IMPACT OF ADDITION OF FLY ASH (AS SAND REPLACEMENT) AND POLYPROPYLENE FIBERS ON SHRINKAGE AND THERMAL CHARACTERISTICS OF FOAM CONCRETE

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Abstract

Foam concrete (FC) has recently received a lot of attention owing to its excellent properties such as high workability, low density, and low thermal conductivity (TC). The aggregate requirements of FC being different from conventional concrete, the fly ash (FA), the most commonly used industrial residue has great potential to serve as filler in FC. Thus, this work quantifies the effects of FA, (as filler replacement) and polypropylene (PP) fibers on shrinkage, thermal, and mechanical properties of FC made with natural hingot surfactant. In this study, three FC densities were used to test four FA replacement levels (0, 25, 45, and 65 %) and four PP fiber addition levels (0, 0.1, 0.2, and 0.3 % by weight of solids). Results show that increasing FA percentage improves FC's pore structure, increasing compressive strength and lowering TC. Addition of PP fibers reduced FC shrinkage by 40 % in this study. Despite the stated benefits, adding more PP fiber (0.3 %) caused uneven distribution, decreasing FC compressive strength. Hence the experimental outcomes of present study have proved that addition of optimum levels of FA and PP fibers are sustainable measures to enhance the performance of FC produced with hingot surfactant without affecting the foam stability.

Keywords: Drying shrinkage; Fly ash; Foam concrete; Light weight; Polypropylene fibers' thermal performance.

1. INTRODUCTION

Foam concrete (FC), a type of cellular concrete is more preferred nowadays in construction sector due to its light weight and thermal insulation characteristics. The cellular structure in FC is more commonly achieved through addition of preformed foam produced with surfactants and foam generators. With the exception of aggregates, the material used to make FC are the same as used for concrete of normal use. Various studies have proved that use of conventional coarse aggregate and coarse sand affects the stability of foam and eventually has negative impact on pore structure and strength of FC [1,2]. Hence, to address the above issues, researchers have tried the inclusion of various fillers such as fine recycled glassy aggregates, expanded shale aggregate, lime, fly ash, clay and quarry dusts aggregates to augment the foam stability and strength [3-9]. In this line, as the fly ash (FA) is the most widely used industrial residue, its suitability as filler in FC need to be explored in detail and surprisingly, only scanty literature is available in this regard. Limited studies have proved that partial or complete replacement of sand with FA results in higher strength to density ratio due to pozzolanic activity of FA. Jones and McCarthy [5] opted for 100 % replacement of sand with FA and reported strength up to six times higher than those of corresponding control mixes with sand, with differences becoming increasingly larger with increasing test ages due to the relatively slow nature of the pozzolanic activity of the FA. Similar observation was reported by Nambiar and Ramamurthy [10] where they have reported 200 % increase in compressive strength at 90 days for 70 % replacement of sand with fly ash. Further, the microstructure of FC with FA as filler is significantly improved due to uniform coating of FA around the foam bubbles which subsequently reduces bubble coalescence and enhances foam stability [1,11]. The above improvement in microstructure due to physical and chemical effects of FA addition affects the mechanical and thermal behavior of FC significantly. For instance, few researchers have proved that use of silica fume (SF) as cement replacement and FA as fine sand replacement result in better mechanical properties and slight increase in thermal conductivity (TC) due to dense microstructure of concrete [12]. On contrary to this some researchers have reported creation of well distributed uniform pore structure upon incorporation FA as filler replacement leading to decrease in TC [8,13]. Gandhi *et al.* [14]

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in their studies reported an improvement in strength of 120 and 61 % for densities 1500 kg/m^3 and 1000 kg/m^3 respectively for 45 % replacement of sand with FA. The improvement in strength was reported due to the combined action of pore structure densification and pozzolanic reaction caused due to incorporation of FA. The pore structure densification leads to early improvement in strength while strength improvement due to the delayed effects of the pozzolanic reaction was clearly evident on the later-age strength development beyond 21 days. Besides the above positive impacts, the major drawback of use of FA as filler, is the higher drying shrinkage of FC mixes. In this context, few studies have highlighted that the FC with FA as filler revealed higher drying shrinkage when compared to that of FC with sand. The above can be attributed to the lesser shrinkage restraining capacity of FA when compared to that of sand [15].

Hence to counteract the shrinkage cracks, fibers have often been recently used in FC mixtures. Researchers have observed from the studies that fiber acts as the aggregate particle and hence its inclusion is effective in reducing the drying shrinkage of foamed concrete [16]. Fibers used in foamed concrete are either synthetic or natural fibers such as alkali resistant glass, asbestos, basalt, steel, oil palm, polypropylene and Kenaf [7,16-18]. Among the above mentioned types, polypropylene (PP) fibers are reported to be more cost effective and efficient in reduction of shrinkage. Further, the hydrophobic nature of PP fibers also aids to retain water and hence delay the rate of water evaporation and lessen the drying shrinkage [19]. In most of the above studies, the authors have established that addition of fibers resulted in uniform closed cellular microstructure of concrete and reduction in drying shrinkage. Few studies have highlighted that the spatial reinforcement achieved with addition of fiber, resulted in directional crystallization of mortar leading to increased strength [20, 21]. Contrary to above, some researchers have reported negative impact of addition of fibers on strength due to uneven distribution and creation of additional air voids [6, 17]. Hence, based on the above review, it is evident that the addition of fibers can affect the pore structure of FC and the related mechanical and thermal properties significantly, however as per the current status, the literature available in this regard is only limited.

Further, another important aspect to be noted is that selection of foaming agent has manifest influence on FC performance as established in numerous studies. Also, synthetic surfactants are more commonly used for FC production. Hence, in light of the rapidly growing environmental concern, recent research has showed tremendous interest in finding naturally occurring surfactant as alternative to harmful synthetic surfactants[22]. Balanites aegyptiaca, often known as Hingot, is one such recently discovered natural surfactant for use in FC [23]. With respect to foam concrete a sizeable amount of literature is available on flyash as a binder replacement. However, the literature pertaining to the fly ash as filler (i.e. sand) replacement is rather limited and this has been reported to give more positive effect on the strength [1,5,10,14,24]. Also studies carried out on shrinkage behavior of foam concrete incorporating polypropylene fibers is also less. Although an extensive research has been carried out on the optimization of the hingot surfactant [25,26] from the foam stability perspective, its performance in FC incorporating various admixtures like FA and PP fibers for various thermo-mechanical and shrinkage parameters is yet to be comprehended. Having highlighted the major research gaps, the main objective of the present study is to carry out systematic investigations on the effect of replacement of sand with class F FA and addition of PP fibers on compressive strength, shrinkage and thermal behavior of FC prepared with hingot surfactant. Further, the variation of above mentioned characteristics with density of concrete is also studied. Three different densities of FC are being chosen i.e. 1000 kg/m^3, 1500 kg/m^3 and 1800 kg/m^3. Generally, lower density can be used for non-structural applications like roof insulation while foam concrete with higher density can be used as walling material and as a sustainable alternative to clay bricks.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

In order to produce stable FC with varying densities ranging from 1000 kg/m^3 to 1800 kg/m^3, the following constituent materials are used in the present study (1) ordinary Portland cement (OPC) of 43-grade conforming to IS: 269 (2015) [27] with a specific gravity - 3.14, sourced from Dalmia Bharat Ltd is used as binder; (2) River sand finer than 300 μm with specific gravity- 2.65 is used as filler; (3) Class F FA conforming to ASTM C 618-22 [28] with specific gravity - 2.16 obtained from national thermal power corporation (NTPC) Ltd Bongaigaon is used as partial replacement for filler; (4) Alkali resistant synthetic polypropylene fiber (PP) with specific gravity - 0.91, aspect ratio - 545 and length- 12 mm, tensile strength- 400-500 MPa and surface area- 250 m^2/kg is used; (5) Saponin based foaming agent derived from Balanites aegyptiaca (also known as Hingot fruit) in combination with additive xanthan gum (XG) as foam stabilizing agent is employed to create a stable foam using laboratory scale foam generator. Table 1 provides the chemical composition and physical properties for cement and fly ash used in the study, further Figure 1 represents the particle size distribution of the Cement, Sand, fly ash and hingot powder used in this study.

2.2 Surfactant preparation and foam production methodology

In accordance with the technique described in the earlier published paper [23,26] and as represented in Figure 2 (a),(b),(c), the surfactant extraction from hingot fruit is carried out

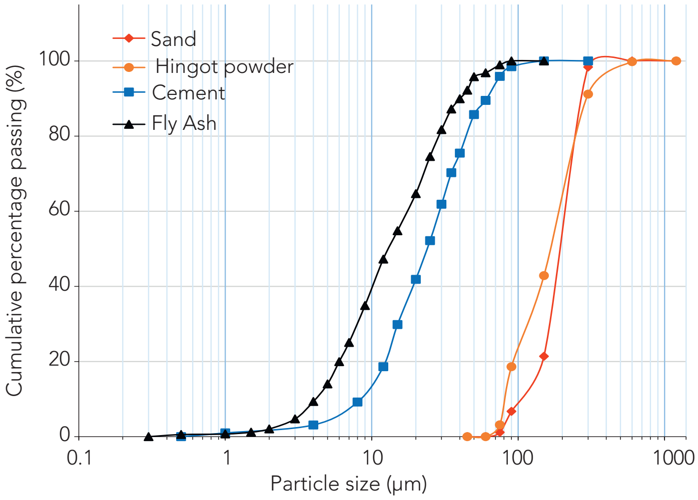

Figure 1: Particle size distribution of cement, sand, fly ash and hingot powder

accordingly. The prominent steps of the process include pre-treatment where activities such as drying and particle size reduction of hingot pericarp are carried out to improve the extraction operation. Further, the pericarp powder that had been dried and pulverised is blended with water at a concentration of 6 % (i.e. 6 grams of surfactant is added to 100 ml of water). The prepared hingot pericarp solution is heated and stirred with a magnetic stirrer at a temperature of

Table 1: Chemical composition and physical properties of OPC cement and fly ash

CHEMICAL COMPOSITION	CEMENT (%)	FLY ASH (%)	PHYSICAL PROPERTIES	CEMENT	FLY ASH
CaO	64.63	1.59	Specific gravity	3.14	2.16
SiO_2	20.19	55.60	Specific surface area	288 m^2/kg	364 m^2/kg
Al_2O_3	5.02	29.80	28 days compressive strength	50 MPa	-
Fe_2O_3	1.45	5.91			
MgO	3.2	1.08	Initial setting time	110 min	-
SO_3	2.22	0.45			
K_2O	0.5	1.94	Final setting time	220 min	-
Na_2O	0.28	0.23			
LOI	2.51	0.47			

90°C for four hours to promote the saponin extraction. After cooling down, the solution is filtered with muslin cloth and mixed with xanthan gum (0.1 % by weight of surfactant solution), which is added as foam stabilizer. As represented in Figure 2(d), the stabilized preformed foam is generated using compressed air foam generator with an output of 200-400 L/min and at a pressure of 5.9 kPa.

Figure 2: (a) Hingot fruit; (b) Pulverized hingot powder; (c) Hingot solution heated on hot plate magnetic stirrer; (d) Foam concrete production setup

2.3 Mix proportioning

For the current experimental program, by adjusting the foam percentage between 50 and 13 %, FC mixes with design densities 1000, 1500, and 1800 kg/m^3 are prepared. The mix proportions are determined using the technique outlined in ASTM C 796-19 [29]. Because the standard solely addresses cement slurry, the mix design technique is altered to incorporate the sand component and FA. The sand is replaced with fly ash at different levels viz., 25, 45 and 65 %. Similarly, PP fibers are added in dosages of 0.1, 0.2 and 0.3 % by the weight of total solids. The water-solids ratios of these mixtures are determined through preliminary trials in order to produce the required target fresh density and consistency (slump flow ranging between 140 to 160 mm). The above range of desired consistency has been fixed considering the stability by various researchers [15,30]. Table 2 shows the mixture composition of several FC mixtures adopted in this study. The mixing process begins with a homogenous base mix of binder and filler slurry prepared in a horizontal shaft paddle type mixer machine, followed by the addition of a determined weight of foam. Based upon the preliminary studies while taking into consideration the economic perspective and the stability of foam concrete, a constant binder to filler ratio of 1:2 by weight is used for all the mixes in this study. The entire mixing procedure is continued for at least 5 minutes, or until the foam is uniformly incorporated into the slurry.

2.4 Test methodology

Compressive strength of the prepared FC samples is measured using Universal testing machine (UTM) in accordance with IS: 516-1 (2021) [31], as shown in Figure 3 (a). Six cubes of 50 mm

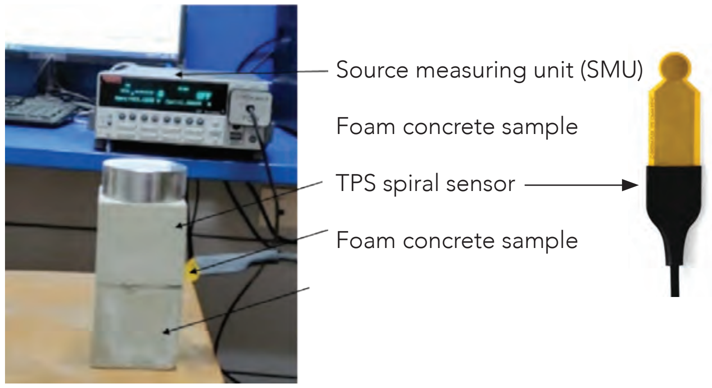

Figure 3: (a) Compressive strength test setup; (b) Drying shrinkage test setup; (c) Thermal conductivity test setup

Table 2: Mix proportion of the prepared samples

MIX CODE	CEMENT (kg/m^3)	SAND (kg/m^3)	WATER (kg/m^3)	FOAM (kg/m^3)	FLY-ASH (kg/m^3)	PPF (kg/m^3)	W/S	FOAM VOLUME (%)	TARGET DENSITY (kg/m^3)
LBm	246.90	493.80	228.90	30.40	0	0	0.35	50.67	1000
LFA45	246.90	271.60	228.90	29.17	222.22	0	0.50	48.62	1000
LPP0.2	246.20	493.80	228.90	30.40	0	1.50	0.35	50.67	1000
MBm	384.60	769.20	330.70	15.40	0	0	0.30	25.67	1500
MFA25	384.60	576.90	331.79	14.36	192.30	0	0.36	23.93	1500
MFA45	384.60	423.08	332.70	13.52	346.15	0	0.43	22.52	1500
MFA65	384.60	269.20	333.50	12.68	500.00	0	0.53	21.13	1500
MPP0.1	384.00	769.20	330.70	15.40	0	1.20	0.30	25.67	1500
MPP0.2	383.50	769.20	330.70	15.40	0	2.30	0.30	25.67	1500
MPP0.3	382.90	769.20	330.70	15.40	0	3.50	0.30	25.67	1500
HBm	480.00	960.00	352.00	8.00	0	0	0.25	13.33	1800
HFA45	480.00	528.00	352.00	8.00	432.00	0	0.36	13.33	1800
HPP0.2	478.60	960.00	352.00	8.00	0	2.90	0.25	13.33	1800

* L - lower density FC(1000 kg/m^3), M - medium density FC (1500 kg/m^3), H - higher density FC (1800 kg/m^3), Bm - base mix, FA - fly ash, PP- polypropylene fibers, last two digits- % replacement/addition.

size are casted for each mix, to evaluate the compressive strength at 7 and 28 days. Three prism specimens of size 40 x 40 x 160 mm are casted for each mix to assess the drying shrinkage as per IS 6441-part II [32] and ASTM C596-18 [33]. The test setup for measuring drying shrinkage is represented in Figure 3(b). To make it easier to quantify length changes, spherical gauge plugs are connected to the specimen's ends on both the sides. Immediately after demoulding, the specimens are submerged in water for 72 hours, after which the specimens will be stored in a humidity chamber, where a controlled environment with a temperature of 23°C and a relative humidity of 50 % is maintained. The length measurements are taken at different time intervals till 28 days in accordance with ASTM C596 [33]. Thermal properties are determined using transient plane source (TPS) method in compliance with ISO 22007 part2-2015 [34]. As per the equipment manual the minimum sample size should be 10 mm thick and 30 mm diameter/edge. For thermal conductivity test, six number of cubical specimens of size 50 mm are tested by sandwiching the flexible, 13 mm FLEX TPS-based sensor in between two samples as represented in Figure 3(c). An electric current is passed through the sensor's spiral heating element, heating the specimen samples. As the temperature changes, the resistance of the spiral also changes, and the resulting voltage drop is measured. By measuring the current and voltage drop through the sensor over a period of time, the thermal properties of the specimen is calculated. In order to ensure good contact between the TPS element and the sample surface, all samples surfaces were polished flat and parallel, and cleaned with compressed air to minimize the influence of contact resistance. Also additional suitable weight is placed on top of the stack to ensure good contact between sample and sensor. Since, moisture content of the sample has an important impact on the measured thermal properties therefore before testing, all specimens were kept in a hot air oven at 60°C until they attained constant weight. Thermal properties like thermal conductivity (W/m*k) is assessed for foam concrete with different densities viz., 1000 kg/m^3, 1500 kg/m^3 and 1800 kg/m^3.

3. RESULTS AND DISCUSSIONS

3.1 Compressive strength of FC

Firstly, the effect of replacement of sand with class F fly ash (0, 25, 45 and 65 % by weight) is studied for FC with design density 1500 kg/m^3 and correspondingly represented in Figure 4. As discussed earlier, the *w/s* ratio has been arrived for mixes with different sand replacement based on trials to achieve uniform consistency of 140 to 160 mm without compromising the stability of mixes. Replacement of 25 % of sand with FA results in 10 and 16.6 % increase in compressive strength at testing ages of 7 and 28 days respectively. Further increase in replacement level say 45 % results in significant increase of 75 and 33 % increase in compressive strength at testing ages of 7 and

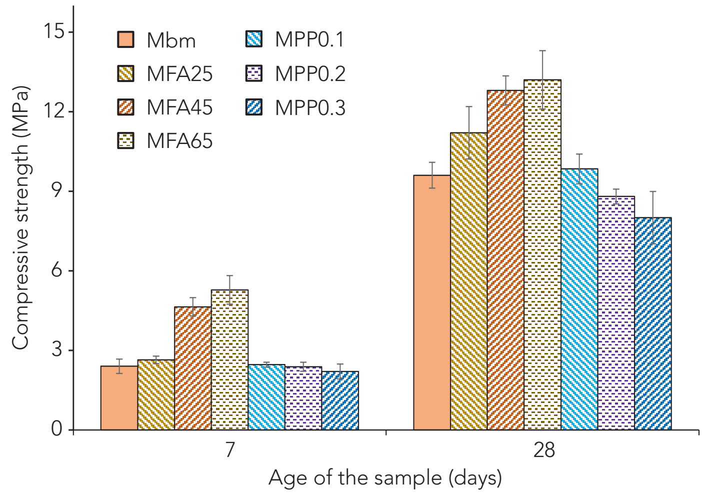

Figure 4: Effect of variation in admixture dosages on compressive strength of FC (design density 1500 kg/m^3)

28 days respectively. However, beyond 45 %, further increase in replacement level did not result in significant improvement in strength. The reason for the above observation can be attributed to the higher *w/s* ratio requirement (say 0.53) for mix with 65 % of sand replaced with FA (MFA65) in order to maintain the consistency at the aforementioned desirable level. Further, with increase in age of testing samples from 7 to 28 days there is significant increase of 150 to 278 % in compressive strength of FC, which can be ascribed to the delayed pozzolanic reaction of FA particles along with superior particle packing and distribution leading to pore structure improvement [5,8].

Figure 4 also shows the effect of variation in fiber content (0, 0.1, 0.2 and 0.3 % by weight of solids) on compressive strength of FC with design density 1500 kg/m^3. Addition of 0.1 % of PP fibers by weight of total solids shows a slight improvement in compressive strength of FC. However, further increase in fiber dosage (say 0.2 and 0.3 %) results in 6 and 10 % reduction in compressive strength of FC particularly at testing age of 28 days. The above observation can be attributed to the poor microstructure of FC with higher proportion of fibers as established in literature. For instance, in this line the researchers have highlighted that the incorporation of PP fibers does not have significant contribution to compressive strength [35,36]. However, increase in dosage of fibers beyond 0.2 % results in uneven dispersion of fibers and also moderately affects the foam stability. Additionally, fibers that are oriented parallel to the direction of loading behave like voids and do not contribute to load carrying capacity [6]. All the above reasons can be ascribed to the reduction in compressive strength of FC mixes with greater proportion of fibers.

Figure 5 shows the effect of variation in compressive strength with density of FC. As established in literature, the strength of FC increases exponentially with increase in density. From Figure 5, it is evident that effect of sand replacement with FA results in 45 % enhancement in strength particularly for higher

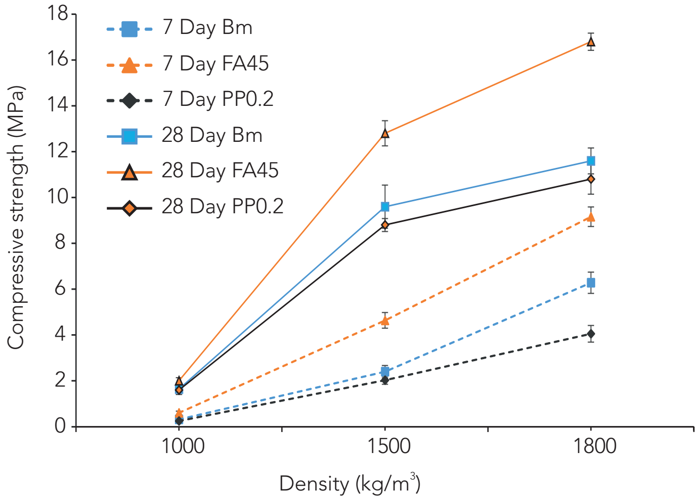

Figure 5: Variation of compressive strength with density of FC

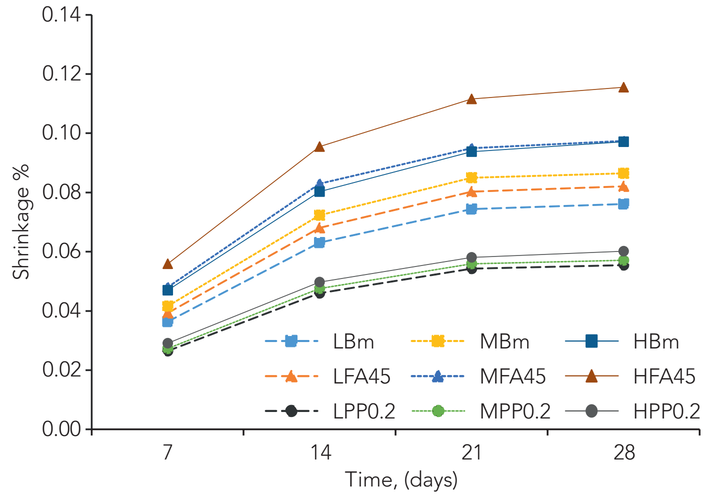

Figure 7: Variation of drying shrinkage with density of FC

density mix (HFA45) at testing age of 28 days. However, for lower density FC (1000 kg/m^3), in line with observations of other researchers, as the volume of air controls the strength to greater extent, improvement in matrix due to FA addition has relatively lesser impact on strength [1,10]. Further addition of 0.2 % fibers in lower density FC (1000 kg/m^3) has no negative impact on strength as can be noted in Figure 5. As mentioned earlier, in lower density mixes, air content is major governing factor of strength.

3.2 Shrinkage of FC

The effect of variation in sand replacement level with FA on shrinkage of FC with design density 1500 kg/m^3 is presented in Figure 6. It is evident from the Figure 6, that increase in % of sand replacement with FA results in increase of shrinkage of FC. For instance, a substantial increment of 25 % can be observed for the mix MFA65 when compared to base mix (MBm). The above mentioned increase in shrinkage of FC with increase in FA content can be attributed to the increase

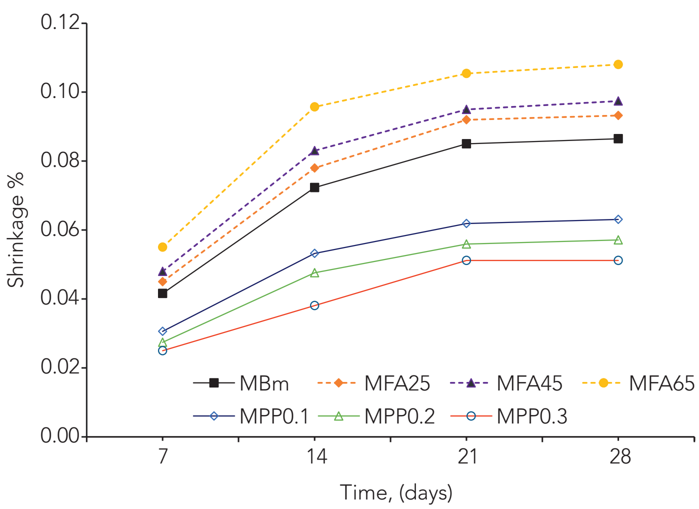

Figure 6: Effect of variation in admixture dosages on drying shrinkage of FC (Design density 1500 kg/m^3)

in fines content and subsequent increase in water demand to maintain the consistency of the mixes. The findings of other researchers as reported in literature also supports the above observation [15]. Further the Figure 6 shows that the significant amount of shrinkage occurs in first 2 weeks and after 21 days, there is not much variation in shrinkage with time. Furthermore, as established in previous studies, addition of fibers helps to reduce the shrinkage of concrete. The basic function of PP fibers as highlighted in various studies is that it helps in bridging the cracks, and hence prevents crack propagation and subsequently reduces the frequency and width of shrinkage cracks [7,37]. Experimental outcomes of present study indicate that addition of 0.3 % fibers by weight of total solids, results in 40 % reduction in shrinkage of FC with density 1500 kg/m^3 (MPP0.3).

Furthermore, Figure 7 shows that shrinkage of FC increases with density of concrete due to increase in paste content. Also, it is to be noted that amount of capillary pores in paste content governs the shrinkage rather than the bigger entrained air voids [15]. HFA45 mix is reported to have the maximum drying shrinkage. This is due to the presence of fewer voids and higher paste content and incorporation of FA in the mix. The lowest shrinkage is reported for LPP0.2 mix which can be which can be attributed to the presence of more entrained air voids as well as PP fibers that limit shrinkage.

3.3 Thermal conductivity of FC

Figure 8 shows that replacement of 25 % of sand with FA results in slight reduction of 4 % in thermal conductivity (TC) of FC with density 1500 kg/m^3. However, further increase in replacement levels by 45 and 65 % reduces TC by 8 and 9 %, respectively. The improvement in concrete microstructure with reduced pore diameter due to particle packing effect of fine FA particles contributes to the above mentioned decrease in TC. Smaller variation in dry density between MFA 25 and MFA 65 due to difference in the *w/s* ratio required to maintain the consistency

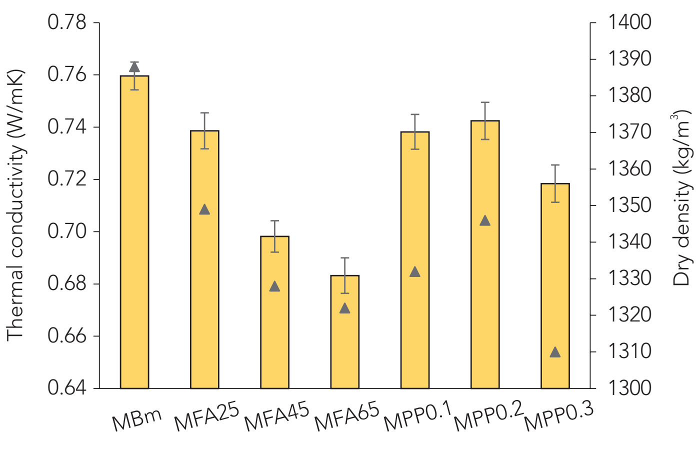

Figure 8: Effect of variation in admixture dosages on thermal conductivity of FC (design density 1500 kg/m^3)

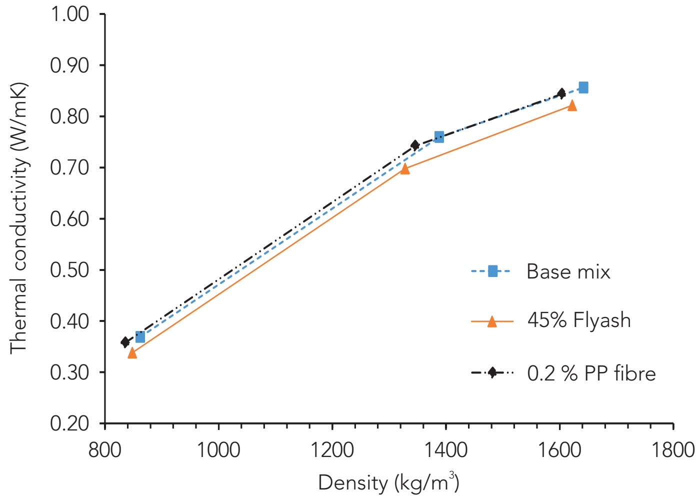

Figure 9: Variation of thermal conductivity with density of FC

within the desired range can also be attributed to the difference in thermal conductivity. The above observations supports the well-established fact that TC is highly dependent on the pore microstructure [8,13,38]. These results are in line with the previous findings of research which have replaced filler with FA, rice husk ash etc. [4,8,39]. Further, addition of PP fibers say 0.3 % by weight of total solids, also follows the trend similar to that of FA resulting in reduction of TC by 7 %. However, these results are due to the generation of additional voids and increase in porosity of FC after incorporation of PP fibers. Generally, the hydrophobic nature of PP fibers tends to retain water on its surface leading to creation of additional pores as the concrete solidifies, and this can be attributed to the reduction in TC of FC [6,40]. This negative impact of addition of fibers on pore microstructure may also affect the compressive strength as discussed in the earlier section.

Considering the effect of density, it is evident from Figure 9, that the Thermal conductivity decreases with reduction in density of concrete due to increase in air content. For instance, with increase in foam volume from 13 to 51 %, TC of FC decreases by 57 %. Figure 9, shows that 45 % replacement of sand with FA reduces TC by 5 to 9 % for various densities of FC studied. The impact of addition of fibers on TC is relatively more in lower density FC than that of higher density. This is due to the creation of larger air voids resulting from foam instability induced by incorporation of PP fibers. Further, it is to be noted that, in case of thermal conductivity, the foam volume i.e. air content is the major governing factor.

4. CONCLUSIONS

In this study, effect of addition of FA (as filler replacement) and PP fiber on various properties of FC such as compressive strength, shrinkage and thermal conductivity are studied for three different target densities of FC. Following is a summary of the findings from this study, which are applicable to the constituents used and the parameters taken into account:

1. Incorporation of FA as filler (sand) replacement, not only improves compressive strength but also enhances thermal insulating properties by reducing thermal conductivity owing to the improvement in microstructure of concrete. The highest improvement of 38 % in 28 day's compressive strength and highest decrement of 9 % in TC was recorded for FC with density 1500 kg/m^3 with FA replacing 65 % of sand. The negative side of addition of higher level of FA is that, shrinkage is found to increase with increase in FA level due to increase in fines content.
2. In the present study addition of PP fibers has reduced the drying shrinkage of FC significantly by 40 %. Nevertheless, incorporation of higher dosage (say 0.3 %) of PP fibers is found to result in decrement of compressive strength by 17 %. The uneven distribution of the fibers and generation of additional voids in mixes with higher dosage of fibers can be ascribed to the above decrement in strength.
3. Foam volume has rather significant impact on thermo-mechanical properties of FC, for instance increasing foam volume from 13.33 to 50.67 % decreased the compressive strength and TC by 85 and 57 % respectively.
4. The present study has verified that FA and PP fibers can be used at optimized levels in FC produced with hingot surfactant without significantly affecting the foam stability. Also the addition of above mentioned constituents helps to improve the FC performance significantly in addition to its contribution to sustainability. However further in depth investigations on microstructure of PP fiber reinforced FC with FA as filler needs to be carried out along with cost-to-benefit and life cycle analysis to prove its sustainable positive impacts.

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