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Analysis of the Foam Generated Using Surfactant Sodium Lauryl Sulfate

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Abstract : The performance evaluation of a sodium lauryl sulfate to qualify as a foaming agent is presented in this paper. When new surfactants are used a systematic study of production parameters on the foam characteristics needs to be undertaken unlike proprietary foaming agents and foam generator for which manufacturer has predefined the parameters. The relative influence of the foam parameters and optimization of factors were carried out through a systematic experiment design. The foam production parameters namely foam generation pressure and dilution ratio of foaming agents are observed to have significant effect on all foam characteristics with the exception of foam output rate on which only foam generation pressure has influence. The foam with good initial foam density need not necessarily be stable foam. The optimum levels of foam production parameters are determined for the surfactant Sodium lauryl sulfate which can be used to produce stable foam for foam concrete production.

Keywords : foam, density, stability, output rate, capacity, sodium lauryl sulfate.

1. Introduction

Foaming agents required for producing aqueous stable foam can be either natural based like resin soap and glue, hydrolysed protein such as keratin, cattle hooves and fish scales, blood, saponin and casein or synthetic based like detergents (sodium lauryl sulfate, alkalyaryl sulphonate.[1] Synthetic foaming agents are preferred for the following advantages; (i) allows a greater control over density of material than protein based foams[2] (ii) possess permanent properties (since they are produced in accordance with technical requirements) and (iii) longer working life. Proper selection of foaming agent is essential as the type of foaming agent used influences the final strength of foamed materials. Sodium lauryl sulfate has been used in the concentration range of 0.1 to 0.4% for the production of foamed gypsum of density less than 1,000 kg/m^3.[3] Surfactant mixture of 2% Sulfanol as foaming agent and 0.3% bone glue hydrosolution as stabilizer in the ratio 1 : 0.15 is reported to produce a stable foam for which stability was assessed by the time taken for surfactant breakdown.[4] Foam produced with high purity hydoxy silicon ester has been used in the manufacture of low density cement composites.[5]

The foam parameters namely dilution ratio and generation pressure to be adopted for stable foam production are predefined by the manufacturer when proprietary foaming agents and a foam generator are used. However such parameters have to be determined for new surfactants. The performance evaluation of a surfactant to qualify as a potential foaming agent is through the following characteristics of foam produced.

Foam capacity is a measure of expansion ratio of foaming solution. Aqueous foams used in fire fighting applications are mainly classified by their expansion ratio which is expressed as ratio of total volume of foam to the liquid volume.[6] Foam capacity is a user friendly term for foam as it gives a volumetric measurement of foam that could be produced per unit quantity of foam concentrate. The foam capacity can also be taken as a measure of foamability or foam generating power of surfactant solution. Foam density is useful to calculate the volume of foam required to be added for achieving a desired density of foam concrete. The foam stability reflects the life of lamellae in the generated foam. One of the important requirements of foam stability is to ensure the fine and uniform texture throughout the whole hardening process of foamed concrete[7] or life time of foam is generally defined as drain time, i.e. the time required for the foam to decompose into the original liquid and the gas phase. It is determined by measuring the amount of separation of surfactant solution at various time intervals[8] either as free drainage or forced drainage.[9]

Selection of economical dilution ratio of foaming agent can reduce the overall cost of foamed concrete production not only by minimizing the quantity of foaming agent requirement, but also by reducing the cost involved in transporting the foam concentrate. The generation pressure also affects the bubble size distribution of foam which is very important to produce good quality of foam concrete with higher compressive strength.[10] The dilution ratio and foam generation pressure are to be varied to study their influence on the characteristics of foam produced. Having identified the important foam characteristics and foam generating parameters, the performance evaluation of a typical surfactant viz., Sodium

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lauryl sulfate has been undertaken with the following objectives:

i. To study the relative influence of surfactant concentration and foam generation pressure, and their interaction on foam characteristics through a systematic experiment design based on Response Surface Methodology.
ii. To determine the optimal level of factors that produce the desired response goals, by adopting numerical optimization method using the predicted regression models.

2. Materials and methods

2.1 Materials and equipment used

Foam was produced by aerating a commercial grade synthetic surfactant Sodium lauryl sulfate (SLS) of purity of around 85%. It is an anionic surfactant, which falls under the general group of alkyl sulfates with bifunctionality in one molecule, and this provides the basic properties to it to act as a foaming agent.[11] Required amount of SLS was weighed to make respectively 0.25, 0.5, 1, 2, 4 and 10% of surfactant in water. Deionized water was used for all the measurements. Homogenous mixing of surfactant in water was achieved with the help of a stirrer. Foam was generated using a laboratory-based foam generator by mixing compressed air and foaming solution in high-density restrictions.[12] The surfactant solution prepared was poured through a nozzle into the pressure container of foam generator. The pressure at which the foaming solution is mixed with compressed air is varied with a help of pressure regulator. After thorough mixing of surfactant solution with compressed air, the foam was generated through the foam outlet. All possible mechanical vibrations were avoided and the measurement conditions were maintained identical during measurement of foam properties. For producing foam concrete, Ordinary Portland Cement conforming to IS 12269-1987[13] and pulverized river sand finer than 300 μm (specific gravity = 2.52) were used. A homogenous mortar mix of cement sand slurry was first prepared by hand mixing followed by the addition of calculated weight of foam to the mortar mix and the mixing was continued till the foam is uniformly blended into the slurry.

2.2 Experimental design

Response surface methodology is adopted when the response of interest is influenced by several variables and the objective is to optimize the response. Hence for the present study, a statistical method of experimental design based on response surface methodology (RSM) using a two factor central composite design (CCD) with rotatability or equal precision (to provide equal precision of estimates in all directions) is employed to study the effect of two independent variables x_1, SLS concentration (SC) and x_2, foam generation pressure (FGP) on four response variables namely Foam output rate (FOR), Foam capacity (FC), Initial foam density (IFD), Foam stability (FS) respectively. SLS concentration (SC) / Dilution ratio (DR) represents the concentration of surfactant in the foaming premix solution prepared. It can also be expressed in terms of dilution ratio say 1: x which means one part of foaming agent is diluted with x parts of water. SLS concentration range adopted for the present study is from 0.25% (1 : 400) to 10% (1 : 10). The pressure at which the foaming solution is mixed with compressed air and the foam is generated is varied from 78 to 292 kPa.

The rate of foam generation is measured by the time taken for collection of foam in a container of known volume. Foam capacity gives the measure of quantity of foam produced per unit foam concentrate used. It is calculated as reciprocal of Initial foam density which is the unit weight of foam measured immediately after its collection. The stability of foam is assessed by free drainage test as prescribed by Def Standard 42–40 (2002).[14] A drainage pan of 1,612 ml nominal volume with a conical base rounded to accept externally a 12.7 mm bore by 25 mm long polymethyl methacrylate tube with a 1.6 mm bore brass cock at its lower end is used. The pan is filled with foam and the volume of the solution drained and the weight of foam is measured at various time intervals. The percentage volume drained is calculated from the measured initial foam density values. Time taken for 25% foam drainage volume is also measured.

Thirteen experimental treatments were assigned based on the CCD with two independent variables at five levels of each variable (Tables 1~2). The actual (natural variables) and coded variables are reported in Table 2. The results were analysed using the Statistical Analysis Software (SAS Release 8.02)[15] to determine the quadratic response surface adopting the following second order model (to take care of curvature in the relationship) for predicting the variation of response variables as a function of independent variables;

$$Yi = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \quad (1)$$

Where Yi is predicted response, β_o is offset term, β_1 and β_2 are regression coefficients for main variable effects, β_{11} and β_{22} are quadratic effects and β_{12} is interaction effect of independent variables. The details of model equations for foam output rate, foam capacity, initial foam density and foam density at various time intervals, % solution drained and density ratio at fifth minute after foam generation are presented in Table 3.

Table 1 Components of central composite rotatable second order design.

No. of variables	No. of design points			Total run	Alpha
	Factorial	Axial	Central		
2	4	4	5	13	1.414

Table 2 Matrix of the central composite design (CCD).

Treatment runs	SLS concentration (%)	Foam generation pressure (kPa)	SLS concentration (%)	Foam generation pressure (kPa)
	Natural variables		Coded variables	
1	10	186.33	1.414	0
2	8.57	110.05	1	−1
3(C)	5.13	186.33	0	0
4	8.57	262.61	1	1
5	0.25	186.33	−1.414	0
6	1.68	110.05	-1	-1
7(C)	5.13	186.33	0	0
8	5.13	78.46	0	−1.414
9(C)	5.13	186.33	0	0
10(C)	5.13	186.33	0	0
11(C)	5.13	186.33	0	0
12	5.13	294.21	0	1.414
13	1.68	262.61	-1	1

Table 3 Model equations for foam properties.

Response	Response model	R^2
Foam output rate (m^3/hr)	$0.321202 + 0.165003 \times SC - 0.00681 \times FGP - 1.8 \times 10^{-18} \times SC \times FGP$ $-0.01631 \times SC^2 + 3.54 \times 10^{-5} \times FGP^2$	0.9521
Foam capacity (m^3)	$0.050506 + 0.003232 \times SC - 0.00015 \times FGP + 2.85 \times 10^{-6} \times SC \times FGP$ $-0.00024 \times SC^2 + 2.36 \times 10^{-7} \times FGP^2$	0.9842
Initial foam density (kg /m^3)	$20.12124 - 2.05373 \times SC + 0.0834(9 \times FGP - 0.0038 \times SC \times FGP)$ $+ 0.184089 \times SC^2 - 9.7 \times 10^{-5} \times FGP^2$	0.9599
Foam density at fifth minute (kg /m^3)	$18.39425 - 1.68899 \times SC + 0.066825 \times FGP - 1.17893 \times 10^{-3} \times SC \times FGP$ $+ 0.15216 \times SC^2 - 1.3224 \times 10^{-4} \times FGP^2$	0.9633
Foam density at tenth minute (kg /m^3)	$7.51031 - 0.19505 \times SC + 1.00621 \times 10^{-4} \times FGP - 2.64309 \times 10^{-3} \times SC \times FGP$ $+ 0.096673 \times SC^2 + 3.67349 \times 10^{-5} \times FGP^2$	0.916
Foam density at fifteenth minute (kg /m^3)	$3.004147 + 0.06465 \times SC + 0.005017 \times FGP - 0.00255 \times SC \times FGP$ $+ 0.042761 \times SC^2 + 2.076 \times 10^{-5} \times FGP^2$	0.84
Solution drained at fifth minute (%)	$8.573218 - 0.26454 \times SC + 0.023221 \times FGP - 0.0057 \times SC \times FGP$ $-0.0263 \times SC^2 + 0.000161 \times FGP^2$	0.9698
Foam density ratio at fifth minute	$0.914268 + 0.002645 \times SC - 0.00023 \times FGP + 5.7 \times 10^{-5} \times SC \times FGP$ $+ 0.000263 \times SC^2 - 1.6 \times 10^{-6} \times FGP^2$	0.9698

*SC: surfactant concentration (%), FGP : foam generation pressure (kPa)

3. Discussion of results

(i) Effect of factors and their interaction: The significance of the estimated regression coefficients for each response variable is assessed by F-ratio at a probability (p) of 0.05. As shown in Table 4, the main effects of independent variables appear to have the most significant effect ($p < 0.05$) as compared to quadratic and interaction effects. From the Table 5, it is observed that the main effect of SLS concentration and foam generation pressure exhibited both positive and negative effects on the response variables. Positive effect implies that any increase in the factor level is associated with a corresponding increase in response variable. Negative effect implies that an increase in factor level is associated with a decrease in response variable. There is no interaction effect observed between SLS concentration and foam generation pressure on all the response variables studied.

(ii) Model adequacy check: The adequacy of response models were determined using model analysis, coefficient of determination (R^2) analysis, and by comparing the experimental data with values predicted by response surface models.[16] Validation of the second order polynomial regression models with additional experimental data were observed to be highly adequate to interpret a reliable relationship between the independent and response variables with a satisfactory coefficient R^2 (> 0.9) for most of the regression models (Table 6). As a next step, each of the foam characteristics are discussed by plotting the response surface graphs using the empirical models.

3.1 Foam output rate (FOR)

The response surface for foam output rate is presented in Fig 1.

Table 4 ANOVA and regression coefficients of the response surface models fitted.

Variables		Main effects		Quadratic effects		Interaction effect
		SLS concentration x_1 (%)	Foam generation pressure x_1 (kPa)	x_1^2	x_2^2	$x_1 x_2$
Foam output rate (m^3/hr)	p-value	0.8826	< 0.0001	0.0069	0.005	1
	F-ratio	0.023	104.19	14.28	16.18	0
Foam capacity (m^3)	p-value	< 0.0001	< 0.0001	< 0.0001	0.0052	0.1422
	F-ratio	190.18	147.31	69.87	15.98	2.73
Initial foam density (kg /m^3)	p-value	< 0.0001	0.0004	0.0005	0.163	0.0737
	F-ratio	80.41	40.21	36.74	2.43	4.42
Solution drained (%)	p-value	< 0.0001	< 0.0001	0.5535	0.1042	0.0579
	F-ratio	138.16	77.43	0.39	3.48	5.13
Foam density ratio	p-value	< 0.0001	< 0.0001	0.5535	0.1042	0.0579
	F-ratio	138.16	77.43	0.39	3.48	5.13

Table 5 Regression coefficients, R^2, adjusted R^2, probability values and F values for the final models.

Factors		Foam output rate (m^3/hr)		Foam capacity (m^3)		Initial foam density (kg/m^3)		Solution drained (%)		Foam density ratio	
SC (%)	FGP (kPa)	P	O	P	O	P	O	P	O	P	O
0.5	137	0.133	0.15	0.036	0.036	30	28	14	15	0.86	0.84
0.5	196	0.427	0.42	0.031	0.033	33	30	19	19	0.81	0.8
0.5	294	1.464	1.56	0.028	0.029	36	34	28	27	0.72	0.72
2	137	0.319	0.2	0.040	0.044	26	23	12	9	0.87	0.9
2	196	0.614	0.53	0.036	0.042	29	24	16	13	0.84	0.87
2	294	1.65	1.69	0.033	0.037	31	27	25	22	0.75	0.78
10	137	0.074	0.054	0.046	0.047	22	21	2	3	0.98	0.97
10	196	0.368	0.3	0.043	0.047	23	21	3	3	0.97	0.97
10	294	1.405	1	0.042	0.043	23	23	7	10	0.93	0.85

SC-surfactant concentration, FGP–foam generation pressure, P-predicted, O-observed.

Table 6 Observed and predicted responses for confirmation of models.

Regression coefficient	Foam output rate (m^3/hr)	Foam capacity (m^3)	Initial foam density (kg /m^3)	Solution drained (%)	Foam density ratio
β_o	0.3212	0.050506	20.12124	8.57322	0.91427
β_1	0.165	3.2316×10^{-3}	−2.05373	−0.26454	2.64536×10^{-3}
β_2	-6.81179×10^{-3}	-1.53713×10^{-4}	0.083490	0.023221	-2.32209×10^{-4}
β_1^2	−0.016305	-2.41946×10^{-4}	0.18409	−0.026298	2.62985×10^{-4}
β_2^2	3.54459×10^{-5}	2.36306×10^{-7}	-9.66707×10^{-5}	1.61118×10^{-4}	-1.61118×10^{-6}
β_{12}	-1.8472×10^{-18}	2.85225×10^{-6}	-3.803×10^{-3}	-5.7045×10^{-3}	$5.7045*10^{-5}$
R^2	0.9521	0.9842	0.9599	0.9698	0.9698
R^2 adj	0.9179	0.9729	0.9312	0.9483	0.9483
Regression P value	0.0002	< 0.0001	< 0.0001	< 0.0001	< 0.0001
F value	27.85	87.29	33.48	44.99	44.99

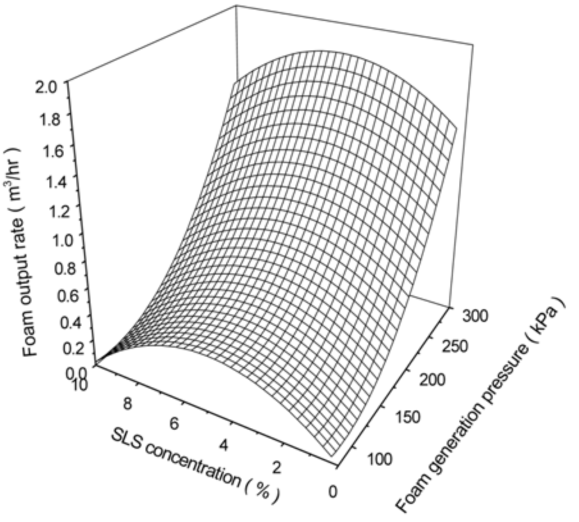

Fig. 1 Variation of foam output rate with foam generation pressure and SLS concentration.

For a constant SLS concentration, foam output rate increases significantly with an increase in foam generation pressure. The variation of foam output rate with SLS concentration is marginal when compared to that with foam generation pressure. Hence the main effect of SLS concentration is observed to be insignificant ($p > 0.05$) from regression model studies. For a given foam generation pressure, the foam output rate increases with SLS concentration up to a dosage of around 6% after which a marginal reduction is observed. This reduction is due to the more viscous foam produced at high SLS concentration. From Table 4 it is observed that there is no interaction effect between SLS concentration and foam generation pressure.

3.2 Foam capacity (FC)

The response surface for foam capacity is presented in Fig. 2. Both the main effects and quadratic effects of SLS concentration and foam generation pressure significantly ($p < 0.05$) influence the foam capacity with no interaction between them. From Fig. 2 it is observed that at lower SLS concentration an increase in foam generation pressure reduces the foam capacity. At lower SLS concentration and higher foam generation pressure, very wet foam with lesser air content is produced resulting in less foam volume and thus lower foam capacity. For given foam generation pressure the foam capacity or foamability increases with an increase in SLS concentration. The maximum foam capacity is achieved when lower foam generation pressure and higher SLS concentration is adopted. This is because at lower foam generation pressure and higher SLS concentration, the foam is relatively dry and hence produces higher volume of foam. Very high foam capacity, say greater than 0.05 m^3, results in over-expanded foam with low densities. Such low-density foams tend to have larger bubbles with thin walls, poor strength and hence are likely to collapse.

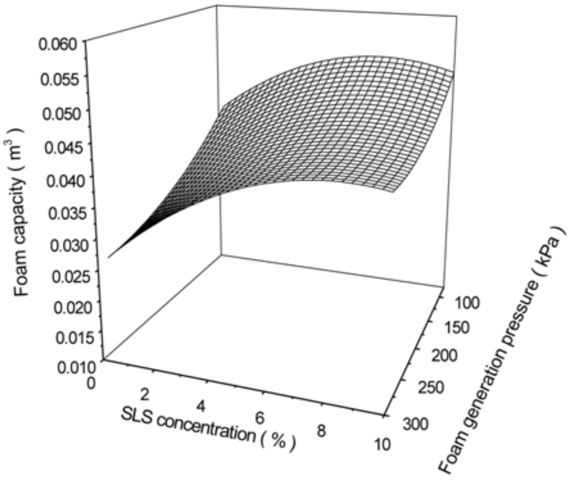

Fig. 2 Variation of foam capacity with foam generation pressure and SLS concentration.

3.3 Relation between foam capacity and foam output rate

From Fig. 3 can be observed that the foam capacity increases with foam output rate up to 4% concentration of SLS. Beyond this concentration, the foam capacity is higher even when the foam output rate is lower. Such behaviour is attributed to the relatively higher influence of SLS concentration on foam capacity than on foam output rate (which is primarily dependent on foam generation pressure) (Table 4). Hence at higher SLS concentration (say 10%) the foam capacity is higher irrespective of foam output rate. It is also observed from the Fig. 3 that the foam generating power of SLS surfactant solution reduces with an increase in foam generation pressure, i.e. ratio of total volume of foam to liquid volume is lower in very wet foam produced at higher foam generation pressures.

3.4 Initial foam density (IFD)

The response surface for Initial foam density (IFD) is presented in Fig. 4. The initial foam density is observed to vary from 20 to 35 kg/m^3 for the range of SLS concentration and foam generation pressure studied. The main effects viz., SLS concentration and foam generation pressure ($p < 0.05$) influenced the initial foam density with no interaction between them (Table 4). Initial foam density varies almost linearly with foam generation pressure and non-linearly with SLS concentration. At lower SLS concentration an increase in foam generation pressure increases the initial foam density. At higher foam generation pressure, initial foam density decreases with increase in SLS concentration. At higher foam generation pressure and lower SLS concentration, foam is observed to have more liquid and less air resulting in higher foam density, which is confirmed by higher drainage values obtained (as discussed in the next section).

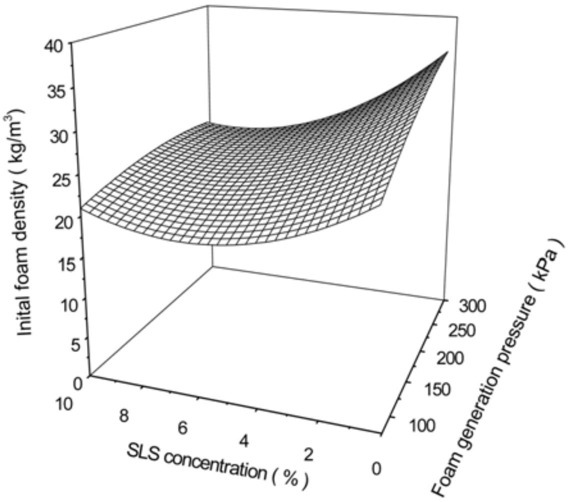

Fig. 4 Variation of foam density with foam generation pressure and SLS concentration.

3.5 Foam stability

The response surface for the percentage solution drained at 5th minute after foam generation is presented in Fig. 5. From Table 4 it is observed that both the main effects of SLS concentration and foam generation pressure have significant effect on percentage solution drained. There is no significant interaction effect ($p > 0.05$) between SLS concentration and foam generation pressure (Table 4). For a constant SLS concentration, the percentage solution drained increases with an increase in foam generation pressure resulting in poor stability foam. This effect is more significant when the SLS concentration is lower. At higher foam generation

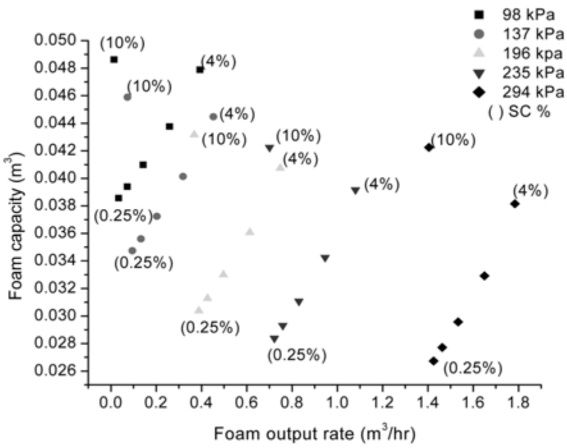

Fig. 3 Variation of foam capacity with foam output rate.

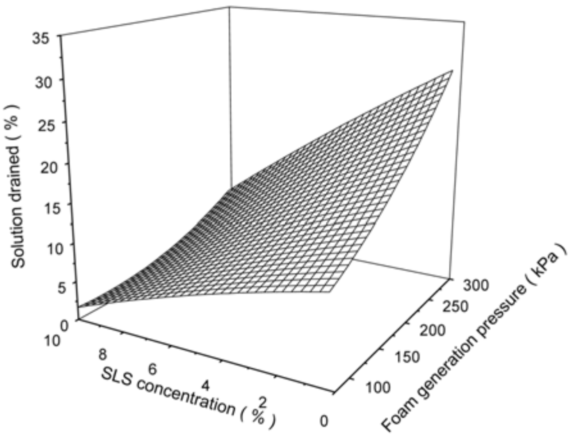

Fig. 5 Variation of percentage solution drained with foam generation pressure and SLS concentration (at fifth minute after foam generation).

pressure an increase in SLS concentration reduces the percentage solution drained. The variation of percentage solution drained with SLS concentration is less pronounced at lower foam generation pressure as compared to higher foam generation pressure. For any combination of surfactant concentration and foam generation pressure, the time taken for 25% foam drainage volume is observed to be more than 210 seconds as prescribed by Def Standard 42-40[14] for synthetic aqueous film forming foam fire extinguishant. Also solution drained in five minutes is lesser than 25% irrespective of surfactant concentration used for foam generation pressure less than 200 kPa.

The response surface for the foam density ratio in five minutes after foam generation is presented in Fig. 6. The foam density ratio, (the ratio of foam density at different time interval to the initial foam density) is the inverse function of percentage solution drained. For a constant SLS concentration, the density ratio decreases with an increase in foam generation pressure resulting in production of poor stability foam. This effect is more significant when SLS concentration is lower. At higher foam generation pressure an increase in SLS concentration increases the density ratio. The variation of density ratio with SLS concentration is less pronounced at lower foam generation pressure as compared to higher foam generation pressure. Hence the SLS concentration and foam generation pressure should not only be based on achieving higher foam density (to satisfy the ASTM specified range of density) but should be based on stability also. Fig. 7 shows the variation of foam density with various time intervals namely 5, 10 and 15 minutes after foam generation. From Fig. 7 it is observed that the rate of drainage increases after five minutes, which is evident from the higher drop in foam density.

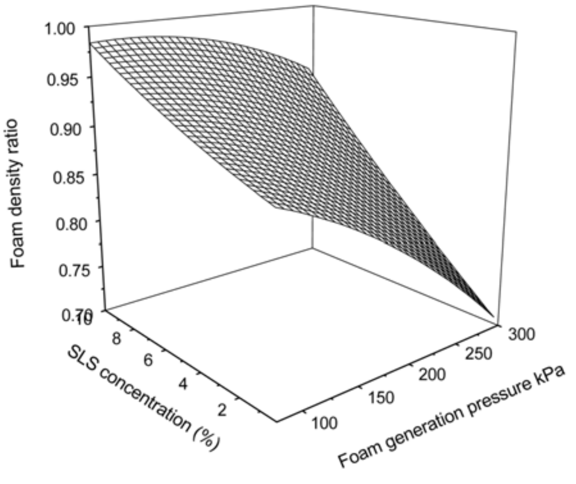

Fig. 6 Variation of foam density ratio with foam generation pressure and SLS concentration (at fifth minute after foam generation).

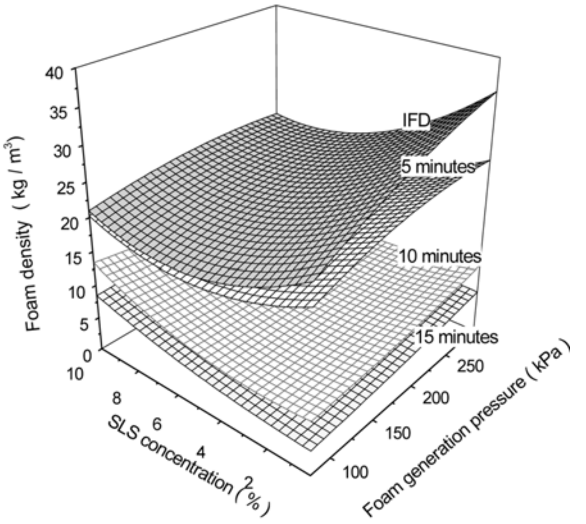

Fig. 7 Variation of foam density with foam generation pressure and SLS concentration at various time intervals after foam generation.

3.6 Optimization and check for stability in the mix

The objective of optimization of foam parameters is to find the optimum level of surfactant concentration and foam generation pressure that could result in production of foam with better foam capacity and foam stability along with reasonable foam output rate. Multiple optimization is carried out by numerical optimization method using SAS Release 8.02 for the following criteria; minimize percentage solution drained, maximize foam density ratio (to increase foam stability), minimize SLS concentration (to reduce cost), and to achieve a target foam output rate of at least 0.09 m^3/hr. Each response has been assigned an importance value (weightage) relative to the other responses. Percentage solution drained and foam density ratio is assigned an importance of 4 and the other responses are assigned an importance of 3 out of 5 scale. Hence more weightage is assigned to foam stability. From the optimal values listed in Table 7, it is observed that the optimal value of foam generation pressure is less than 150 kPa and SLS concentration of around 2%, which are economically feasible values. Under the optimum condition the corresponding predicted response values of foam characteristics were satisfactory. The expansion rate achieved under optimum condition is 42, which is a quite high value. The optimized factors were verified with the ASTM prescribed range for Initial Foam density[17] and the foam stability was assessed based on the guideline prescribed by Defence standard for fire fighting foam (Def Standard 42-40 (2002).[14] The ASTM specified range of initial foam density (i.e. 32 to 64 kg/m^3)[17] could not be achieved when foam is produced at optimum level of foam generation pressure and SLS concentration selected by considering foam stability. However by increasing the foam generation pressure above 250 kPa and by using SLS concentration below 1%, higher initial foam density satisfying ASTM requirement[17] could be produced. But such foam is observed to be less stable with higher drainage, which results in lower density beyond five minutes. Hence apart from foam density, foam drainage is also an important parameter in the selection of foaming agent. Increasing the SLS concentration to 10% could reduce the percentage solution drained in five minutes. But within ten minutes minimum drainage of 35% solution occurs irrespective of SLS concentration and foam generation pressure adopted. Time taken for 25% foam drainage volume under optimum condition was observed to be 366 seconds which is far greater than the value of 210 seconds prescribed by Def Standard 42-40 (2002)[14] for synthetic aqueous film forming foam used in fire extinguishers. Thus when the optimum levels of foam production parameters are adopted, the foam produced has better characteristics and it can be used to produce stable cellular structure when used in foam concrete.[18]

Table 7 Optimized factors and corresponding response goals.

SLS concentration (%)	Foam generation pressure (kPa)	Foam output rate (m^3/hr)	Foam capacity (m^3)	Initial foam density (kg/m^3)	Solution drained (in 5 minutes) (%)	Foam density ratio (in 5 minutes)
1.8	115	0.25	0.042	25	11.6	0.88

Having identified the optimal surfactant concentration and foam generation pressure, as a next step, the suitability of this surfactant for the production of foam concrete needs to be verified. This is done in two steps, viz; (i) evaluation of performance of SLS in cement paste and validation of the same to check whether the requirements of ASTM C 869[19] with respect to fresh density, strength and water absorption of foamed cement paste are fulfilled (ii) evaluation of its performance in cement sand mortar (foam concrete). The test method prescribed by ASTM C 796-97 for assessing the performance of a foaming chemical to be used in producing foam for making cellular concrete for achieving a cement paste of known design density 641 kg/m^3 and water-cement ratio of 0.58 was adopted. The same test procedure and mix proportioning relationship were appropriately modified and adopted to produce cement sand mortar of different design densities. The stability of test mixes was assessed by comparing the calculated and actual quantity of foam required to achieve a plastic density of foam concrete within ±50 kg/m^3 of the design value. The foamed cement paste made with the foam produced at the optimized surfactant concentration and foam generation pressure, meets the physical requirements of ASTM (Table 8) confirming the foam stability.

Having evaluated the suitability of the surfactant for production of foam cement paste as per ASTM requirements, as a next step, its performance in cement-sand mortar needs to be studied. Cement-sand mortar mixes of ratio 1:1 of different design densities 1,000, 1,250 and 1,500 kg/m^3 were produced by varying the foam volume from 46 to 18%. The properties of foam concrete at the optimized surfactant concentration and foam generation pressure are presented in Table 9. It was observed that the foam produced with the surfactant Sodium lauryl sulfate could result in stable foam concrete mixes with satisfactory properties.

4. Conclusions

The conclusions drawn from this study and discussed below are applicable to the characteristics of materials used and the range of parameters investigated.

1) The variation of foam output rate with SLS concentration is marginal when compared to that with foam generation pressure.

2) The maximum foam capacity is achieved when lower foam generation pressure and higher SLS concentration is adopted.

3) SLS concentration has more significant effect on foam capacity than that of foam output rate particularly at higher dosages of surfactant.

4) At higher foam generation pressure and lower SLS concentration, foam is observed to have more liquid and less air resulting in higher foam density which is confirmed by higher drainage values obtained.

5) It is observed that the optimal value of foam generation pressure is less than 150 kPa and SLS concentration of around 2% and the corresponding predicted response values of foam characteristics were satisfactory under optimal conditions.

6) From the foam stability test in cement paste and mortar, it is observed that the surfactant is suitable for use in foamed concrete production when optimized foam production parameters are adopted.

Table 8 Comparison of foam cement paste test results with ASTM specifications.

Properties of foam cement paste	Experimental results	ASTM C 869-91 requirements
Fresh density (kg/m^3)	642	641 ± 48
Dry density (kg/m^3)	516	487 ± 40
Comp. strength (MPa)	2.01	1.40 (min)
Water absorption (% by volume)	15	25% (max)
Actual/calculated foam required to produce foam concrete within ±50 kg/m^3 of the design density	1	1

Table 9 Test results of foam cement sand mortar.

Properties of foam cement sand mortar	Foam volume (%)		
	18	32	46
Fresh density (kg/m^3)	1500	1250	1000
Dry density (kg/m^3)	1215	1042	850
Water-solids ratio	0.4	0.425	0.45
Comp. strength (MPa)	12.5	7	4.3
Water absorption (% by volume)	28.2	25.14	22.62
Actual/calculated foam required to produce foam concrete within ±50 kg/m^3 of the design density	1	1	1

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