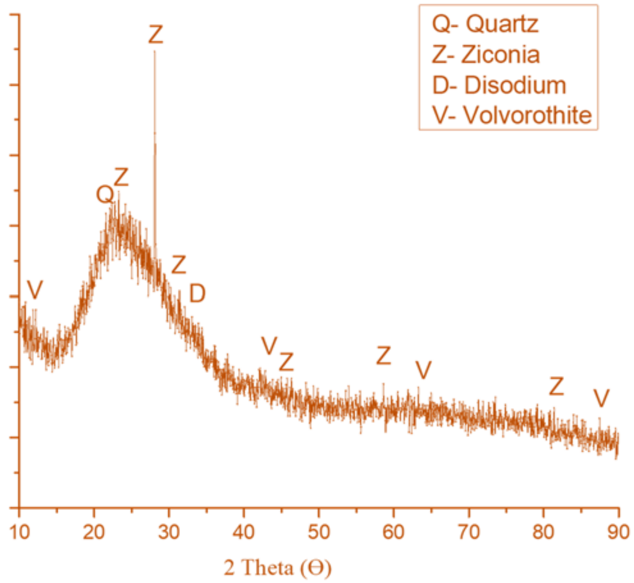


Figure (1): XRD-analysis of PP used in the research

XRD analysis was conducted for identifying the mineral composition of PP. Fig. 1 shows the XRD pattern of perlite used in the research. Quartz (Q) is the most common mineral composed of crystalline SiO_2. Other minerals, such as zirconium (Z), disodium (D) and volborthite (V), were involved. During the hydration process, disodium not only prevents the mix from corrosion, but also displays hydrophobic properties that prevent the moisture from entering into concrete. The amorphous form irregular in shape will be SF which helps in increasing strength.

EXPERIMENTAL PROCEDURE

For this research, M30 grade concrete has been designed according to Indian Standard (IS) code 10262-2009. The quantities of materials required for the various TBC and BC mixes are illustrated in Table 3.

Table 3. Mix proportions of TBC and BC conforming to IS: 10262:2009

Mix no.	TBC				BC			F.A. (kg/m^3)	C.A. (kg/m^3)	Water (litres)
	Concrete mix	Cement (kg/m^3)	PP (kg/m^3)	SF (kg/m^3)	Mix Type	Cement (kg/m^3)	PP (kg/m^3)			
1	NC	438.35	0.00	0.00	NC	438.35	0.00	718.47	1123.77	188.49
2	1PP10SF	390.57	3.94	43.83	1PP	433.97	4.38	718.47	1123.77	188.49
3	3PP10SF	382.68	11.83	43.83	3PP	425.20	13.15	718.47	1123.77	188.49
4	5PP10SF	374.79	19.72	43.83	5PP	416.43	21.92	718.47	1123.77	188.49
5	7PP10SF	366.91	27.61	43.83	7PP	407.66	30.68	718.47	1123.77	188.49

The mix proportions of concrete thus arrived at were 1:1.63:2.55 with a W/C ratio of 0.43. A total of 5 sets each for TBC and BC mix proportions were prepared, one among them being Normal Concrete (NC) which is the same for both proportions. The other four mix proportions of TBC were made by partially replacing cement with SF and PP by uniform mixing to make a homogeneous mix. The TBC mixes were named as mentioned in Table 3, by signifying 10% of SF in each of them along with percentages of PP, respectively. For BC, cement is partially replaced with 1%, 3%, 5% and 7% of PP. The mixes were respectively named as 1PP, 3PP, 5PP and 7PP.

For finding the compressive strength of the various concrete mixes, a total of 150 cube specimens with dimensions of (10x10x10) cm were used. Casting of the cubes was carried out by filling the concrete into the moulds. During the casting process, care is taken while placing and transporting the mixes. Specimens were demoulded after 24 hours and immersed in a curing tank for a period of 28 days. To keep away external factors, like development of fungi, water was renewed for each seven days. After the age of 28 days, the specimens were taken out and kept for complete drying for a couple of hours and then their weights were recorded.

Later, they were exposed to different elevated temperatures of 200°C, 400°C, 600°C and 800°C in a bogie furnace for one hour after reaching the target temperature. The target temperatures of 200°C and 400°C were attained in half an hour and the same was carried out for the target temperature of 600°C, but in one hour. The highest temperature; i.e., 800°C was accomplished in one hour and 20 minutes. The rates of heating at different temperatures that were recorded in the bogie furnace are graphically represented in Figure 4.

Figure (2): Specimens kept at elevated temperatures

Figure (3): Compressive strength test

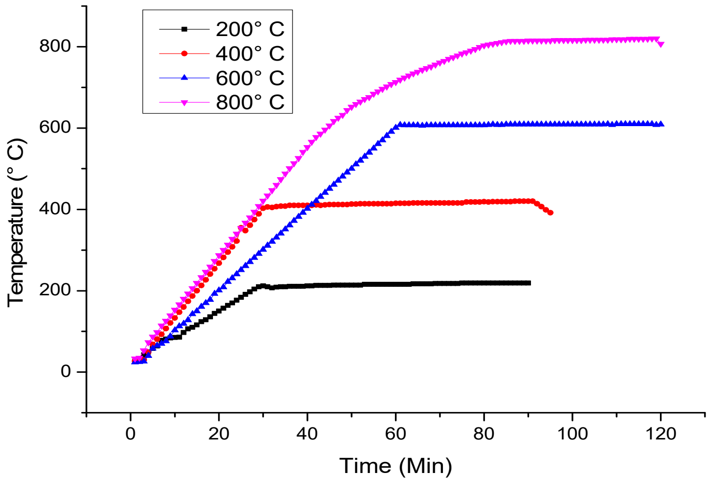


Figure (4): Time-temperature curve

Later, when the specimens were taken out of the furnace, they were left for air-cooling to bring them down to room temperature. Thereafter, strength tests were performed on the specimens.

RESULTS AND DISCUSSION

Weight Loss vs. Compressive Strength

From Fig. 5, it is evident that the unit weight of concrete specimens varies from 2836 kg/m^3 to 2344 kg/m^3 for TBC, whereas the unit weight recorded for BC is between 2836 kg/m^3 and 2388 kg/m^3 and these values are less compared to NC. The values varied for the specimens with 0% to 7% of perlite, with a reduction percentage of 21.3%. This shows the tiny nature of perlite that helps change the internal pore structure of concrete.

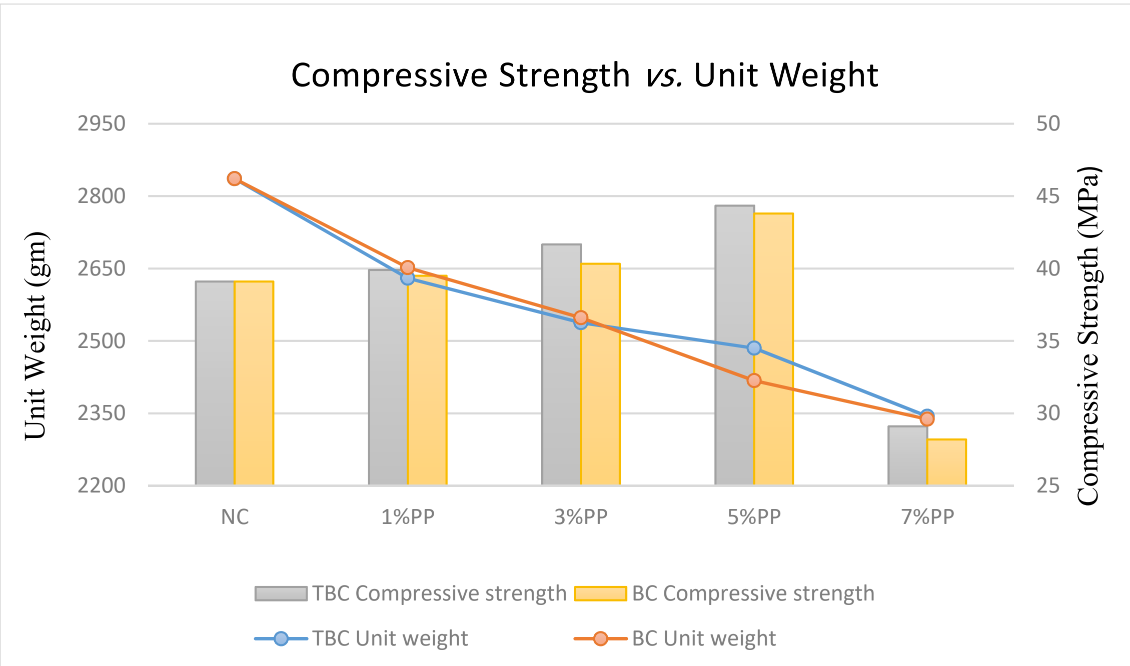


Figure (5): Compressive strength *vs.* unit weight

Usually, weight loss would adversly affect the strength of concrete, whereas in this case, the reduction in weight tends to enhance the compressive strength of PP upto 5% and thereafter there is a sudden fall in strength. This is because of the increased volume of PP in 7% replacement. In Fig. 5, the marked lines indicate unit weight and the customed columns indicate compressive strength. It is evident that the decrease in unit weight of both TBC and BC is helpful to concrete to reduce the stresses produced due to seismic load in the internal structural elements (Barnat-Hunek et al., 2018).

Compressive Strength

The compressive strength test for TBC and BC mixes was carried out according to IS: 516-2008. Fig. 6 gives the graphical illustration of compressive strength of concrete.

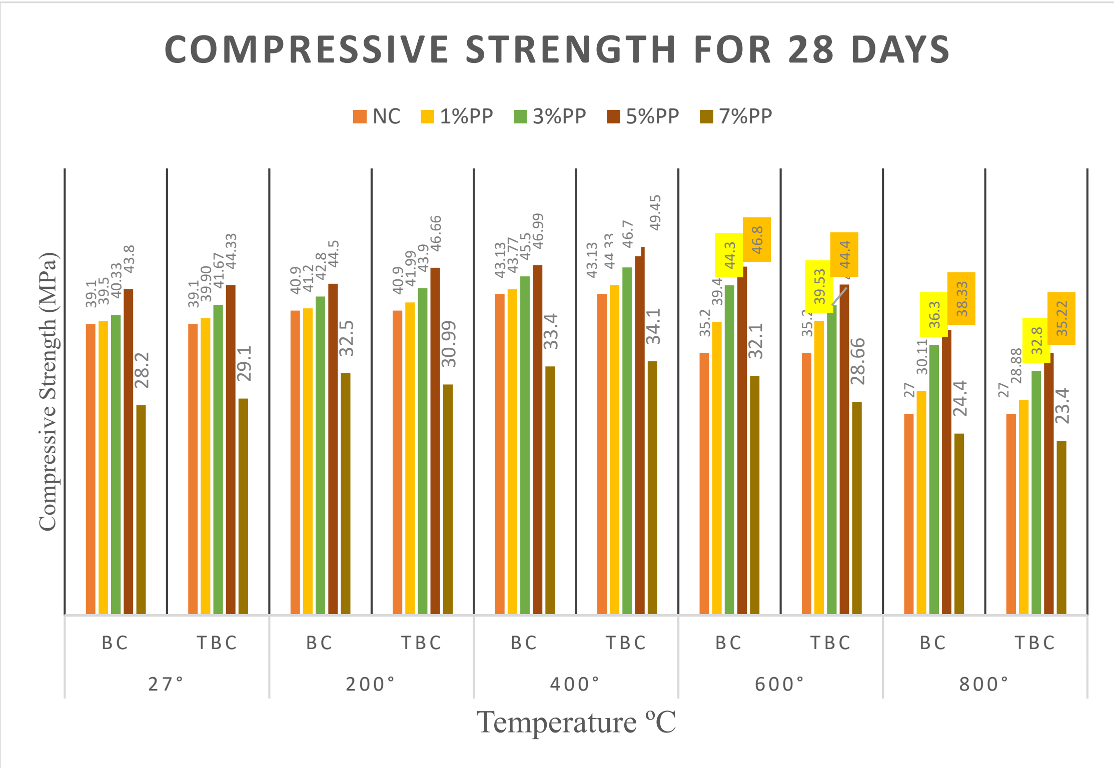


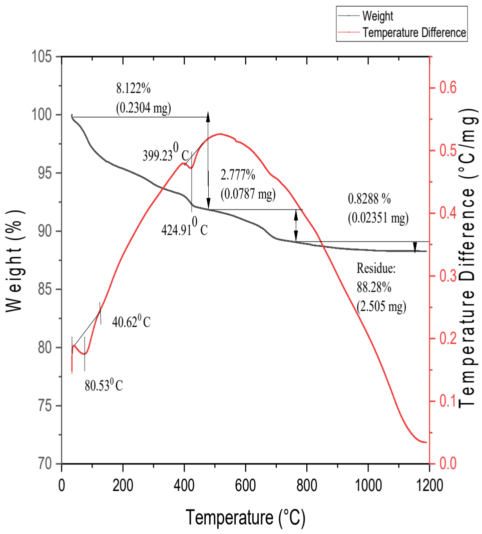
Figure (6): Compressive strength of binary concrete

PP has a notable influence on the compressive strength of concrete. It is observed that for the TBC mixes, the highest strength was recorded at 400˚C which is greater than in BC mixes. Beyond 400 ˚C, the strength tends to decrease, but it shows values almost equal to those in NC. In BC mixes, NC and 1%PP mixes, the highest strength was recorded at 400˚C. From 3%PP onwards, the highest strength was recorded at 600˚C; i.e., greater than in TBC. This is attributed to that SF in TBC after 400˚C does not show much reaction with PP. Bastami et al. (2011) concluded that SF does not affect the strength at higher temperatures, but it controls the spalling ratio.

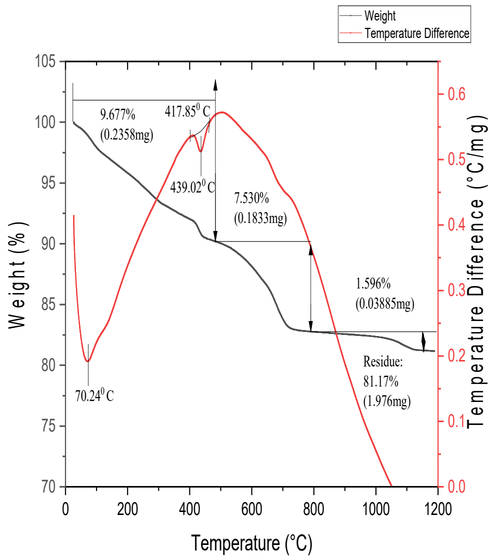
The increase of strength at different elevated temperatures is explained as follows: up to 200˚C, the un-hydrated cement paste is heated up and the water content present will be removed and the forces between the gel particles increase, thereby leading to an increase in compressive strength. Beyond 200˚C, water in the inner layer C-S-H gel and some chemically-combined water present in both sulfo-aluminate hydrates and C-S-H gel would be lost. Further, after 400˚C, strength decreases due to loss of water from the gel pores. Further, at 600˚C and beyond that, the dehydration of cement paste starts and causes loss of strength.

TG-DTA Analysis

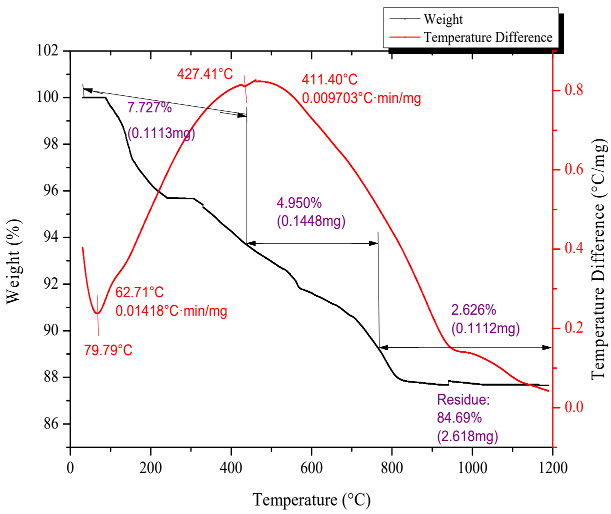
The weight loss of NC mix, 5PP10SF and 5PP samples was identified by analyzing them with SDT Q600 instrument with Version 20.9, Build 20 by using the ramp method. The sample was placed at a range of temperatures from 0°C to 1200°C in steps of 20°C/min. By increasing the temperature, all the specimens exhibit weight loss as expected. The temperature range is divided into 3 different phases as shown in Fig 7; the temperature range from 0˚C to 475 ˚C belongs to the first phase, while the second phase extends from 475˚C to 750˚C and the third phase extends from 750˚C to 1200˚C.



a) Normal Concrete



b) 5PP10SF TBC Mix



c) 5PP Binary Concrete Mix

Figure (7): TG-DTA graphs

The percentage weight loss for NC in the corresponding 3 phases was recorded as 8.122%, 2.777% and 0.828%, respectively, while for the TBC 5PP10SF mix, the same were noted as 9.677%, 7.530% and 1.596%, whereas for the BC 5PP mix, the percentage weight loss was recorded as 7.727%, 4.950% and 2.626%, respectively. Due to the replacement of cement with perlite, the weight loss is exhibited more in the 5%PP mix for both TBC and BC compared to NC.

From Fig. 7(b), at the initial stage, the weight loss peak was observed below 200°C, which corresponds to the dehydration reactions of C-S-H, mono-sulfoaluminate, gehlenite and ettringite. In the second phase, the weight loss peak was observed in 5PP10SF mix at the temperature range from 400°C to 600°C. This was due to the dehydration of portlandite $Ca(OH)_2$ (Xu, 1992). In the third phase, the weight loss has reduced and thereafter it almost vanished.

Similarly, in the case of 5PP from fig 7(c), the same was recorded as 7.727%, 4.950% and 2.626%. At the initial stage, the weight loss peak occurred below 200°C, which corresponds to the dehydration reactions of C-S-H, mono-sulfoaluminate, gehlenite and ettringite. In the second phase, the weight loss peak, observed in 5PP mix at temperatures from 400°C to 700°C, was due to the dehydration of portlandite $Ca(OH)_2$. In the third phase, the weight loss got reduced and thereafter it almost vanished. The weight loss of 5BC mix is slightly more compared to that of NC, which is due to the absence of $CaCO_3$, which was shown in the EDAX graph. The weight loss observed in NC and perlite- incorporated concrete is because of the difference in the pore structure of the specimens, thereby showing that an increase in the perlite percentage increases the weight loss of the concrete sample.

In Fig. 7, black and red lines indicate the weight percentage and temperature run of the sample on the instrument. For NC mix, two exothermic peaks were identified at temperature levels of 80.53°C and 424.91°C. These are formed because of the reversible reaction of organic compounds such as silver sulphate and 4-Nitrotoluene Biphenyl Naphthalene, respectively. The evaporation of extra water present in the mix is the reason for the formation of initial reaction (Abdulkareem, 2014). Further, the second exothermic reaction was found because of the initial and regular destruction of the matrix as a result of decrease in water content.

For the replacement of 5% PP in TBC mix, the initial exothermic peak is formed at 70.24°C and the second peak was formed at 439.02°C. The initial peak is formed due to the melting of 4-Nitrotoluene Biphenyl Naphthalene and the second was formed because of the reversible reaction of silver sulphate. The formation of these peaks is due to the dehydration of CO_2 in the internal structure which is caused by heat consumption of the sample (Mackenzie, 1970).

From Fig. 7(c), for 5PP BC mix, two exothermic peaks were observed, the first one at 79.79°C because of melting of 4-Nitrotoluene Biphenyl Naphthalene, followed by the second exothermic peak observed at 427.41°C due to the reverse reaction of silver sulphate. The number of peaks formed in both the samples was less, but compared to NC, the sudden fall in the temperature due to the melting points observed in 5PP was less, which shows that the mix with PP has a good flow. The formation of these peaks is due to the dehydration of CO_2 in the internal structure (Mackenzie, 1970).

XRD-Analysis

The XRD analysis was carried out to find out the internal microstructure of concrete and the graphs for various mixes of concrete are given in Fig. (8).

From Fig. 8, it is evident that the highest peaks in both NC, TBC and BC mixes were noticed for quartz which is formed by the reaction of cement and water. It helps in accomplishing more strength, since it reacts with excess calcium hydroxide. Later, ettringite was formed during the initial stage, which in turn got converted into calcium aluminate sulphate. Wollostonite- which contains more silica - also formed and reacted with water to form Calcium-Silicate-Hydrate (CSH). The quantity of CSH gel formed in BC 5PP mix was more compared to NC, which can clearly be observed from Fig. 8 (a) and Fig 8 (b), whereas from Fig. 8(c), in TBC 5PP10SF mix, the presence of rubidium in abundance is because of the existence of perlite in the mix; subsequently it was obtained from the earth crust. Furthermore, it is evident that the substantial characteristic of this mineral is that at high temperatures, it becomes a major reactive element. Another mineral named berlinite is found, which has superior thermal properties; hence, this also can be attributed due to the existence of PP present in the mix.

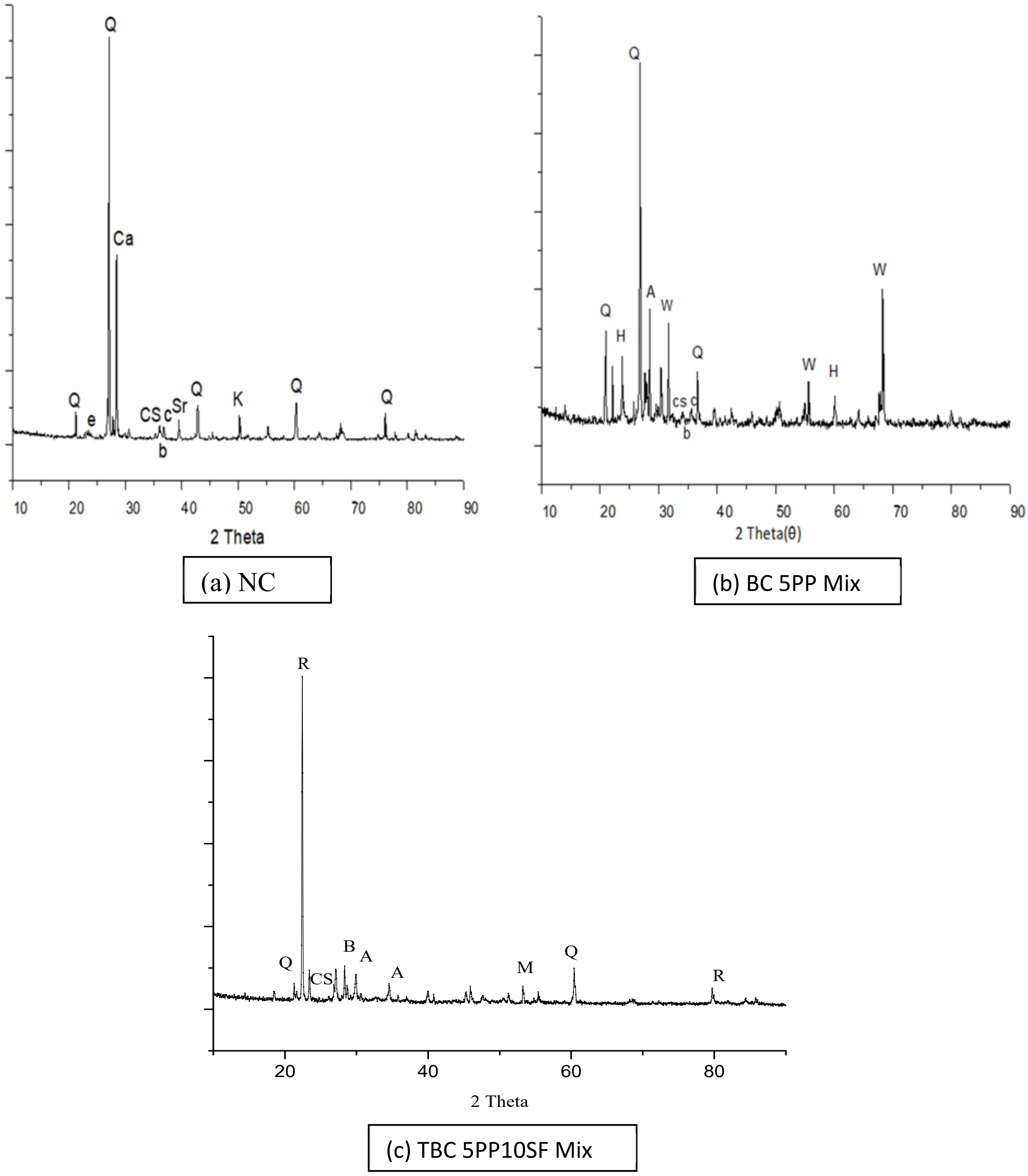


Figure (8): XRD graphs (Q-Quartz, E-Ettringite, C-Calcite, b- Belite, CS-CSH gel, W- Wollostonite, K-Potassium, H- Hauyne, A-Albite, B- Bernilite, M- Molybdenium tri-fluoride, A- Ammonia, R- Rubidium)

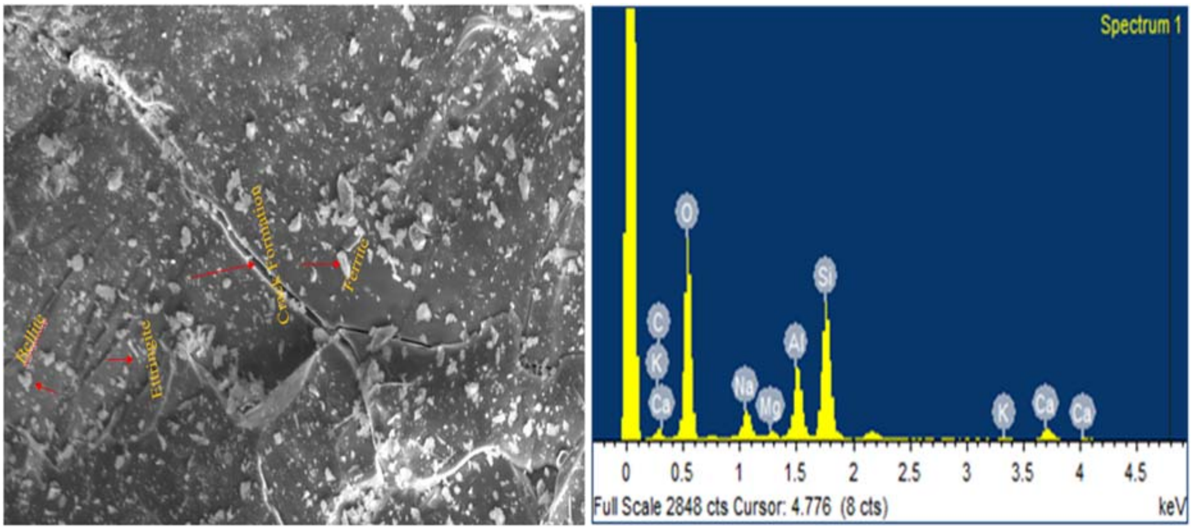


Figure (9): SEM and EDAX analysis of TBC-5PP10SF mix

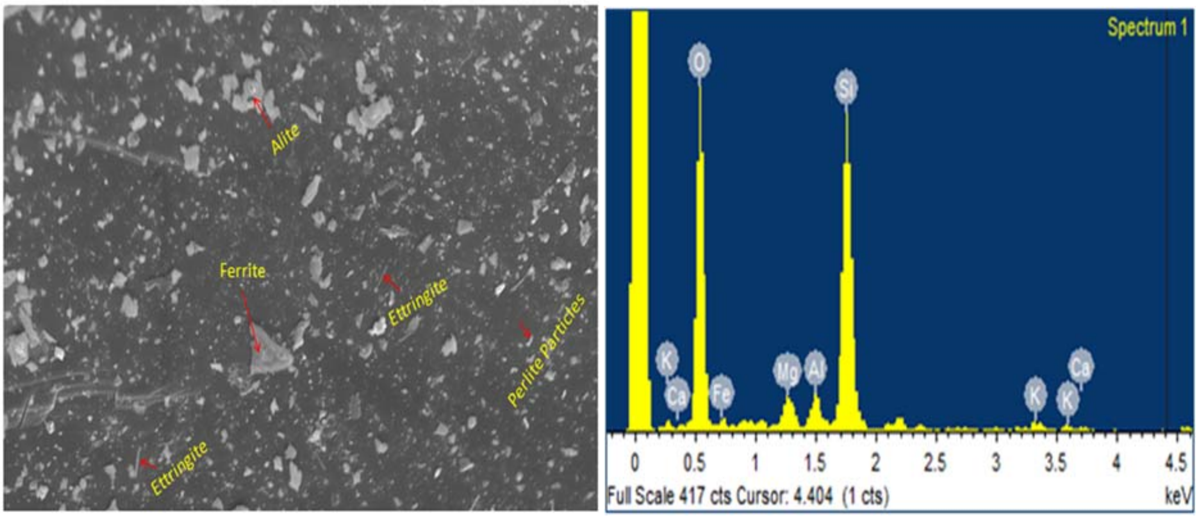


Figure (10): SEM and EDAX analysis of BC-5PP mix

SEM Analysis

The results of SEM for the NC and for the BC-5PP mix are depicted in Fig. 9 and Fig.10, respectively. From Fig. 9 (a), the formation of pores and fractured plates are clearly observed; the EDAX graph in Fig. 9 (b) shows the highest amount of SiO_2 which plays a major role in the hydration process and strength development. In Fig. 10 (a), it is clearly observed that there is a presence of minerals such as ferrite, alite and ettringite. In Fig. 10 (b), the peaks of SiO_2 were much higher compared to those of normal concrete. An increase in the content of SiO_2 is responsible for the better strength in the 5PP concrete mix.

In the case of normal concrete, the EDAX graph shows compounds/minerals like $CaCO_3$, SiO_2, albite, Mg, Al_2O_3, feldspar and wollostonite; the same compounds exist in 5PP too, except for $CaCO_3$, in addition to that a new mineral; namely, Fe, also existed. $CaCO_3$ in 5PP mix acts as an inert filler and helps act as a nucleation position for cement hydrates. It further helps speed-up the setting reaction time and strength development (Matschei et al., 2007). Because of having finer-grained phases, such as ferrite, the reaction between cement materials gave better performance for the 5PP mix. Ferrite is formed in good quantities at the early age of hydration and later it slows down because it acts as a barrier that prevents further hydration (Stutzman, 2004; Landa-Cánovas, 1999).

CONCLUSIONS

Unit weight of concrete has decreased by 21.3% for TBC and 13.69% for BC, from 0% to 7% replacement of cement with PP, whereas strength has been enhanced by decreasing the weight. However, for mixes up to 5% PP, strength has shown a gradual increase, showing that 5% of PP is the most ideal level of replacement. Further increase in PP up to 7% resulted in a sudden strength fall.

The test results on compressive strength shed light on various conclusions for TBC. Firstly, for temperatures up to 400°C, both normal and PP-added concrete mixes have shown an increase in strength; so, it may be presumed that a rise in temperature up to 400°C is indeed an advantageous factor. Secondly, irrespective of temperatures, replacement of 5PP10SF mix has shown the highest strength, whereas increase in PP beyond this percentage showed deterioration in strength. From the above observations, it could be concluded that 5% is the optimal replacement level for PP. Thirdly, at 600°C, for all PP replacements, strength has a value which is almost near to that at room temperature. This leads to the conclusion that addition of perlite helps retain its compressive strength at room temperature and even at a temperature as high as 600°C.

Compressive strength of binary concrete shows comparatively better results than normal concrete. At 5PP, the highest strength has been achieved compared to other replacement levels. Later, at elevated temperatures, for mixes with up to 1PP, the maximum strength was obtained at 400°C, whereas for 3% replacement, the highest strength was observed at 600°C. The increase in strength at 600°C is due to the increase in the PP content and hence, it may be concluded that a rise in temperature up to 600°C is certainly an advantageous factor for the replacement level of 5PP, while there is a deterioration in strength thereafter. From this, it could be inferred that 5% is the optimal replacement level for PP.

XRD analysis shows the minerals that formed during the hydration process. Quartz is the mineral which shows the highest peak in both NC and 5PP mixes. The formation of ettringite is at the initial stage and wolostonite containing more silica reacted with water to form CSH. SEM analysis clearly shows that a decrease in the number of pores in the 5PP mix is because of the addition of PP. The formation of an extra element with fine-grained phases such as ferrite in the 5PP mix is shown in the EDAX analysis to help in achieving better performance of the hydration process.

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