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Determination of lightweight foamed concrete thermal properties integrating various additives

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ABSTRACT

This paper reports the study carried out to examine the thermal properties of lightweight foamed concrete (LFC) integrating various additives. Various densities of LFC samples ranging from 600, 1000 and 1400 kg/m^3 with constant cement-sand ratio of 1:1.5 and water-cement ratio of 0.45 were produced. Fly ash, lime and polypropylene fiber with different percentages were used as additives. The main purpose of this study is to explore the effect and divergence of reaction on each additive that influences the thermal properties of LFC. Detail experiments were setup to study the behavior and reaction of additives which is expected to give different results on thermal properties of LFC. Each additive has different properties and reaction which will impinge on the thermal properties of LFC. The reaction during the hydration process is significant to be examined seeing that it will create complex particle that results in different microstructure formation. Detail observation by using scanning electron microscopy (SEM) will provide better understanding on thermal properties that is influenced by microstructure formation, moisture content and porosity of LFC. Experimental results show that lower density LFC translates to lower thermal conductivity. The density of LFC is controlled by the porosity where lower density LFC indicates greater porosity thus thermal conductivity changes significantly with the porosity of LFC because air is the poorest conductor compared to solid and liquid due to its molecular structure.

Introduction

Thermal conductivity, *k*, is the progression of the conduction of high-temperature thermal energy within an object or between two objects in contact, which lowers the temperature. In physics, thermal conductivity, *k*, is the property of a material describing its ability to conduct heat. It appears principally in Fourier's Law for heat conduction. When an object is heated, the vibration of the molecules or atoms and the floating of free electrons discharge thermal energy to the lower temperatures in the course of kinetic energy conduction.

According to molecular dynamics, an object's temperature is in a direct proportion to the mean kinetic energy of its composition [1]. Thermal conductivity (W/m K) is the result of thermal diffusivity (cm^2/s), specific heat (J/g K) and density [2] and is influenced by its own mineral characteristics, pore structure, chemical composition, moisture and temperature. The energy performance of a building greatly depends on the thermal conductivity of the building materials which depicts the capability of heat to flow across the material in the presence of a differential temperature [3].

Hence, the use of low thermal conductivity building materials is important to decrease heat gain through the envelope into the building in hot climate country like Malaysia. LFC has been acknowledged for its superior performance in thermal insulation and sound insulation characteristics due to its cellular microstructure. LFC is produced by mixing cement and sand as slurry with foam. The slurry or mortars which will entrap air-voids produce the LFC. The bubbles will create pore and give different microstructure formation that affect the properties of LFC. LFC can be classified as material with porous characteristic. LFC gives many advantages such as good in thermal and acoustic insulation, easy to fabricate, self flowing ability and others. LFC could be used as one of important construction material with consideration on sustainability for the future. LFC can contribute more to improve our construction industries with latest innovation. Nowadays, LFC is extensively used as filler material and small scale product for building material. Compared to normal concrete, LFC give low mechanical properties that is not suitable for high rise construction. Although the LFC is weak in mechanical properties, it still can be used as partition or light load bearing walls for low rise residential construction. The LFC properties can be improve by using suitable additives. Fly ash, lime and polypropylene fiber with different percentage was used in this study. Each type of materials has their own behavior which will give different effect on the properties of LFC.

The thermal conductivity of LFC typically is 5 to 30% of that of normal weight concrete and range from between 0.1 and 0.7 W/mK for dry density values of 600 to 1600 kg/m^3 respectively [4,5]. In practical terms normal weight concrete would have to be 5 times thicker than LFC ones to achieve similar thermal insulation [6]. The thermal conductivity of LFC with 1000 kg/m^3 density is reported to be one-sixth the value of typical cement-sand mortar [7]. Since LFC is produced by injecting air into a cement based mixture, the density of LFC is directly a function of the air inside LFC. Expectedly, the density of LFC should play an important role in determining its thermal properties.

To date, thermal properties have been one of the most important topics to be studied but there is lack of research to

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look into the effect of additives on the thermal properties of LFC. Detailed investigation will be done to examine thermal properties of LFC. This paper reports the results of an experimental investigation on thermal properties of LFC with different densities and additives.

Material and Mix Proportion

In order to manufacture LFC, appropriate supervision is needed as the mix will be affected by many factors. Materials such as cement and sand need to be chosen with careful consideration of many factors taken into account. The foaming agent is another important material as the properties of foam such as stability, density and flow ability need to be addressed. All of the materials used were produced locally in Malaysia.

As mentioned earlier, the main objectives of this study are to determine the thermal conductivity of LFC at ambient temperature hence only a constant cement-sand ratio of 1:1.5 and water-cement ratio of 0.45 will be used for all batches of LFC samples made for this study. A water-cement ratio of 0.45 was found acceptable to accomplish sufficient workability [9]. Three densities of 600, 1000 and 1400 kg/m^3 densities were cast and tested. Mix proportion of LFC with different densities and additives shown in Table 1. Below are detailed descriptions of the material and mixture proportions used in this experiment.

Ordinary Portland cement and fine sand

The Cement used in this study is an Ordinary Portland Cement (OPC) from Cement Industries of Malaysia Berhad (CIMA Group) labelled “Blue lion.” The cement is classified as MS 522, as well as BSEN 196. The product is available in 50 kilogram bags in bulk form. Fine inorganic material will form a paste after water is added into the mix.

Foam

The protein foaming agent was used, known as “NORAITE PA-1,” was also manufactured in Malaysia. The foaming agent was diluted in water with a ratio of 1:33 by water volume. The foam density needed to be between 75 to 80 g/L before being mixed with other materials. Flow ability times are also calculated as the time will be used as a reference to add the required amount of foam into the mix. The flow ability, known as flow rate, usually valued between 2.3 to 2.7 litres per second to achieve 75 to 80 g/L density of the foam depended on the foam machine used. The density of LFC was determined by the volume of foam added for certain mixes. The stability of the foam is important in producing LFC. A foaming generator will act as a medium to transfer the chemical into stable foam. TM1 that was supplied by DRN resources was used as a foaming generator in this study. This type of foaming generator has a mixing capacity of up to 7m^3 of lightweight foamed concrete per day.

Additives

Each of the additives used has its own properties that will give different results and reactions. In this experimental investigation, additives were used with different percentages. The latest concrete technology has urged and awakened people to the use additives in the production of concrete. The sustainability advantage to the properties of concrete is essential to date. Fly ash, lime and polypropylene fibre were used with different percentages. Table 2 gives detailed properties and specifications on each material used in this experimental investigation.

Experimental Program

Thermal properties of LFC were measured by using hot disk thermal constant analyzer. Hot disk thermal constant analyser is one of the most precise and convenient technique for studying thermal properties by adapts the Transient Plane Source (TPS) method. The censor used will be sandwiched between two samples. Size of sample used is 25 x 50mm with 10mm of thickness. All specimens that will be tested need to be in dry state condition. Data such as probing depth, time and power used need to be set until constant and allowable rate was accepted. The hot disk thermal constant analyser will give all data such as thermal conductivity (w/mk), thermal diffusivity (mm^2/s) and specific heat (MJ/m^3 K). Figure 1 shows the set-up of hot disk thermal constant analyser for thermal test.

Figure 1: Set-up on Hot disk thermal constant analyzer for thermal test

Digital image analysis, or a light microscope, was used to observe the formation of LFC microstructures. The observation from this microscope is limited, as the best view is found from 6.3 to 57 magnifications. The light microscope has some effects on our observations as it will give some blurred images, which happened due to the uneven surface of samples. The samples needed to be cut, shaped into a cube and dried before being viewed in the microscope. Scanning electron microscopy (SEM) was used to give a detailed view on each of the particles produced by the reaction of additives in the hydration process. A detailed view of each particle, with some other objects, can be seen clearly from many types of magnification. Each sample needs to be prepared using a small sized (10 mm x 10 mm x 10 mm) cube. The samples needed to be dried and were put into a vacuum to remove air. The samples were coated with gold before any further procedure was done. The views of the samples were done up to 40 times magnification.

Result and discussion

i. Thermal properties of LFC with different densities

LFC can be produce with a wide range of density. Each density gives different effect on the properties of LFC. Density of LFC influenced by the amount of foam added into the mix. In this study, different densities of LFC were cast and tested. The results show that the thermal conductivity of all LFC samples is positively proportionate with the density (Table 3). For instance, the thermal conductivity for LFC reduced from 0.59 to 0.43W/mK and further reduced to 0.19W/mK for corresponding densities of 1400, 1000 and 600 kg/m^3, respectively

This happened due to formation and size of pore that consist inside LFC. The thermal conductivity gives a better result as the density decrease. This is due to different formations and size of pores on the microstructure formation of LFC.

Figure 2 show the differences on microstructure formation of LFC with different densities. It can be seen that more and large size of pores were produced with 600 kg/m^3 density. Taking mortar as a reference, all the sample porosities were calculated. Based from Table 3, it can conclude that density of LFC is governed by the porosity or amount of air content inside the material. Lower density of LFC indicates larger porosity value or greater amount of air contained (larger pore size). As a result, thermal conductivity changes significantly with the porosity of LFC because air is the poorest conductor compared to solid and liquid due to its molecular structure.

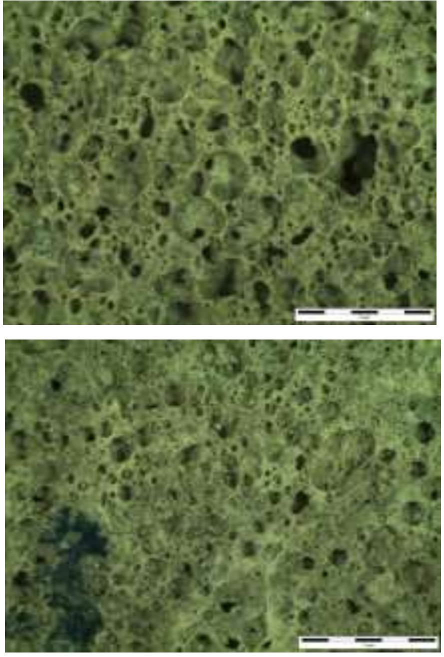


Figure 2: Size and formation of pore with 600 kg/m^3 (left) and 1000 kg/m^3 (right) densities of control LFC

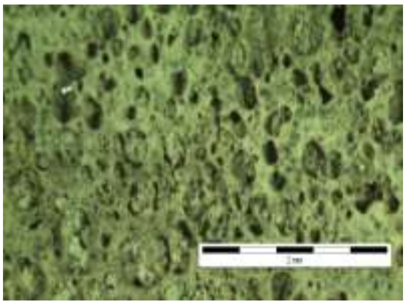
Moisture is another factor that will influence the thermal properties of LFC. In this experimental study, all specimens were tested under dry state condition. Moisture content in each sample with different ages in the hydration process was shown in Table 4. Moisture content for 600 kg/m^3 density gives higher percentage of moisture compared with other densities. Based on the literature, moisture content changes the thermal conductivity. As LFC classified as porous material and characterized as hygroscopic, the thermal conductivity cannot be measured with specific moisture content. In this study, LFC with 600 kg/m^3 density contributes to thermal properties even with higher moisture content. Hygroscopic characterization of material is important to study as it will explain the behavior of porous material for thermal properties.

ii. Thermal properties of LFC integrating different additives

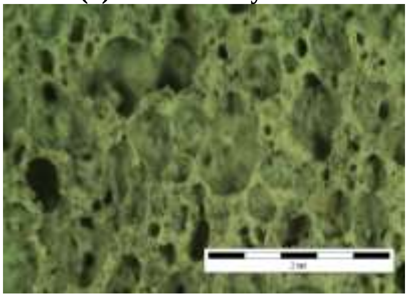
Fly ash, lime and polypropylene fiber were used with different densities and percentages. Table 4 shows the result of thermal properties of LFC with different additives. Fly ash and lime were used as cement and aggregate replacement. Both additives can be classified as fillers. Fly ash and lime react chemically in the hydration process. There is some complex particle produced that will have an effect on the microstructure formation of LFC. This will result in different thermal properties. Polypropylene fiber used as an addition to the mix will affect the formation and size of pores and does not react chemically. Lime as additives gives a better results on thermal properties of LFC compared with other additives. Principally, each additive used will give different reaction and result in different thermal value. This happened due to several factors, which will be investigated and explain in the next sections.

Fly Ash

Fly ash as cement replacement can improve the properties of LFC. For this study, class F fly ash based from ASTM C618 was used. Fly ash characterized as pozzolan material improves the strength with a longer curing period. The utilization of fly ash also will reduce green house emission effects that are produced by the cement hydration process. Fly ash will react as filler which will result in compact microstructure and also will produce a good binder. Due to compact composition of microstructure, closed-cell structure was deformed. Addition of fly ash will reduce the heat created as the hydration process goes on [8].



(a) LFC with fly ash



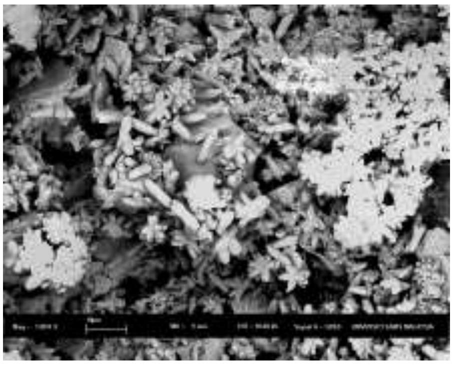
(b) Control LFC

Figure 3: Formation and pore sizes with same density

High amount of fly ash will reduce the usage of cement thus reduce the heat. The result shows that high percentage of fly ash results in good thermal conductivity as fly ash reduces and controls the heat of temperature. Fly ash as additives also reduces the amount and size of pores. Fly ash as filler prevents the bubbles from merging with each other and gives uniform distribution of pore. Figure 3 shows the influence of fly ash on microstructure formation. It can be clearly seen from both figures that incorporating fly ash in LFC mix reduced the size and amount of pore. This will influence the thermal properties of LFC as well.

It should be pointed out that there are some particles produced in the hydration process as shown in Figure 4. The particle produced is another factor to be considered in determining the thermal properties of LFC as it changed the microstructure formation. By using fly ash, it could be assumed that it only contributes in slender enhancement of thermal properties of LFC. The heat and temperature control is the main reasons that assist LFC performing better thermally. Detail investigation on the complete formation of microstructure will lead to better understanding on how thermal properties were affected by adding fly ash.

(a) Complex Spherical formation

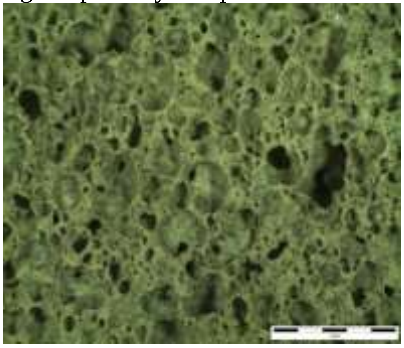


(b) Production of crystalline particle

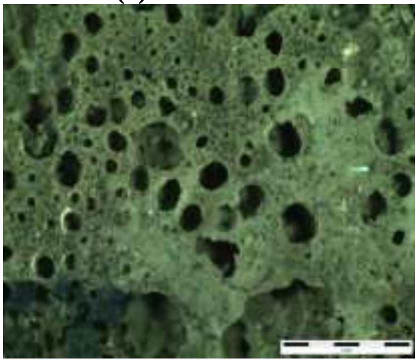
Figure 4: Production of particles in hydration process with the addition of fly ash

Lime correct

Lime was used as an aggregate replacement for this investigation. Lime is classified as filler due to its finer size, and it reacts chemically during the hydration process. It is proven to offer high workability and superior plasticity. Lime also will contribute to closed-cell structure formation of LFC. Addition of lime causes a decrease in porosity [9]. Figure 5 proved that the pore size decrease compared with normal LFC. This will reduce the effectiveness of thermal for LFC as well. It can be seen from Table 4 that lime as aggregate replacement gives a higher percentage of porosity compared with other additives.



(a) Control LFC



(b) LFC with lime

Figure 5: Microstructure formation for control LFC compared to LFC with the addition of lime as sand replacement

Scanning electron microscopy was used to observe the microstructure formation of LFC. As mentioned before, during hydration process, lime will react chemically and some particles produced. Figure 6 shows that there were prismatic forms of needle produce in the hydration process. The prismatic forms of needle create more voids and cavity, which give good thermal properties for LFC.

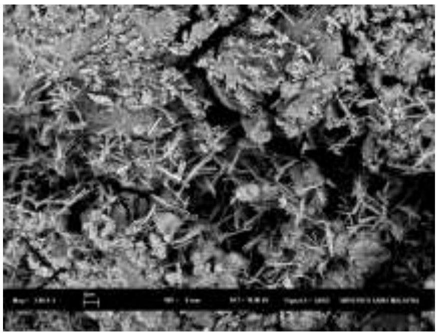


Figure 6: Prismatic forms of needles with cavity and pores formation which result in good thermal conductivity values

Moisture content is another factor that influenced the thermal properties of LFC. The result shown that, lime give high moisture content compared with other additives. It can be concluded that, moisture content is not major factors that influence the thermal properties. There are other factors also need to be taken under consideration for further investigation.

Polypropylene

Polypropylene fibers with 19mm long were used at a 0.20 and 0.40 percent by volume in this study. Essentially, usage of fiber will improve the properties of LFC such as compressive and flexural strength [5]. Polypropylene fiber characterized as hydrophobic will retain water. Air will be retained during mixing process leading to more voids and high porosity. In this experimental investigation, higher addition of fiber results in higher percentage of porosity. The result from Table 4 clearly shown that LFC with 0.40 percent of fiber gives better thermal properties compared with LFC with 0.20 percent of fiber. Therefore, higher addition of fiber will create more pores thus lead to better thermal properties. Even though the moisture content is slightly higher compared with normal LFC, it still gives better thermal conductivity value.

Conclusions

From the experimental results, the following conclusions may be drawn

i. Densities of LFC give different thermal properties. Low density of LFC gives better thermal properties as it was influenced by production of pores. Large amount of foam was required to produce low density LFC. The size and formation of pores will be affected. Low densities of LFC produce larger size and amount of pores.

ii. Hydration process involves of chemical reaction produced some complex particle that is vital to be discovered. The particle produced will affect the microstructure formation thus influence thermal properties of LFC.

iii. Fly ash as cement replacement improves slightly on thermal properties of LFC. By reducing the amount of cement, heat can be reduced and controlled. Although LFC with fly ash produced small sizes and uniform distribution of pores, the heat in the hydration process will help in producing better thermal conductivity. Higher addition of fly ash could improve the thermal properties. Detail analysis need to be done on the effect of fly ash for thermal properties with longer age of hydration process.

iv. Lime as an aggregate replacement result in better thermal properties compared with other additives. Higher percentage of porosity is one of the factors that influenced the thermal properties. Even though lime gives a higher percentage of moisture content, it does not influence and affect the thermal properties.

v. Polypropylene fiber produce more pores as it characterized as hydrophobic. As more pores created, it will aid in performing better thermal properties. Higher addition of polypropylene fiber produced more pores and improves thermal properties of LFC.

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Table 1: Mix proportion of LFC with different densities and additives

Sample	Remark	Mix ratio (cement:sand:water)	Composition of mixture			Dry density (kg/m^3)	Wet density (kg/m^3)	Foam volume (m^3)	Slump (mm)
			Cement (kg)	*Sand (kg)*	*Water (kg)*				
600 kg/m^3									
Normal LFC	NF-A	1:1.5:0.45	15.32	22.97	6.89	600	700	0.050	25
0.20 % Polypropylene fiber	PF20-A	1:1.5:0.45	15.32	22.97	6.89	600	700	0.048	25
0.40 % Polypropylene fiber	PF40-A	1:1.5:0.45	15.32	22.97	6.89	600	710	0.046	25
15 % lime	RL15-A	1:1.5:0.45	15.32	22.97	6.89	600	700	0.048	25
30 % lime	RL30-A	1:1.5:0.45	15.32	22.97	6.89	600	720	0.046	26
15 % fly ash	FA15-A	1:1.5:0.45	15.32	22.97	6.89	600	720	0.050	25
30 % fly ash	FA30-A	1:1.5:0.45	15.32	22.97	6.89	600	710	0.051	25
1000 kg/m^3									
Normal LFC	NF-B	1:1.5:0.45	25.15	37.73	11.32	1000	1105	0.037	23
0.20 % Polypropylene fiber	PF20-B	1:1.5:0.45	25.15	37.73	11.32	1000	1085	0.035	26
0.40 % Polypropylene fiber	PF40-B	1:1.5:0.45	25.15	37.73	11.32	1000	1070	0.032	25
15 % lime	RL15-B	1:1.5:0.45	25.15	37.73	11.32	1000	1100	0.033	25
30 % lime	RL30-B	1:1.5:0.45	25.15	37.73	11.32	1000	1090	0.031	25
15 % fly ash	FA15-B	1:1.5:0.45	25.15	37.73	11.32	1000	1120	0.037	23
30 % fly ash	FA30-B	1:1.5:0.45	25.15	37.73	11.32	1000	1130	0.037	25
1400 kg/m^3									
Normal LFC	NF-C	1:1.5:0.45	42.49	63.73	19.12	1400	1500	0.029	25
0.20 % Polypropylene fiber	PF20-C	1:1.5:0.45	42.49	63.73	19.12	1400	1480	0.028	25
0.40 % Polypropylene fiber	PF40-C	1:1.5:0.45	42.49	63.73	19.12	1400	1510	0.029	25
15 % lime	RL15-C	1:1.5:0.45	42.49	63.73	19.12	1400	1500	0.025	25
30 % lime	RL30-C	1:1.5:0.45	42.49	63.73	19.12	1400	1510	0.017	25
15 % fly ash	FA15-C	1:1.5:0.45	42.49	63.73	19.12	1400	1530	0.030	25
30 % fly ash	FA30-C	1:1.5:0.45	42.49	63.73	19.12	1400	1530	0.029	25

Table 2: Properties of material used

	Fly ash	Lime	Polypropylene fibre
Size	5µm to 100µm		19mm length
Specific gravity	2.3	1.9	0.90 kg/dm^3
Material	Waste from electricity	Form quarry or mines	100% virgin polypropylene
E- modulus	-	-	3900 N/mm^2
Chemical composition	SiO_2 Al_2O_3 Fe_2O_3 CaO MgO SO_3 Na_2O	SiO_2 Al_2O_3 Fe_2O_3 CaO MgO R_2O LOI	C-33% H- 67%
Classification	Class F fly ash-ASTM C618	-	-

Table 3: Thermal properties of control LFC of different densities

Density (kg/m^3)	**Thermal conductivity (W/mK)**	**Thermal diffusivity (mm^2/s)**	**Specific heat (MJ/m^3 K)**	**Percentage of porosity (%)**	**Moisture content (%)**		
					7 days	***28 days***	***60 days***
600	0.19	0.35	0.54	69	15.3	14.8	13.3
1000	0.43	0.54	0.81	49	12.8	8.3	11.2
1400	0.59	0.60	0.98	36	11.6	10.1	10.1
Mortar	1.4	0.96	1.47	-	-	-	-

Table 4: Thermal properties of LFC with different densities and additives

	Thermal conductivity (W/mK)	**Thermal diffusivity (mm^2/s)**	**Specific heat (MJ/m^3 K)**	**Percentage of porosity (%)**	**Moisture content (%)**		
					7 days	***28 days***	***60 days***
600 kg/m^3							
NF-A	0.1871	0.3493	0.5355	69.49	15.35	14.8	13.26
FA15-A	0.1734	0.3796	0.4598	68.89	14.00	12.44	11.73
FA30-A	0.1620	0.3937	0.4152	70.46	13.93	12.51	11.48
RL15-A	0.1646	0.3369	0.4942	71.99	16.57	16.35	15.46
RL30-A	0.2026	0.4769	0.4807	70.31	17.21	16.57	15.31
PF20-A	0.1780	0.3187	0.5604	69.81	14.20	12.97	12.15
PF40-A	0.1773	0.3014	0.5891	70.52	16.52	14.22	13.36
1000 kg/m^3							
NF-B	0.4324	0.5440	0.8138	49.02	12.82	8.28	11.24
FA15-B	0.3827	0.4902	0.7924	49.80	14.70	10.88	12.57
FA30-B	0.3592	0.5234	0.6904	50.85	13.12	12.13	11.95
RL15-B	0.3061	0.4564	0.6745	52.83	12.35	14.82	14.42
RL30-B	0.3143	0.4442	0.7075	52.91	11.79	15.75	15.49
PF20-B	0.3107	0.4270	0.7281	54.14	13.42	11.95	12.50
PF40-B	0.3153	0.4200	0.7506	56.60	14.10	14.80	13.10
1400 kg/m^3							
NF-C	0.5851	0.6005	0.9765	35.82	11.62	10.09	10.06
FA15-C	0.5824	0.6178	0.9504	35.07	12.40	11.07	10.28
FA30-C	0.6052	0.6497	0.9314	34.77	11.84	10.74	9.32
RL15-C	0.5891	0.5969	0.9874	36.29	13.49	11.04	11.04
RL30-C	0.5297	0.5359	0.9885	36.91	15.53	14.14	13.96
PF20-C	0.5962	0.6614	0.9138	35.62	13.37	10.86	10.12
PF40-C	0.5638	0.6376	0.8925	35.34	12.18	10.87	9.85
Mortar							
Mortar	1.4040	0.9561	1.4690	-	-	-	-

* NF – normal LFC , FA – Fly Ash , RL – Raw Lime , PF - Polypropylene fibre