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Sorption characteristics of foam concrete

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Abstract

Knowledge of sorption characteristics like absorption and sorptivity of building materials are of importance as they affect the durability and other properties. In the case of lightweight concrete like aerated and foam concrete, the moisture movement behaviour becomes more complex as such concretes contain much larger volume of air voids. This paper is aimed at investigating the sorption-related properties of foam concrete as affected by its composition and pore structure. Water absorption by complete immersion and sorptivity are measured for various mixes with different fly ash replacement levels for sand and different foam volume. It was found that sorption values are lower than the corresponding base mix (without foam) and the values reduce with increase in foam volume. It is also found that sorption depends on the filler type, density and pore structure and also on permeation mechanisms.

Keywords: Foam concrete; Water absorption; Sorptivity; Fly ash replacement; Tortuosity

1. Introduction

The transport of aggressive liquids into concrete depends on its permeation characteristics, like permeability, water absorption and sorption. Permeability is a measure of the flow of water under pressure in a saturated porous medium [1] and for deep sea structures or water-retaining structures the ingress of water into concrete will be governed by this mechanism under a head of water [2]. But in other structures, concrete is rarely saturated while in use and therefore saturated permeability is the wrong parameter for modeling of capillary flows in building structures and represents an incomplete behaviour [3,4]. Thus sorptivity and water absorption have emerged as the most useful parameters explaining the moisture dynamics of concrete. The water absorption mainly depends on the total volume of pores.

Several researchers have proposed the use of sorptivity as a measure of the potential durability of porous building materials, such as concrete, mortar and masonry [1,5–8], which characterises the tendency of a porous material to absorb and transmit water by capillarity. These studies demonstrated that specimen preconditioning, mix composition and curing history were the major factors influencing sorptivity. It was also reported that the water movement into concrete is not a simple function of porosity but depends on the pore diameter, distribution, continuity and tortuosity. Thus in the case of aerated and foam concretes, the moisture movement behaviour become more complex as they contain much larger volume of air voids.

Limited studies made on aerated and foam concretes, as summarized in Table 1, have indicated that the presence of pores and its characteristics along with mix composition can have considerable influences on the sorption characteristics. Hence the aim of this investigation is to determine the influence of pore structure along with density and composition on the sorption characteristics of foam concrete made of preformed foam method.

2. Materials and methodology

2.1. Constituent materials and mix proportioning

The materials used are i) ordinary Portland cement conforming to IS 12269-1987 [19], ii) pulverized river sand finer than 300 microns (specific gravity = 2.52), iii) class F fly ash (specific gravity = 2.09) conforming to ASTM C618-1989 [20], and iv) foam produced by aerating an organic based foaming agent (dilution ratio

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Table 1
Salient literature on sorption characteristics of aerated and foam concrete

Author (s)	Mix details	Properties studied	Salient observations
Prim and Wittmann (1983) [9]	Aerated concrete	Sorptivity	Sorption characteristics are related to pore structure. Capillary coefficient decreases with increase in artificial air pores
Tada and Nakano (1983) [10]	Aerated concrete	Water absorption	Classification of pore space of AAC. Influence of moisture content on water absorption. Lowering density by introduction of larger air pore exhibit low water absorption
Narayanan (1999) [11], Narayanan and Ramamurthy (2000) [12]	Aerated concrete (non-autoclaved and Autoclaved)	Sorptivity	Effect of composition and curing has been brought out. Sorptivity of NAAC is more than ACC.
Goual et al. (2000) [13]	Aerated concrete made of clay, cement and water	Sorptivity	Investigations on average capillary transport coefficient as a function of water content for different porosities. Macropores dampen the diffusion phenomenon
Kearsley and Wainwright (2001) [14]	Foam concrete (cement paste with and without fly ash replacement)	Water absorption	Volume of water absorbed was independent of volume of air entrainment
Madjoudj et al. (2002) [15]	Foam concrete made of clay, cement and water	Sorptivity	Sorptivity of lightened material is less than that of dense material
Giannakou and Jones (2002) [16]	Foam concrete with sand and fly ash as fine aggregate	Sorptivity	Sorptivity increases with density
Jones and McCarthy (2005) [17]		Sorptivity	Mix with fly ash filler showed slightly higher sorptivity
Nambiar and Ramamurthy (2006) [18]	Foam concrete with different filler type	Water absorption	Water absorption is lower at lower densities

1:5 by weight) using an indigenously fabricated foam generator to a density of 40 kg/m^3. Different mixes of foam concrete were made by varying i) Fly ash replacement for sand (FA) from 0 to 100% by weight, and ii) foam volume (FV) from 10 to 50% by keeping the filler–cement ratio at 2. The water–solids ratio of these mixes were arrived based on (i) the stability of the foam concrete mix which is defined as the state of condition at which measured density is equal to or nearly equal to design density and (ii) the consistence of mix

Table 2
Composition of mixtures with filler–cement ratio (FC) of 2

Mixture No	FA (%)	FV (%)	Composition of mixture per m^3					Fresh density kg/m^3	
			Cement (kg)	Sand (kg)	Fly ash (kg)	Water (kg)	Foam volume (m^3)	Theoretical	Measured
1	0	10	438	876	0	412	0.1	1731	1753
2	0	20	385	771	0	371	0.2	1535	1546
3	0	30	332	665	0	330	0.3	1339	1339
4	0	40	279	558	0	289	0.4	1142	1132
5	0	50	225	451	0	249	0.5	945	952
6	20	10	418	669	167	421	0.1	1679	1682
7	20	20	368	588	147	379	0.2	1490	1513
8	20	30	317	508	127	336	0.3	1300	1321
9	20	40	266	426	107	295	0.4	1110	1106
10	20	50	215	344	86	254	0.5	918	889
11	40	10	399	479	319	430	0.1	1630	1629
12	40	20	351	421	281	387	0.2	1447	1469
13	40	30	303	363	242	343	0.3	1263	1286
14	40	40	254	305	203	301	0.4	1079	1080
15	40	50	204	245	163	259	0.5	892	925
16	60	10	380	304	456	439	0.1	1584	1577
17	60	20	335	268	401	395	0.2	1406	1425
18	60	30	288	231	346	351	0.3	1228	1251
19	60	40	242	193	290	308	0.4	1048	1054
20	60	50	194	155	232	266	0.5	866	898
21	80	10	363	145	580	449	0.1	1541	1524
22	80	20	319	127	510	404	0.2	1368	1382
23	80	30	274	110	439	359	0.3	1194	1216
24	80	40	229	92	367	315	0.4	1018	1028
25	80	50	182	73	292	273	0.5	840	817
26	100	10	345	0	691	459	0.1	1499	1472
27	100	20	303	0	607	413	0.2	1331	1338
28	100	30	260	0	521	368	0.3	1161	1181
29	100	40	217	0	433	323	0.4	989	1002
30	100	50	171	0	342	282	0.5	814	840

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(for a flow cone spread value of 45 ± 5%) [21]. For the given filler–cement ratio, fly ash replacement level, foam volume % and water–solids ratio arrived at as mentioned above, the material requirement per m^3 of foam concrete was calculated using solid-volume calculations. Knowing the weight of material required per m^3 of foam concrete, the theoretical density was arrived at by adding the same. The mix proportions of all foam concrete mixes reported are given in Table 2.

Foam concrete was produced in laboratory using a paddle mixer by addition of the preformed foam to a base mortar mix (cement–sand or cement–sand–fly ash mix). The mixing sequence consisted of combining the cement and filler (sand/fly ash) with water and mixing it until a homogeneous base mix was achieved. The required weight of foam was, calculated by multiplying the foam density with the foam volume to be added, generated and added immediately to the base mix and mixed for a minimum duration till there was no physical sign of the foam on the surface and the foam was uniformly distributed and incorporated in the mix. The actual mix density was measured by filling foam concrete produced in a pre-weighed standard container of known volume and weighing it. The acceptable variation between the design and achieved densities has been fixed as ±50 kg/m^3, which is typical of industrial practice for foam concrete production [22]. From Table 2, it is observed that this variation is within the above defined tolerance limit.

2.2. Methodology—water absorption

Absorption is usually measured by drying the specimen to constant mass, immersing it in water and measuring the increase in mass as a percentage of dry mass. Various procedures can be used like 24 h immersion in water [23], immersion till constant mass [24] and vacuum saturation method [25] resulting in widely different results. Absorption was measured on 3 cube specimens of size 50 mm for each mix of foam concrete which had been moist-cured for 7, 28 and 90 days. Absorption of normal concrete is usually expressed as the increase in mass as a percentage of oven dry mass. But in the case of foam concrete, it is to be expressed as a percentage of volume [26], as expressing it as percentage by weight gives misleading results [14,18]. The saturated water absorption/permeable porosity were determined using vacuum saturation method as per ASTM C 1202-1997 [25] which is reported to be the most efficient method of measuring permeable porosity of concrete [27].

2.3. Methodology—sorptivity

The movement of water into building material is described through classical square-root-time relationship by Hall [3], $i = A + St^{0.5}$ where t = elapsed time, i = cumulative volume absorbed per unit area of inflow surface, S = sorptivity of the material obtained from the slope of the i versus $t^{0.5}$ curve using best fit linear regression and A = constant term which is the intercept at $t = 0$. Three cube specimens of size 70.7 mm were cast for each mix and corresponding base mixture (without foam), the specimens were demoulded after 24 h and moist cured till testing. A slice of 5 mm was cut from the bottom of the specimen (specimen size become 70.7 × 70.7 × 65.7 mm after slicing) using a diamond rotary cutter and this cut surface was made to contact with water while testing to ensure uniformity in the suction surface (in order to eliminate local variations in as-cast surface). These specimens were preconditioned in the oven at about 105 °C until constant mass before measurements for capillary sorption were carried out. The above preconditioning procedures may affect the absolute sorptivity to some extent. Since the aim of the work is to evaluate the relative sorption characteristics of various mixes, the effect of such preconditioning may have a constant effect on all the specimens. The lower areas on the sides of the specimens were coated with a water proof paint to achieve unidirectional flow. Even though the sorptivity is taken as the slope of best fit line passing through few initial measurements, the measurements were continued for 2 days in order to find out the duration over which linearity in the plot can be observed which is also a useful index [8].

3. Water absorption behaviour

3.1. Effect of foam volume

Fig. 1(a) and (b) shows the variation in water absorption with time for foam concrete, respectively for cement–sand and

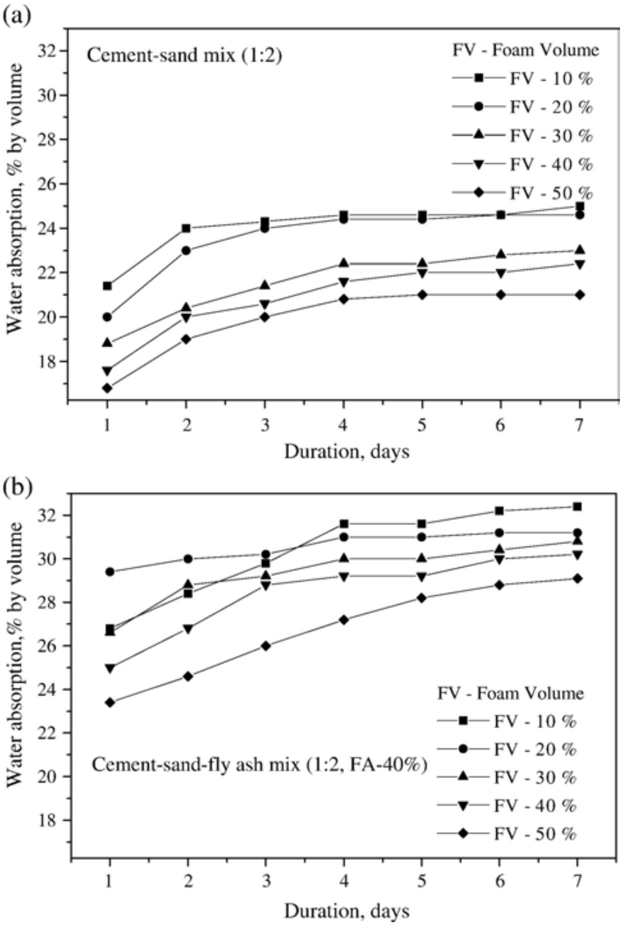

Fig. 1. (a) Variation in water absorption with time and foam volume. (b) Variation in water absorption with time and foam volume.

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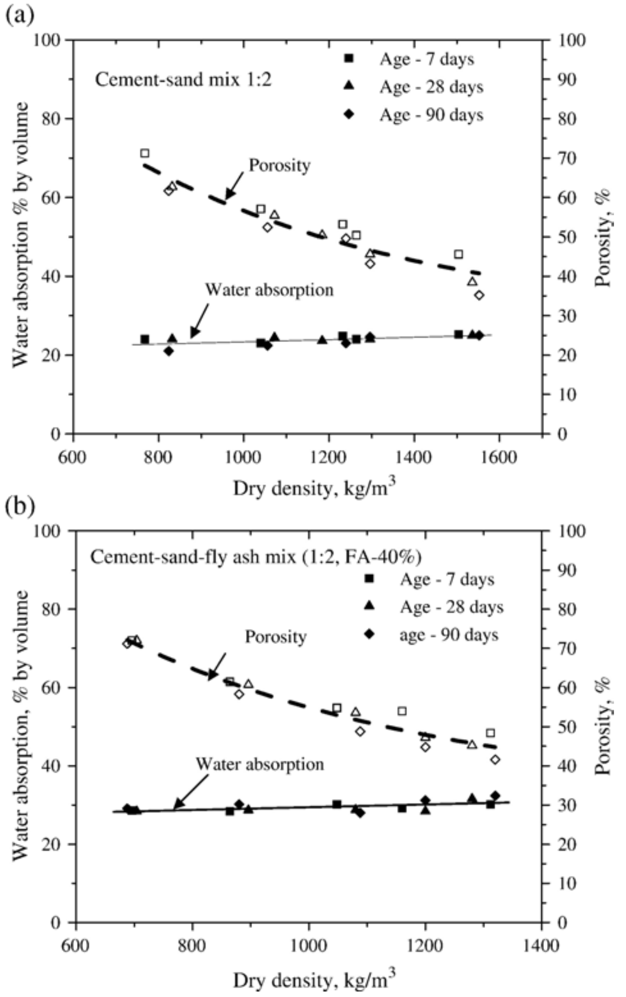

Fig. 2. (a) Water absorption and accessible porosity cement–sand mixes. (b) Water absorption and accessible porosity of cement–sand–fly ash mixes.

cement–sand-fly ash mixes. The initial rate of absorption was high (up to 24 h), it reduces beyond this period and absorption becomes almost a constant within 7 days. An important observation is that the water absorption reduces with a reduction in density of concrete (i.e. increase in foam volume). For explaining this behaviour, the total accessible pores (sum of capillary pores and entrained air voids) was determined using vacuum saturation method and plotted against dry density along with water absorption in Fig. 2(a) and (b).

For both cement–sand and cement–sand–fly ash mixes, even with an increase in porosity with a reduction in density of foam concrete (increase in foam volume), the water absorption exhibits a marginal reduction. This demonstrates that not all the artificial pores are taking part in water absorption, indicating that all of them are not inter-connected, due to which the air is being trapped in the entrained air voids. Thus the effective porosity for water absorption at normal condition is lower than the porosity determined by vacuum saturation method [28,29]. Hence the contribution to water absorption is only by the capillary pores, which depends on the paste content. As the foam volume increases the volume of entrained air pore increases reducing the paste content and causing a reduction in the volume of capillary pores and thus showed a decreasing trend of water absorption. The water absorption of base mixes (before adding foam) were higher than that of corresponding foam concrete mixes, which further emphasizes the influence of paste content on water absorption. Similar observations of effect of paste volume on water absorption of conventional concrete was observed by Kolias and Georgiou [30] and on aerated concrete by Prim and Wittmann [9].

3.2. Effect of replacement of sand with fly ash

Comparing Fig. 2(a) and (b), for a given density of foam concrete, the water absorption is relatively higher in mixes with fly ash replacement (as compared to cement–sand mixes), even though the variation in permeable pores between these mixes is only marginal. To achieve a particular density, mixes with fly ash require lesser foam volume due to its lower specific gravity compared to sand, resulting in higher paste volume and higher absorption. For a given foam volume, even though the paste volume remains same, water absorption of foam concrete increases with fly ash replacement level (Fig. 3). For achieving a workable and stable mix (spread flow value of 45±5% [21]), the water requirement increases with an increase in the level of replacement of sand by fly ash. A relatively higher water–solids ratio produces a weaker and pervious matrix, leading to higher capillary porosity which is in turn responsible for the increase in water absorption of mixes with fly ash. The above discussions highlight the major direct role of capillary porosity on water absorption than the entrained air voids, even though they indirectly contribute to water absorption by increasing the paste volume as the entrained air content is decreased.

4. Sorptivity behaviour

4.1. Effect of foam volume

Table 3 shows the sorptivity values for cement–sand and cement–sand–fly ash mixes at various foam content. For both the mixes, the sorptivity reduces with an increase in foam volume. As sorptivity is characterised by the capillary suction and that the entrained air voids do not contribute to this transport mechanism, it essentially depends on the number of pores which participate in

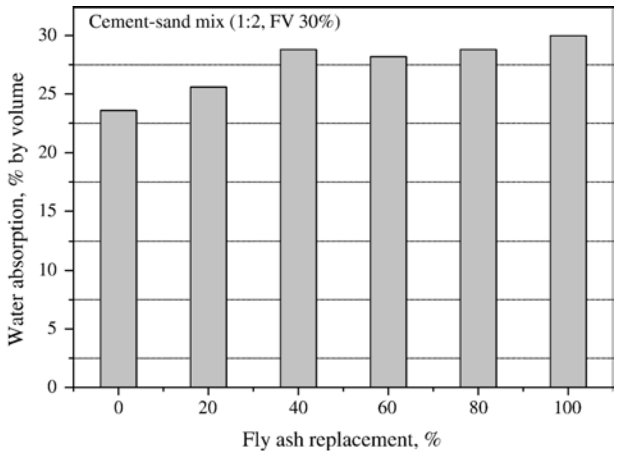

Fig. 3. Influence of fly ash replacement level on water absorption.

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Table 3
Sorptivity of foam concrete with regression coefficients for cement–sand mixes and mixes with 40% flyash as sand replacement

Foam volume	10%	20%	30%	40%	50%
Sorptivity mm/min$^{0.5}$ cement–sand mix	0.626	0.538	0.493	0.4156	0.360
R^2-value	0.997	0.998	0.997	0.978	0.987
Sorptivity mm/min$^{0.5}$ cement–sand-fly ash (FA-40%)	0.627	0.588	0.552	0.504	0.447
R^2-value	0.998	0.998	0.998	0.997	0.984

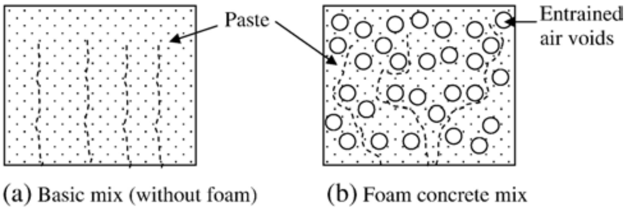

Fig. 5. Advancement of water in to base mix and corresponding foam concrete.

the capillary suction process. Hence the reduction in sorptivity is due to the reduction in capillary pores (due to reduction in paste volume) with the increase in foam volume (or with reduction in density). This conforms to the observations made by Prim and Wittmann [9]; Tada and Nakano [10] and Goual et al. [13] in aerated concrete and Jones and McCarthy [17], Madjoudj et al. [15] and Giannakou and Jones [16] in foam concrete.

Fig. 4 (a) and (b) shows a comparison of sorption characteristics of foam concrete and the corresponding base mixes (mix without foam). A typical foam concrete mix exhibits lower sorptivity than the corresponding base mix, which again illustrates clearly the effect of paste content (lower paste content in foam concrete mix as compared to the corresponding base mix) and thus the capillary pores on the sorptivity. Further, the foam concrete mixes exhibit a longer linear behaviour with reduced moisture intake as compared to the corresponding base mix. Visual examination after the test, showed the presence of water on the top surface of the base mix specimens, while such behaviour was not observed on foam concrete specimens. These are attributed to the increased average path of water migration due to an increase in the entrained air voids [9] as depicted in Fig. 5, which assumes that the discrete unconnected entrained air voids deviates the path of capillary flow of water. Thus the entrained air voids (macropores) creates an increasingly tortuous path for the capillary flow in proportion to foam volume and dampen the transport phenomenon.

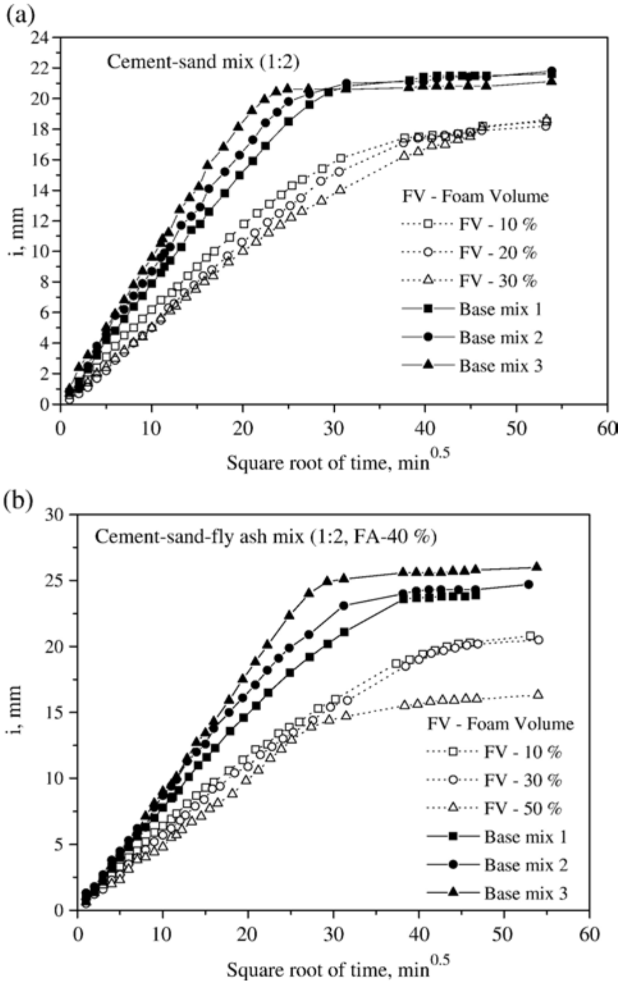

Fig. 4. (a) Comparison of capillary absorption rate of foam concrete with base mix. (b) Comparison of capillary absorption rate of foam concrete with base mix.

4.2. Effect of replacement of sand with fly ash

For a given foam volume, the sorptivity increases with increase in replacement level of sand with fly ash (Table 4). Similar observation on sorptivity of foam concrete with unclassified low lime coal ash was reported by Jones and McCarthy [17]. In the case of conventional properly cured fly ash concrete, the sorptivity was reported to be lower than mixes without fly ash but with same water–solids ratio [6]. Unlike conventional concrete, the water–solids ratio of foam concrete can not be kept constant for all replacement levels of fly ash as the water demand is based on the stability and consistence requirement of the mixes [21]. Thus the increased sorptivity of foam concrete with fly ash is attributed to the increased water requirement of mixes which results in a more pervious matrix. A similar increase in sorptivity with increased water content in normal concrete was reported by many researchers [2,5].

Fig. 6 shows relationship between the sorptivity, oven-dry density and foam volume. For a given density, foam concrete mixes with fly ash (typically for a fly ash content of 40%) exhibited relatively higher sorptivity than foam concrete mixes with cement–sand mix. This is again attributed to the higher volume of sorbing paste in fly ash mixes due to lower foam volume requirement, increased water demand making a

Table 4
Influence of fly ash replacement level on sorptivity (Mix 1:2, FV-30%)

Fly ash replacement level %	0	20	40	60	80	100
Sorptivity mm/min$^{0.5}$	0.493	0.507	0.552	0.575	0.616	0.665
R^2-value	0.997	0.996	0.998	0.998	0.997	0.998

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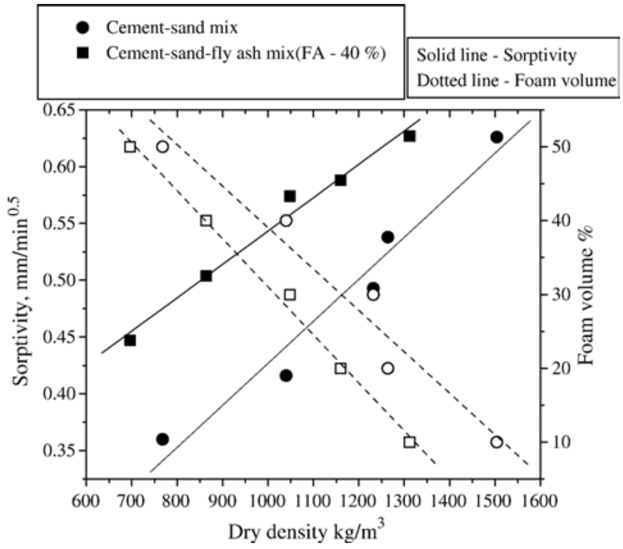

Fig. 6. Variation sorptivity with density.

pervious matrix compared to cement–sand mix, and reduced level of tortuosity resulting from lower foam volume.

5. Sorption characteristics and pore types

Tada and Nakano [10] classified the pore system of AAC as capillary pores (microcapillary (<50 nm) and macrocapillary (50 nm to 50 µm)) and artificial air pores (50 µm to 500 µm). In a similar way, with an objective of studying water transport phenomena, the total permeable pores of foam concrete is considered as the sum of the entrained air voids (artificial air pores) and capillary pores. The total permeable porosity was determined by vacuum saturation method. The images of polished and prepared cut surfaces of specimen (30 images for each mix) were captured by an optical microscope and after suitable morphological operations on the images, they were analysed by image processing software to find out the amount of entrained air voids present in each mix. Fig. 7 shows few typical binary images. Table 5 shows the total permeable porosity % (PP), volume of entrained air voids % (AV) and capillary porosity % (CP) (which is the difference between PP and AV) of various foam concrete mixes with different foam volume % (FV) along with density, sorptivity, water absorption and compressive strength of these mixes.

Though the variation in water absorption is marginal with density, the sorptivity varies considerably. This shows that the permeation mechanism between these two cases is different. The water absorption is mainly dependent on the total volume of pores, whereas sorptivity (capillary absorption rate) in addition to pore volume is also affected by the fineness, discontinuity and the level of tortuosity [13,31]. From the table it can be concluded that for a given mix type, sorptivity and water absorption are mainly controlled by capillary porosity while the reduction in strength with density is mainly governed by the volume of the entrained air voids.

Table 5
Sorption characteristics of foam concrete with cement–sand mixes and mixes with 100% flyash as sand replacement-a comparison with different pores

FV %	Oven-dry density Kg/m^3	PP %	AV %	CP %	Sorptivity mm/min$^{0.5}$	Water absorption %	90-day strength MPa
Cement–sand mix							
10	1504	45.6	11	34.6	0.626	25.2	15.33
20	1264	50.4	18.7	31.7	0.538	24	8.96
30	1232	53.2	27.8	25.4	0.493	24.8	4.45
40	1040	57.1	36.7	20.4	0.416	23	1.80
50	768	65.2	44.4	20.8	0.360	24	1.30
Cement–fly ash mix (100% replacement level)							
10	1312	48.4	10.4	38	0.696	30.9	19.17
20	1160	54	18.8	35.2	0.667	30.2	12.94
30	1048	58.4	28.1	30.3	0.664	30.0	8.15
40	864	61.5	36.4	25.1	0.579	29.6	4.78
50	696	71.2	44.8	26.4	0.516	29.6	2.85

6. Practical implications

The processes of deterioration in concrete are mediated largely by water. Sorption characteristics like absorption and sorptivity express in a very direct and simple way the tendency of a porous building material to absorb and transmit water. Also, it can give an indication of the possibility for the penetration of deleterious materials like chloride and sulfate ions which can lead to, in many times, long term deterioration in concrete structures. As it has been reported in conventional concrete and mortar [7], an understanding of moisture transport in foam concrete is important to estimate their service life as building material and to improve their quality.

7. Conclusions

- Water absorption and sorptivity of foam concrete are lower than the corresponding base mixes. They decrease with an increase in foam content. The reduction in water absorption and sorptivity with foam volume is attributed to the reduction in paste content. In the case of sorptivity, increased tortuous path for water migration in accordance with the proportion of air voids tends to dampen the transport phenomenon also.

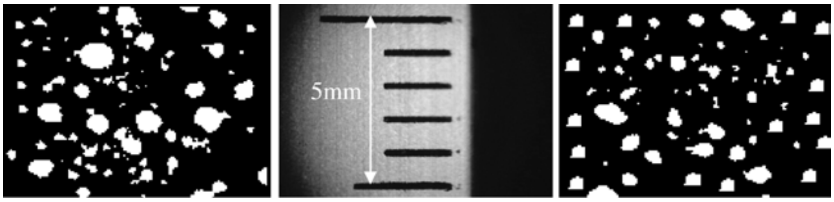

Fig. 7. Typical binary images (a) for cement–sand mix (b) scale (c) for cement–fly ash mix (100 % replacement level) (20X magnification).

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- Difference in the values of permeable porosity by vacuum saturation and water absorption under normal condition shows that all entrained pores (air-voids) are not taking part in the water absorption as they are not interconnected.
- For a given foam content, cement–sand-fly ash mixes showed relatively higher water absorption and sorptivity than cement–sand mixes due its higher water–solids requirement for achieving a stable and workable mix. For a given density, added to the above effect, increased paste volume due to reduced foam content will also contribute to the increase in sorption of fly ash mixes.
- For a given mix type sorptivity and water absorption are mainly controlled by capillary porosity while the reduction in strength with density is mainly governed by the volume of the entrained air voids.

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