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Investigation of foamcrete mechanical and physical properties

T Youssef [1], Y Elsayed [2], T A Elsayed [2] and S M Lawaty [2,3],

[1] Faculty of Engineering, l'Université Française d'Égypte, Cairo, Egypt
[2] Faculty of Engineering (Mataria), Helwan University, Cairo, Egypt
[3] Faculty of Engineering & Technology, Badr University in Cairo, Egypt

E-mail: Tarik.youssef@ufe.edu.eg

Abstract. Engineered Material Arresting Systems (EMAS) serve as a substitutional alternative/solution to airport runways when the Runway Safety Area (RSA) does not meet international Federal Aviation Administration (FAA) standards. The length of the runway can be shortened if an EMAS is installed on both ends of the runway. This paper provides experimental test results on foamcrete material used for such an important safety application. The objective of the paper is to present the required and measured properties of foamed concrete (density, compressive strength and water absorption) and results of an evaluation of a first phase of testing. In this study, a total of fourty eight mixes were conducted; yielding a range of densities, compressive strength(s) and water absorption characteristics that are: 554 to 1528 kg/m^3, 1.1 to 21 MPa and 7.4 to 28.3 %, respectively. It is demonstrated herein – though the Analysis of Means statistical method – that foam volume is predominantly the main factor affecting the observed output characteristics. This is followed by Sand/Filler and Filler/Cement that yield marginal effect compare to the former foam volume ingredient.

1. Introduction

Engineered Material Arresting Systems (EMAS) have been developed and enhanced as a solution to safely stop an over-running aircraft on runways; where obtaining the Federal Aviation Administration (FAA) standards of 1000 ft (304.8 m) length is not practical/applicable[1]. EMAS is typically composed of cellular cement-based blocks designed to stop an aircraft safely whilst over-running a runway at 70 knots (118 ft/sec) or less with minimal damage to the aircraft and equally minimal risk to passengers. It is mandatory that such system fully satisfies the safety requirements of “Part 139 Inspection” of the FAA Standards [2].

As the aircraft enters the EMAS, it makes a great transition from the paved ramp into the cellular cement arresting bed. Aircraft wheels then establish a tire to material interface; crushing the blocks as it moves through them (See **Figure *1*** and **Figure *2***). It is this contact that creates resistive drag force that quickly slows down and ultimately stops the aircraft. EMAS systems – in turn – are supposed to be customized to airport needs and limitations. They should also be tailored to accommodate specific aircraft types and a range of runway exit speed. As a result, arrester bed design(s) rely on complex computer analysis and modelling through incorporating many variables for each aircraft operating at the airport. The obtained models are continuously validated using the measured output of FAA testing.

Figure 1. Coastal Carolina Regional Airport, ending with Arrested Bed Zone

Figure 2. Tire-to-Foamcrete Interface Crushing, ultimately stopping aircraft

On site, the arrester bed area is prepared for EMAS and individual blocks are set into place. They are adhered to the pavement and sealed to further maintain the integrity of the system, in a simple and straightforward manner. Many real-life incidents/accident, demonstrated the effectiveness of the EMAS system; one of which is when an Eastern Air Lines Boeing 737-700, with 37 people on board, landed on La Guardia's runway 22 in rain and reduced visibility, overran the end of the runway, was slowed by the runway arrestor bed (EMAS) and came to a stop about 60 meters/200 feet past the runway end and about 40 meters/130 feet to the right of the extended runway center line. One occupant received minor injuries, the aircraft received minor if any damage [3].

Preliminary radar data suggested that the aircraft was on a normal approach profile descending through 250 feet AGL at 135 knots over ground, after touch down was still doing 132 knots over ground about 1400 meters/4600 feet past the runway threshold with about 700 meters/2300 feet of runway remaining. Ground observers reported it was raining hard at the time of touch down, water was splashing everywhere from the aircraft (The Aviation Herald, 2016).

2. Study Objectives

Now that cellular concrete, a multi-functional key solution material [4] to [10], is gaining more popularity in the aviation safety domain and construction field, its characteristics need further investigation to exploit its capacity. Superior traits, such as low density, high thermal insulation and high fire resistance, are also attributed to foamed concrete; making it gain popularity in other fields such as the construction domain. Nonetheless, lack of knowledge remains regarding the prediction of the mechanical and physical properties of foamed concrete; necessitating further experimentation and modeling.

Many researchers have conducted investigations on foamed concrete to improve its mechanical properties and reported that the dry density and the pore structure have the most significant influence on the mechanical properties of foamed concrete [11], [12]. However, further research is yet necessary to: (i) increase the currently available knowledge, (ii) develop a mix-design approach to produce foamed concrete for different purposes and anticipated aircraft contingencies. In this study, the main objectives are to investigate the influence of different mix proportions of preformed foamed concrete on its physical and mechanical properties (particularly compressive strength, density and water absorption). The statistical approach used for this investigation is the graphical Analysis of Means (ANOM) approach that depicts significant differences among groups of information in a visual form. ANOM methodology compares the average of each group to the mean of the overall process to discover statistical differences of significance; thus, highlighting on the most influential input variable. Analysis of means is a systematic statistical procedure, active mostly in quality control.

This effort comprises a total of fourty eight mix proportions (experiments) with two different types of fillers (sand and lime powder), cement, water and protein-based foam. The resulting outputs, density, compressive strength and water absorption, are observed and discussed herein. This study is considered an initial phase in a more comprehensive study to produce such materials to serve the local Egyptian market whether in the aviation safety field or construction industry.

3. Experimental Program

3.1. materials

In this program, ordinary Portland cement (CEM I 42.5R) is used as a binder, where the chemical composition is displayed in Table 1 and mechanical-and-physical properties are displayed in Table 2. Natural sand of specific gravity (S.G = 2.59) - sieved to avoid particles larger than 1.18 mm - is used as filler. Lime powder (calcium carbonate, CaCO3) of (S.G = 2.59) serves as a partial and full replacement for natural sand. X-Ray Diffraction analysis (XRD), conducted for the latter, shows that it is predominantly formed of calcite (See Figure 3).

Table 1. Chemical composition of ordinary Portland cement.

Oxide	SiO_2	Al2O_3	Fe_2O_3	CaO	MgO
%	19.29	4.52	3.59	62.08	1.80
Oxide	SO_3	K_2O	Na_2O	Cl	
%	3.61	0.29	0.45	0.09	

Table 2. Mechanical and physical properties of ordinary Port-land cement.

Compressive strength- 2 days	(MPa)	19.50
Compressive strength- 28 days	(MPa)	51.25
Setting time	(minutes)	123
Fineness (Blaine)	(cm^2/gm)	3732

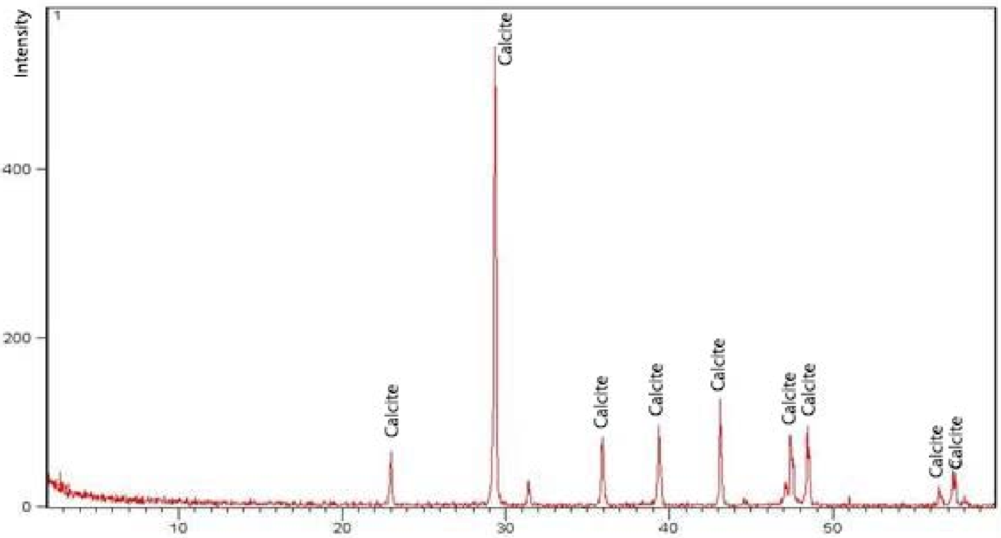

Figure 3. XRD test results of lime powder.

Foaming agent, LithoFoam SL 200-L, based on highly-active foam forming proteins, pre-foamed foam (at 80 kg/m3) was used. The foam is produced by blending foam agent, water and compressed air in a foam generator, as shown in Figure 4.

a. Foam agent tank. b. Generator set. c. Produced foam.

Figure 4. Foam Generator

3.2. Mix proportion

Forty-eight mix proportions were designed and conducted to investigate the influence of each ingredient on the foamed concrete physical/mechanical properties. These ingredients/factors are overall filler to cement ratio (F/C), sand-to-overall filler ratio (S/F) and foam volume per unit volume of concrete (V_f); noting that filler F, herein indicates both Sand and $CaCO_3$, that vary in percentage(s) depending on the mix (See Table3 below).

Table3 . Proportions of concrete mixes per one m^3

Ser.	Cement (kg)	Sand (kg)	Lime (kg)	Water (kg)	Foam (L)
S 73	798	80	319	389	479
S 75	641	64	257	312	641
S 77	526	52	211	256	736
S 79	424	42	169	206	763
S 81	345	35	138	169	760
S 83	343	34	137	167	892
S 85	598	119	478	379	478
S 87	506	102	404	321	675
S 89	455	91	363	289	848
S 91	343	69	274	218	822
S 93	269	54	215	171	791
S 95	254	51	203	161	878
S 109	736	147	221	348	441
S 111	642	129	192	303	642
S 113	701	140	211	331	981
S 115	462	92	139	218	831
S 117	347	69	104	164	763
S 119	336	67	101	159	876
S 121	572	229	343	357	458
S 123	240	96	144	150	320
S 125	447	178	268	279	834
S 127	342	136	206	213	820
S 129	336	134	201	209	984
S 131	273	109	164	171	949
S 145	754	226	150	356	452
S 147	636	191	127	300	636
S 149	569	170	114	269	797
S 151	537	161	107	254	967
S 153	426	127	85	201	936
S 155	351	105	70	166	915
S 157	597	358	239	369	478
S 159	411	247	164	254	548
S 161	395	236	158	244	737
S 163	335	201	133	207	803
S 165	297	178	119	184	873
S 167	263	158	105	163	912
S 181	694	277	69	308	417
S 183	562	224	56	249	562
S 185	567	227	57	252	794
S 187	438	175	44	194	787
S 189	371	149	37	165	817
S 191	316	126	32	141	821
S 193	547	438	109	282	438
S 195	435	348	87	225	580
S 197	367	294	73	190	687
S 199	310	248	62	160	745
S 201	312	250	62	161	914
S 203	262	211	53	136	910

3.3. *Water-solid Ratio*

Preformed foamed concrete is manufactured by adding preformed foam to cement mortar with a specific consistency (defined in terms of water-solid ratio). Optimal consistency is crucial; since using mortars at higher or lower consistency than the optimal, leads to foamed concrete with density ratio (defined as ratio of measured fresh density to design density) above unity. It is recommended - by the foam manufacturers - to use mortars with percent flow (measured by standard flow table [13]) in the range of 40 % to 50 % to obtain optimal consistency. Stiff mixes with low water-solids ratio causes bubbles to break. On the other hand, loose mixes with high water-solids ratio causes bubbles to merge and segregate [14]. Contrary to conventional concrete, water-cement ratio is not an influential factor on the compressive strength of foamed concrete [5], thus not considered in this study

3.4. *Specimens Preparation*

The process of foamed concrete manufacturing is described as follows: Portland cement and filler (sand and/or lime powder) were initially mixed in a horizontal mixer; water was added to the mixer; foam - at its final form was then added - to the homogeneous paste. Finally, full homogeneous foamed concrete was cast in 600 x 600 x 100 mm steel panels. The concrete panels were cured using wet burlap sheets for 28 days. Figure 5 shows the process of foamed concrete manufacturing.

a. Empty mixer. b. Solid materials. c. Adding water.

d. Mixing paste. e. Adding foam. f. Final product.

Figure 5. Foamed concrete manufacturing process.

3.4 Description of Experimental Procedures

3.4.1. Density: Five cubes with dimensions 100 x 100 x 100 mm - (according to ASTM C513-89 R95) - were saw-cut from each concrete panel to be tested. Oven-dry mass (A), saturated sur-face-dry mass in air (B) as well as the immersed mass of saturated specimen in water (C) were recorded according to ASTM C642-97; from which the bulk density is calculated in Equation 1:

Equation 1:

$$\rho = (A/(B-C))\rho_w \qquad (1)$$

where ρ is the density of foamed concrete and ρ_w is the density of water.

3.4.2. Compressive Strength: Four cubes of dimensions 100x100x100 mm were saw-cut from each concrete panel to be tested - (according to ASTM C513-89 R95) - to determine the 28-day compressive strength.

3.4.3. Water Absorption: Cubes with dimensions 100 x 100 x 100 mm were cut from each concrete panel to be tested. Oven dry mass (A), saturated surface-dry mass in air (B) and immersed mass of saturated specimen in water (C) were recorded according to ASTM C642-97 Equation 2.

Equation 2 *Water absorption (%) =* (B-A)/A ×*100* **(2)**

Porosity can be determined by the following Equation 3:

Equation 3 *Porosity (%) =* (B-A)/(B-C) × *100* **(3)**

Where ρ = water density.

4. Results and Discussion

As per the experimental procedures explained above, **Table 4** below demonstrates the obtained results for density, compressive strength and water absorption of the tested 48-foamcrete mixes.

Table 4. Test Results

Ser.	Density (kg/m^3)		Compressive strength (MPa)	Water absorption (%)
	Fresh	Hardened		
S 73	1625	1487	21.00	13.42
S 75	1326	1249	11.28	12.38
S 77	1105	1020	7.50	16.94
S 79	902	754	2.52	24.16
S 81	747	631	1.68	26.35
S 83	753	666	1.77	21.01
S 85	1612	1528	17.45	19.41
S 87	1387	1309	11.30	9.57
S 89	1265	1131	6.26	18.97
S 91	969	859	3.54	27.2
S 93	773	698	1.94	24.99
S 95	738	593	1.62	23.21
S 109	1487	1415	18.32	12.03
S 111	1318	1257	12.89	13.32
S 113	1461	1377	6.86	18.15
S 115	977	880	2.95	16.22
S 117	745	647	2.27	31.34
S 119	734	609	1.56	26.3
S 121	1538	1451	11.05	10.62
S 123	655	596	6.46	14.05
S 125	1239	1133	4.45	25.88
S 127	963	826	2.65	27.34
S 129	959	814	2.18	21.33
S 131	793	660	1.65	26.18
S 145	1522	1374	14.46	7.4
S 147	1305	1179	10.35	16.62
S 149	1186	1049	6.47	17.11
S 151	1136	1001	4.79	19.86
S 153	914	791	2.41	21.26

Ser.	Density (kg/m^3)		Compressive strength (MPa)	Water absorption (%)
	Fresh	Hardened		
S 155	766	627	1.73	26.19
S 157	1600	1496	15.33	13.72
S 159	1120	1046	5.01	14.73
S 161	1092	953	3.8	18.25
S 163	940	845	3.19	19.47
S 165	849	721	1.84	23.35
S 167	762	614	1.38	26.38
S 181	1382	1233	12.16	13.63
S 183	1136	1030	5.34	14.18
S 185	1166	1029	4.78	16.7
S 187	913	785	2.65	19.72
S 189	787	692	1.32	21.11
S 191	680	554	1.09	25.45
S 193	1411	1305	9.76	13.44
S 195	1142	1038	4.19	15.58
S 197	980	876	2.49	13.96
S 199	841	735	1.53	24.14
S 201	858	710	1.12	21.24
S 203	734	617	1.12	28.31

Figure 6, below, demonstrates that the main effective parameter on density is foam volume (V_f) followed by Sand/Filler and finally Filler/Cement input parameters. The differences in mean responses of Filler/Cement, Sand/Filler and (V_f) are 16.2, 113.3 and 781.1, respectively. For this study, the optimal parameters for minimum density are Filler/Cement = 1.0, Sand/Filler = 0.2, and a (V_f) of 92%, by volume.

Foam volume dosage is the main influential factor on the density of foamed concrete. Filler/Cement has a little effect on density as resulted from analysis of means. It is inversely proportional to density which can be explained by the fact that specific gravity of filler is less than that of cement. This in turn results in lower density. Sand/Filler is significantly more effective than Filler/Cement. It is inverse proportional with density which can be explained by the fact that finer filler results in better distribution of air bubbles and less bubbles loss which results in positive effect on density.

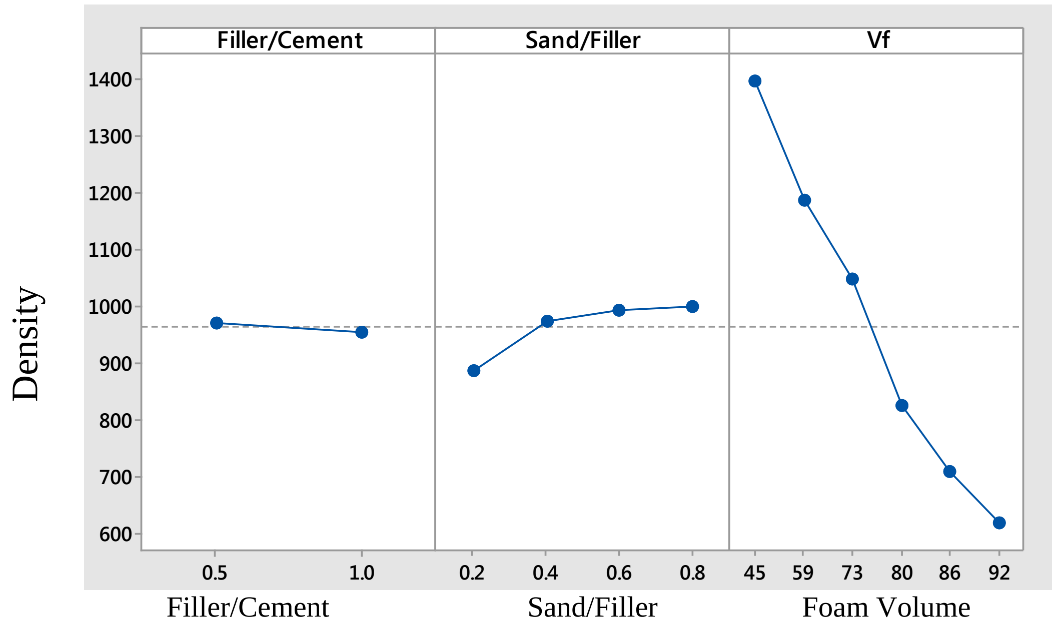

Figure 6. Factors affecting foamcrete density

Figure *7*, below, demonstrates that the main effective parameter on density is foam volume (V_f) then the Sand/Filler and Filler/Cement parameters. The differences in mean responses of Filler/Cement, Sand/Filler and (V_f) are 1.56, 3.61 and 12.98, respectively. For this study, the optimal parameters for maximum compressive strength are Filler/Cement = 0.5, Sand/Filler = 0.2, and a (V_f) of 45%, by volume. Foam volume dosage is the main influential factor on the compressive strength of foamed concrete. Filler/Cement has a marginal effect on compressive strength as shown by the analysis of means. It is inversely proportional to compressive strength whereas Sand/Filler is more effective than Filler/Cement.

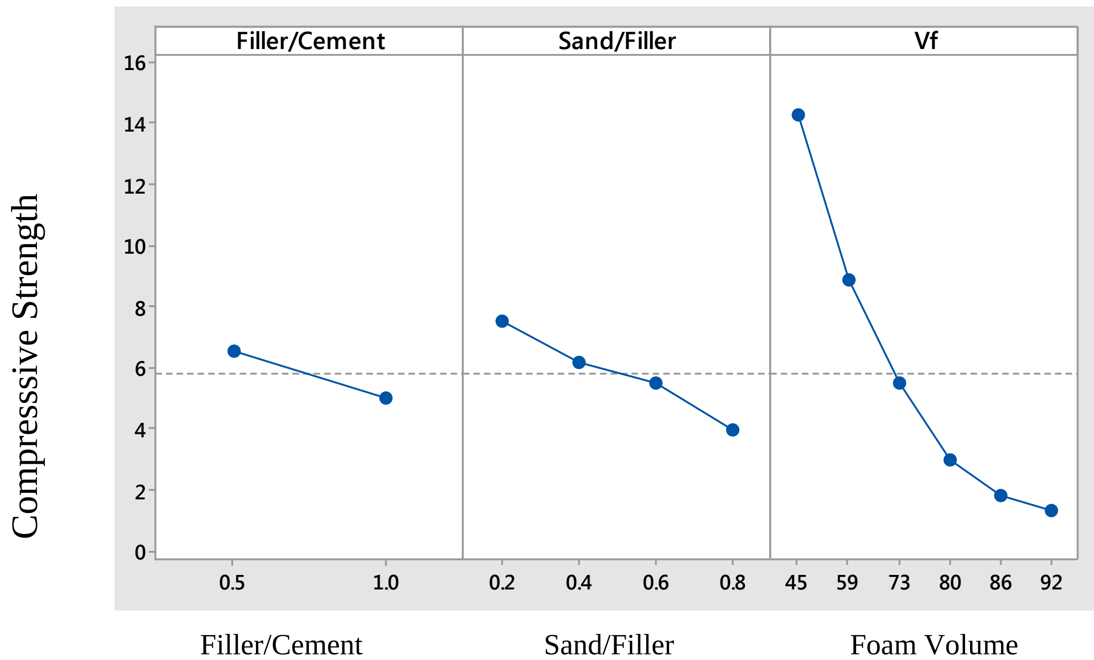

Figure 7. Factors affecting foamcrete compressive strength

The latter is also inversely proportional to compressive strength which can be explained by the fact that finer filler results in better distribution of air bubbles; resulting in positive effect on compressive strength. This is in addition to the micro filling effect. This explanation also meets the conclusions obtained in earlier research studies.

On the other hand, **Figure *8*** illustrates that the main effective parameter on water absorption is, once again, foam volume (V_f) then the Sand/Filler and Filler/Cement parameters. The differences in mean responses of Filler/Cement, Sand/Filler and (V_f) are 0.08, 1.58 and 13.57, respectively. For this study, the optimal parameters for minimum water absorption are Filler/Cement = 1.00, Sand/Filler = 0.80, and a (V_f) of 45%, by volume. Foam volume dosage is the main influential factor on the water absorption of foamed concrete. Filler/Cement has a little effect on water absorption as demonstrated through resulted analysis of means. Sand/Filler is more effective than Filler/Cement in this regards. The former is inversely proportional with water absorption which can be attributed to the increase in sand content, which leads to decrease in shrinkage and water demand; thus consecutive decrease in water absorption.

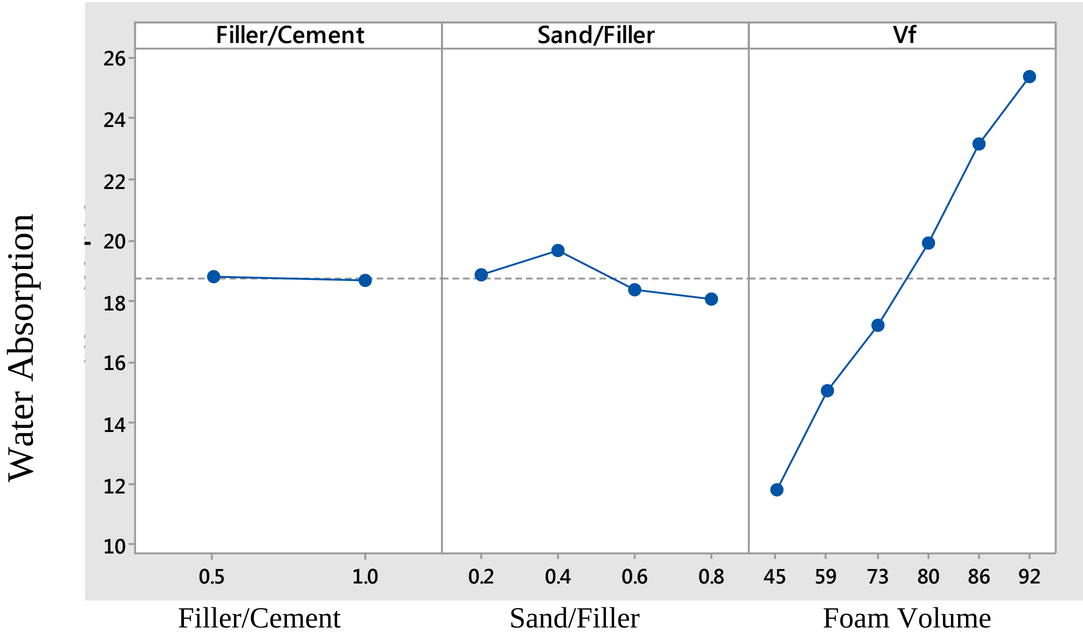

Figure 8. Factors affecting foamcrete water absorption

5. Recapitulation / Conclusion

In this study forty eight mixes were conducted; yielding a range of densities, compressive strength(s) and water absorption characteristics that are: 554 to 1528 kg/m^3, 1.1 to 21 MPa and 7.4 to 28.3 %, respectively.

Using the statistical Analysis of Means (ANOM) method allowed to deduce that foam volume (V_f) is predominantly the main factor affecting the observed output characteristics. This is followed by Sand/Filler and Filler/Cement that yield marginal effect compare to the former foam volume ingredient.

Further research is ongoing using different types of foam and filler, in a quest for better performance for the previously mentioned and other characteristics geared to aircraft tire arresting.

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