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# Desirability analysis of Commercial-off-the-shelf (COTS) alternative foaming agents for foamed concrete production

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**Abstract**

Foamed concrete (FC) offers potential for various lightweight construction applications, making the need for industry-standard foaming agents crucial in achieving its desired properties. However, the limited availability of quality foaming agents hampers FC's widespread use in many economies. To address this, the potential of commercial-off-the-shelf (COTS) products capable of foaming has been explored in this paper. Three widely available COTS alternatives – Coconut Diethanolamide (CDEA), liquid detergent, and dishwashing liquid – were examined for FC production. Response Surface Methodology (RSM) and desirability analysis were employed to differentiate the effects of these COTS alternatives on various FC properties. Moreover, adjusting additional factors like foam volume, water-to-cement ratio, and maximum aggregate size – known influencers of FC properties – during the experiments revealed distinct impacts of each COTS alternative foaming agent on FC properties. Results revealed that FCs exhibiting highest compressive strengths are those made using CDEA, then followed by liquid detergent, and dishwashing liquid. In terms of absorption, FC samples made using CDEA exhibited the lowest values, followed by liquid detergent, then dishwashing liquid. In terms of unit cost, FC samples made using CDEA is the most economical, followed dishwashing liquid, then liquid detergent. However, regardless of the type of COTS alternative foaming the impact of FC density and CO2 emission equivalence values is similar. Furthermore, desirability analysis identified that CDEA yields the most desirable FC with optimal values for factors such as foam volume of about 60.073%, water-cement ratio of about 0.50, and maximum aggregate size of 1.611mm. Liquid detergent and dishwashing liquid also yields combinations of input factors which can produce FC conforming to corresponding ASTM standards for foamed concrete but with lower desirability. In conclusion, the investigation demonstrated the potential effectiveness of locally available COTS alternative foaming agents in FC production, contributing to their practical utilization and promoting more sustainable construction materials.

**Keywords:** Foamed concrete, Response surface methodology, Desirability analysis, Coconut Diethanolamide, Liquid detergent, Dishwashing liquid

## 1. Introduction

Concrete ranks second only to water as the most utilized material globally. The demand for concrete continues to rise to fuel socio-economic development which resulted in a surge in Portland cement production, contributing significantly to global environmental challenges. Approximately 5% of annual anthropogenic $CO_2$ emissions stem from cement-related activities [1]. As such, recent trends in the concrete sector emphasize optimizing concrete products to align with sustainable development objectives.

Concrete material optimization encompasses validating alternative cementitious composites [2], quantifying concrete's sustainable traits [3], and employing alternative and innovative materials [4]. These strategies significantly improve concrete products' sustainable characteristics. Foamed concrete (FC) is a prime example of a product that embodies sustainable properties. FC, for example, is regarded to have superior sound and heat insulation, lower dead weight [5], and seismic resilience [6]. Moreover, foresight groups worldwide have identified the future need for construction materials that are light, durable, simple to use, economical, and yet more environmentally sustainable [7].

FC production, however, faces challenges in many locations due to the scarcity of a key element: the foaming agent. Common industry-standard foaming agents are often imported from countries like the United States, the United Kingdom, and India (see e.g., [8, 9]), posing difficulties for local manufacturers. This has spurred interest in the use of alternative agents to improve the adaptability of the technology worldwide. However, care should be exercised in the use of alternatives due to the hypersensitivity of FC to the variations in constituent proportions including foam volume [10], foaming agent dosage [11], and aggregate size [12]. Such changes significantly impact FC's density and internal structure, consequently affecting its mechanical properties.

Utilizing local resources, particularly alternative foaming agents, tackles challenges in adopting foamed concrete, streamlining the technology for local manufacturers. However, due to formulation disparities influenced by geographical limitations, the applicability of COTS alternative agents is constrained, resulting in a country-specific utilization. Moreover, there is a dearth of substantial research

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on locally available COTS agents, impeding their effective utilization in FC production. In this vein, this study aims to enhance the discourse on foamed concrete production by systematically exploring the viability of commonly available alternative foaming agents within the Philippine market. Specifically, three (3) COTS alternative foaming agents were investigated: coco diethanolamide (CDEA), liquid detergent, and dishwashing liquid. These agents, commonly used in households and widely accessible, present a promising avenue for large-scale FC production.

The literature on FC highlights the potential of CDEA, detergent, and dishwashing agents for FC application. The use of powdered detergent yields cost-effective FC with strength comparable to standard foaming agents [13]. Dishwashing liquid is considered a suitable candidate due to it having the same properties as a detergent with a slight difference in pH level [14]. CDEA has been suggested as an alternative foaming agent, showing promising stability for FC utilization [15]. Nonetheless, given COTS product variability, localized investigation of their preparations and optimal dosage for foamed concrete production remains crucial.

The aim of employing COTS alternative foaming agents is to create functional FC adaptable for diverse construction applications. As such, the study has three core objectives. Firstly, it characterizes and compares the three chosen COTS alternative foaming agents based on their foaming capacity, stability, and density, to identify the ideal water-to-foaming agent (*w/fa*) ratio for each. Secondly, the ideal *w/fa* is used for FC sample production and characterization. Lastly, using desirability analysis, the study assesses foamed concrete behavior, considering factors like water-to-cement (*w/c*) ratio, maximum aggregate size, and foam volume. Response surface methodology (RSM), a collection of mathematical and statistical techniques designed to evaluate response levels against input factors [2], is employed to create the experimental design and conduct desirability analyses. Furthermore, desirability analysis assists in determining input factor combinations to produce foamed concrete meeting criteria for construction applications.

### *1.1 Research significance*

This study is of substantial academic significance as it introduces a systematic methodology for integrating foamed concrete (FC) technology into local economies. Through a rigorous assessment of commercially available alternative foaming agents as viable substitute in FC production, the research streamlines implementation for local manufacturers. This emphasizes ease of replication without necessitating sophisticated equipment. The research also serves as a seminal guide not only contributing to scholarly discourse by customizing FC mixes for diverse construction applications but also underscores the transformative impact of FC on the building section and structural design.

The innate lightweight characteristics of FC reduce the structural footprint of buildings, fostering unprecedented design flexibility, creativity, and potential cost savings by minimizing materials requirements for support elements. The versatile FC production methodologies introduced here could provide robust foundation for the systematic exploration of other COTS, facilitating the optimization of FC to align with the unique requirements of specific regional economies.

The rest of the paper is organized as follows. Section 2 presents the material used and the methods. Section 3 discusses the input-response relationship of foam and FC properties and the result of desirability analyses. Section 4 concludes the work.

## 2. Materials and methods

### *2.1 Research design*

The research design, as depicted in Figure 1, aimed to assess the viability of CDEA, dishwashing liquid, and liquid detergent as commercial-off-the shelf (COTS) alternative foaming agents for foamed concrete (FC) production. These COTS alternative foaming agents were differentiated by foam characterization considering foam density, capability, and stability by varying the *w/fa* ratio (Phase I in Figure 1). Following foam characterization, the optimal *w/fa* ratio for each COTS alternative foaming agents was determined through desirability analysis. Subsequently, response surface methodology (RSM) was employed in the design of experiments (DOE) to produce FC samples, as in Phase II in Figure 1.

The DOE generated random combinations of input factors considered in this research, including foam volume, w/c ratio, maximum aggregate size, foaming agent type, and curing time (Phase II in Figure 1). Finally, the produced FC samples underwent characterization, evaluating compressive strength, water absorption, density, cost, and CO2 emission equivalent (Phase III in Figure 1). Desirability analysis was again employed in this phase to identify the optimal combination of input factors satisfying predetermined criteria (refer to Section 2.7) for construction applications.

### *2.2 Response Surface Methodology (RSM)*

RSM comprises three core components: design of the experiment (DOE), modeling, and desirability analysis/optimization. In DOE, input factors (independent variables) and the responses (dependent variables) are defined. The input factors are placed in a design space, and data points are randomly generated to fill it. Model fitting in RSM establishes a polynomial model, with term inclusion determined by p-value and F-test. Numerical optimization and desirability analysis in RSM are performed to pinpoint optimal input factor combinations for maximizing or minimizing dependent variables. For more details on RSM, readers are referred to Ma et al. [2], Awolusi et al. [3], and Sinkhonde et al. [16].

### *2.3 Cement, fine aggregates, and water*

FC samples were produced using Type IT cement conforming to ASTM C595 [17], water conforming to ASTM C1602 [18], and fine aggregates meeting ASTM C33 [19] standards. Type IT cement was used as it is the most common type available in the locale of the study. The chemical and physical parameters of the Type IT cement used with ASTM C595 [17] are compared in Table 1.

The fineness modulus of the sand used is 2.93. Since the maximum size of sand was included as an input factor, three (3) maximum sizes were considered: 1.00mm, 1.40mm, and 2.00mm (see also Table 2 and [12]). The sand was sieved using the corresponding sieve number to control the maximum size. This causes the density of sand to vary with values of 2819.2 kg/m$^3$, 2804.50 kg/m$^3$, and 2766.19 kg/m$^3$ (following ASTM C128 [20]) for maximum fine aggregate sizes of 1.00mm, 1.40mm, and 2.00mm, respectively.

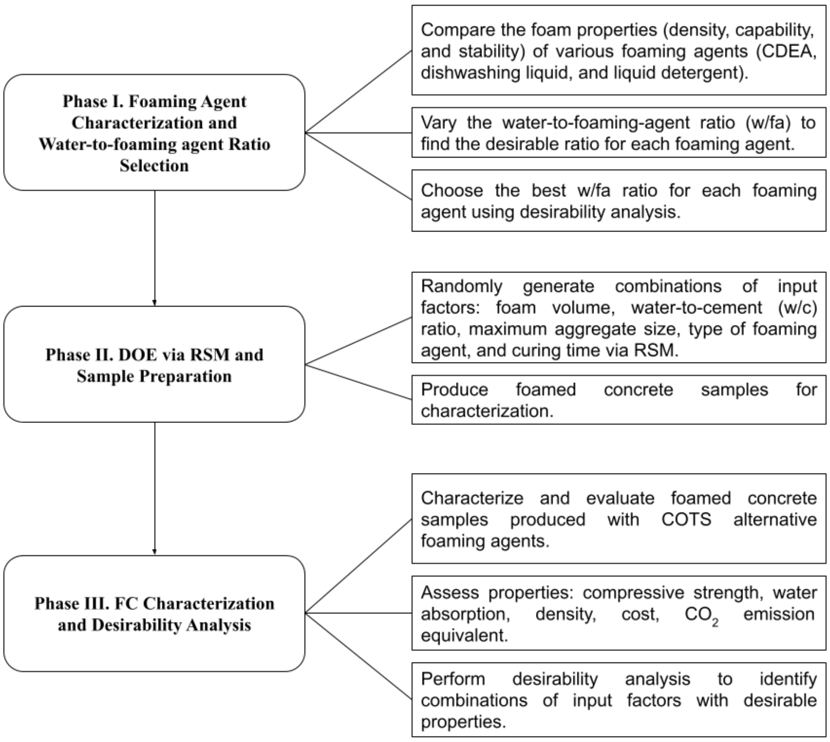



**Figure 1** Flow of the research design

**Table 1** Chemical and physical properties of Type IT cement compared to ASTM C595

| Chemical parameters | Result for Type IT | ASTM C595 | Physical parameters | Result for Type IT | ASTM C595 |
|---|---|---|---|---|---|
| Silicon Dioxide ($SiO_2$) (%) | 22.34 | n/a | Loss of Ignition (LOI) (%) | 3.64 | <5.0 % |
| Aluminum Oxide ($Al_2O_3$) (%) | 6.73 | n/a | Fineness in Blain ($m^2$/kg) | 410 | n/a |
| xFerric Oxide ($Fe_2O_3$) (%) | 3.14 | n/a | 3$^{rd}$-day Compressive Strength (MPa) | 20.5 | >13.0 MPa |
| Calcium Oxide (CaO) (%) | 59.10 | n/a | 7$^{th}$-day Compressive Strength (MPa) | 25.1 | >20.0 MPa |
| Magnesium Oxide (MgO) (%) | 1.88 | <6.0 % | 28$^{th}$-day Compressive Strength (MPa) | 31.1 | >25.0 |
| Sulfur Trioxide ($SO_3$) (%) | 2.46 | <4.0% | Autoclave Expansion (%) | 0.02 | <0.80 % |
| Insoluble Residue (IR) (%) | 6.09 | n/a | Air content (%) | 8.0 | <12.0 % |
| Free Lime (%) | 1.12 | n/a | Specific Gravity | 3.15 | n/a |

*2.4 Foaming agent characterization and optimal water-to-foaming agent ratio determination*

While there are many variants for CDEA, detergent, and dishwashing available in the market, the specific brands were selected based on their availability and the lowest unit cost. To produce foam, foaming mixtures with varying *w/fa* ratios from 5, 10, 20, 40, and 80 were prepared. The *w/fa* ratio is the dilution ratio of the foaming agent and the mixing water. The foaming mixture was then agitated for 2 minutes with a hand mixer at 1200 rpm.

The foam capability ($F_c$) was measured as the ratio in percent of the initial volume of the foaming mixture ($V_i$) to the final volume of foam produced after agitation ($V_f$). The foam stability ($F_s$) refers to the foam's ability to retain its volume and is determined by placing a lightweight ball weighting 2.10 grams on top of a layer of foam (see e.g., [21]) and measuring its displacement over 30 minutes. The stability is calculated as the ratio in percent of the final position of the ball ($H_f$), and the initial position of the ball ($H_i$). Lastly, the density of the foam ($\rho_f$) is calculated by filling a beaker to a known volume and dividing the mass of the foam by the volume reading.

The optimal *w/fa* ratio for each COTS alternative foaming agent was obtained via RSM. This is by taking the *w/fa* ratio and type of foaming agent as the input factors and density, stability, and capability as the responses. The determination of the appropriate *w/fa* ratio via desirability analysis is done by maximizing the stability while limiting the lowest possible value of foam stability to 50% (see e.g., [21]), maximizing capability, and minimizing density. The *w/fa* ratio with the highest desirability score for each foaming agent was adopted in the FC sample preparation.

*2.5 Foamed concrete production*

*2.5.1 Design of Experiment (DOE)*

The DOE utilizes Design Expert Version 13 with input factors (see Table 2): foam volume (*A*), water-to-cement ratio (*B*), maximum aggregate size (*C*), type of foaming agent (*D*), and curing time (*E*). The type of foaming agent (*D*) is indicated as *D1* for CDEA, *D2* for liquid detergent, and *D3* for dishwashing liquid. The investigated ranges of the input factors were based on previous studies as shown in Table 2. Experiment responses encompass density (*R1*), $CO_2$ emission equivalence (*R2*), unit cost (*R3*), water absorption (*R4*), and compressive strength (*R5*). Input factors were selected for their relevance to FC's performance, sustainability, and production cost impact. The DOE produced 36 random experimental combination points, with each point considering 3 replicates for robustness.

**Table 2** Range and levels of factors

| Factor/ Response | Type | Range/Levels | Units | References |
|---|---|---|---|---|
| *A* | Numeric | 50 to 65 | % | [21] |
| *B* | Numeric | 0.40 to 0.50 | g/ g | [22] |
| *C* | Numeric | 1.00, 1.40, and 2.00 | mm | [12] |
| *D* | Categoric | D1, D2, and D3 | | [13] |
| *E* | Categoric | 14.00, and 28.00 | days | [23] |
| *R1* | Response | | kg/m$^3$ | [21] |
| *R2* | Response | | kg/m$^3$ | [12] |
| *R3* | Response | | Cost/m$^3$ | [13] |
| *R4* | Response | | % | [24] |
| *R5* | Response | | MPa | [22] |

*2.5.2 FC constituent materials proportioning method*

In preparing FC samples, only masses of the constituent materials are derived from the values of the input factors *A*, *B*, and *C*. To determine the masses, a new proportioning by volume method was developed akin to the proportioning of normal-density concrete (e.g., ACI PRC 211.1-22 [25]). In this proportioning, the theoretical volume of FC ($V_{fc}$) is equated to the sum of the volumes of foam ($V_f$), cement ($V_c$), aggregate ($V_A$), and water ($V_w$) as in Eq. 1.

$$V_{fc} = V_f + V_c + V_A + V_w \quad \text{Eq. 1}$$

The initial requirement of the proportioning method is defining the foam volume as a ratio (*K*) of $V_{fc}$ (Eq. 2) since foam volume is the most significant determinant of FC's density and compressive strength.

$$V_f = KV_{fc} \quad \text{Eq. 2}$$

Further, the limit density of FC for our samples is about 1000kg/m$^3$, to take advantage of FC's lightweight property. As such, the volume of the aggregate was limited only to 10% percent of the cement paste (combined volume of cement and water) as in Eq. 3. This relationship, however, can be generalized by using a variable if higher density FC is desired.

$$V_A = 0.1(V_c + V_w) \quad \text{Eq. 3}$$

Volume-mass-density relationship defines $V_c = \frac{m_c}{\rho_c}$ and $V_w = \frac{m_w}{\rho_w}$, where $m_c$ represents the mass of cement, $m_w$ represents the mass of water, $\rho_c$ represents the density of cement, and $\rho_w$ represents the density of water. Using water to cement ratio, $m_w = Zm_c$, and utilizing Eq. 2 and Eq. 3, Eq. 4 can be derived.

$$(1 - K)V_{fc} = 1.1m_c\left(\frac{1}{\rho_c} + \frac{Z}{\rho_w}\right) \quad \text{Eq. 4}$$

Eq. 4 assumes that all the foam volume will stay stable throughout the mixing process; however, this is not true as some foam may be destroyed or increase during mixing. To account for this, a coefficient '$x$' is added to increase the foam volume in the mix. The new foam volume is defined by Eq. 5.

$$V_v = KxV_{fc} \quad \text{Eq. 5}$$

Utilizing Eq. 5, the mass of cement can be obtained as in Eq. 6. The rest of the constituent material proportions can be determined by substituting the value of cement from the relationships defined previously.

$$\frac{(1 - Kx)V_{fc}}{1.1\left(\frac{1}{\rho_c} + \frac{Z}{\rho_w}\right)} = m_c \quad \text{Eq. 6}$$

*2.5.3 FC sample preparation*

For FC sample production, the method by Safawi et al. [24] was adopted. The mixing begins by making a slurry of fine aggregates, cement, and water for 2 minutes. The required foam volume is added and mixed for an additional 4 minutes using a hand mixer at 1200 rpm – the same speed used for foam generation. The foamed concrete samples are then molded into an 8 x 6 x 2 inches mold. Then, the samples undergo spray curing for 5 days using wet fabric, followed by demolding, and continued spray curing until 28$^{th}$ day [26]. Larger samples were used, which were later cut into 2 x 2 inches cubes to minimize molds needed, similar to concrete field sampling [27]. While cutting might affect strength due to disturbance, this could better reflect the practicality and usability of FC in actual scenarios wherein cutting concrete is a common practice.

*2.6 Characterization of FC by response factors*

The density (*R1*) of FC was determined by dividing the mass and volume of the sample after curing. The estimated $CO_2$ emission equivalence (*R2*) of producing 1 $m^3$ functional unit of FC sample is calculated using Eq. 7 as the sum of the product of associated $CO_2$ emissions factors $E_f$, $E_A$, and $E_c$ and the masses of constituent materials used $m_f$, $m_A$, and $m_c$, respectively. The conversions used for the associated $CO_2$ emissions for a corresponding constituent material are in Table 3. In this study dishwashing liquid and detergent have the same average $CO_2$ emission equivalence since both have a similar composition [28].

$$E = (E_f m_f + E_A m_A + E_c m_c) \quad \text{Eq. 7}$$

**Table 3** Factors for $CO_2$ emission equivalence

| Materials | Code | Average $CO_2$ Emission | References |
|---|---|---|---|
| Cement | $E_c$ | 810 (kg/ton) | [29] |
| Aggregates | $E_a$ | 8.1 (kg/ton) | [30] |
| CDEA | $E_f$ | 887 (kg/ton) | [31] |
| Dishwashing/Detergent | $E_f$ | 760 (kg/ton) | [32] |

To determine the unit cost (*R3*) of producing 1 $m^3$ of FC, the quantity of each constituent material used was multiplied by the corresponding unit cost (Table 4) as in Eq. 8. Local rates and purchase prices were used for the unit cost of each constituent material. In determining the cost for foam, the amount of foaming agent and water needed to produce one cubic meter of foam was used.

$$C_{fc} = C_f V_f + C_A V_A + C_c m_c + C_w V_w \quad \text{Eq. 8}$$

**Table 4** Unit cost for each constituent material

| Constituent Material | Variable | Unit Cost |
|---|---|---|
| Cement | $C_c$ | Php 6.13 / kg |
| Sand Aggregate | $C_A$ | Php 1250.00 / $m^3$ |
| Water | $C_w$ | Php 3.84 / $m^3$ |
| Foam (CDEA) | $C_f$ | Php 882.20 / $m^3$ |
| Foam (Liquid Detergent) | $C_f$ | Php 3599.60 / $m^3$ |
| Foam (Dishwashing Detergent) | $C_f$ | Php 1951.67 / $m^3$ |

Note: Php indicates Philippine Peso

The water absorption (*R4*) of FC was obtained following ASTM C642 [33]. The compressive strength (*R5*) was measured following ASTM C109 [34] standards. A total of 108 samples at 28-day curing period were tested using a digital hydraulic compression testing machine.

*2.7 Criteria for desirability analysis*

The desirability analysis in RSM followed the optimization criteria in Table 5, which align with ASTM C869 [35] for foaming agents used in cellular concrete.

**Table 5** Optimization criteria for FC

| Response | Units | Criteria |
|---|---|---|
| Density | $kg/m^3$ | In range |
| $CO_2$ equivalent | kg/ton | Minimize |
| Cost | Price/ $m^3$ | Minimize |
| Water absorption | % | <25 % |
| Compressive strength | MPa | >1.4 % |

## 3. Results and discussion

*3.1 Foam characterization*

*3.1.1 Foam stability*

Figure 2 shows the stability test results for the COTS alternative foaming agents. CDEA's stability decreased as *w/fa* increased (Figure 2a), while both liquid detergent (Figure 2b) and dishwashing liquid (Figure 2c) displayed steadier foam stability with rising *w/fa*. This could be attributed to the high percentage of water already present in liquid detergent and dishwashing liquid which ranges from 55% to 75% [36], leading to over-dilution of the foaming mixture. Notably, each COTS agent exhibited better stability than reported by Hashim and Tantray [21], which is crucial for FC production.

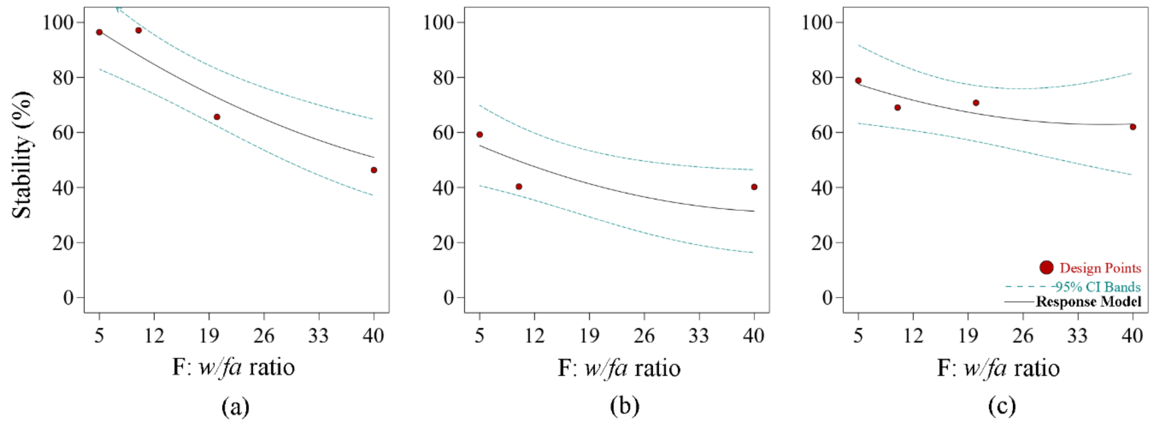



**Figure 2** Foam stability of (a) CDEA, (b) liquid detergent, and (c) dishwashing liquid

*3.1.2 Foaming capability*

Figure 3 summarizes foaming capability test results. CDEA's capability ranges from 287.50% to 799.33%, yielding 2 to 8 times the original volume (Figure 3a). Comparatively, the capability of liquid detergent ranges from 1046.00% to 1083.33% (Figure 3b), and for dishwashing liquid ranges from 1043.00% to 1143.00% (Figure 3c). CDEA's capability increases with higher *w/fa*, while liquid detergent and dishwashing liquid maintain constant capability, notably surpassing CDEA's.

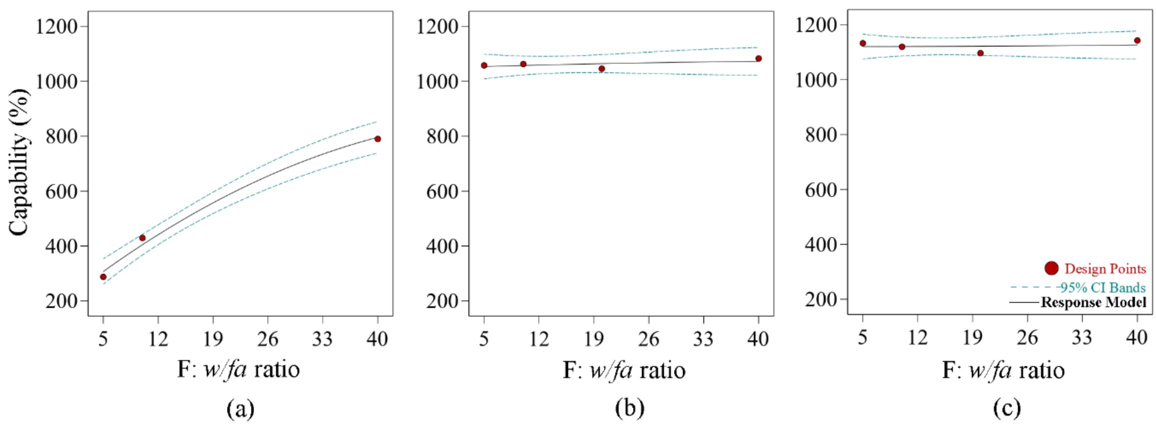



**Figure 3** Foam capability of (a) CDEA, (b) liquid detergent, and (c) dishwashing liquid

*3.1.3 Foam density*

Figure 4 summarizes foam density results. CDEA's foam density spans 77.88 to 308.243 kg/m$^3$ (Figure 4a), which increases as *w/fa* increases. In contrast, liquid detergent and dishwashing liquid exhibit minimal foam density variations across the considered *w/fa* range. The foam density for liquid detergent ranges from 88.75 to 94.58 kg/m$^3$ (Figure 4b), while for dishwashing liquid ranges from 68.26 to 87.28 kg/m$^3$ (Figure 4c).

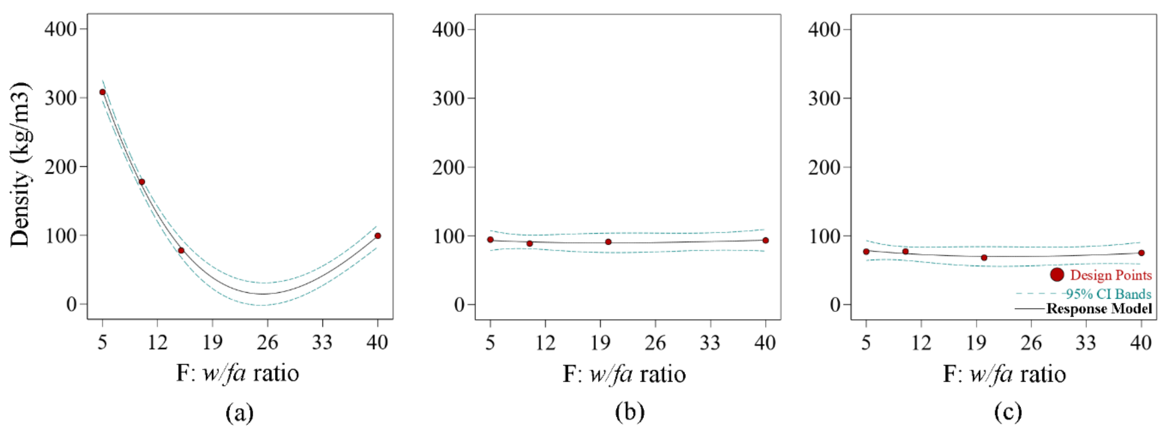



**Figure 4** Foam density of (a) CDEA, (b) liquid detergent, and (c) dishwashing liquid

*3.2 Desirable w/fa for each COTS alternative foaming agent*

The response models for the different properties of each COTS alternative foaming agent are in Table 6. Using these models, the desirable *w/fa* for each COTS agent was determined by desirability analysis and the results are in Table 7, showing the desirability scores. Water-to-foaming agent ratio for liquid detergent and dishwashing liquid is set to 5, while CDEA's *w/fa* is set to 15 instead of 16.59 to reduce confusion in measuring with non-integer values.

**Table 6** Response models of foam properties of each COTS alternative agent

| Foaming Agent | Property | Response Model | $R^2$ | Adj. $R^2$ |
|---|---|---|---|---|
| CDEA | Stability | Stability = +106.35454 -1.98005 ($F$) +0.014867 ($F^2$) | 0.91 | 0.83 |
| | Capability | Capability = +200.03896+22.32736 ($F$) - 0.185643 ($F^2$) | 0.99 | 0.99 |
| | Density | Density =+502.88433 - 44.36247 ($F$) + 1.22132 ($F^2$) - 0.009118 ($F^3$) | 0.99 | 0.83 |
| Liquid Detergent | Stability | Stability = +61.63802 -1.35083 ($F$) + 0.014867 ($F^2$) | 0.91 | 0.83 |
| | Capability | Capability = +1049.59477 +0.889627($F$) - 0.007687 ($F^2$) | 0.99 | 0.99 |
| | Density | Density = +96.47524 -0.763517 ($F$) +0.025693 ($F^2$) 0.000210 ($F^3$) | 0.91 | 0.83 |
| Dishwashing Liquid | Stability | Stability = +82.55907 - 1.08116 ($F$) + 0.014867 ($F^2$) | 0.91 | 0.83 |
| | Capability | Capability = +1120.70588 -0.020409($F$) +0.004141($F^2$) | 0.99 | 0.99 |
| | Density | Density = 85.08524-1.48084($F$) +0.042462($F^2$) - 0.000295($F^3$) | 0.99 | 0.83 |

**Table 7** Optimal *w/fa* ratio for each alternative COTS foaming agent

| Foaming Agents | Desirable *w/fa* ratio | Desirability score |
|---|---|---|
| CDEA | 16.59 ml of water/ml of CDEA | 0.605 |
| Liquid Detergent | 5.00 ml of water/ml of Liquid Detergent | 0.547 |
| Dishwashing Liquid | 5.00 ml of water/ml of Dishwashing Liquid | 0.859 |

*3.3 Results of Characterization of FC response factors*

*3.3.1 FC density (R1)*

*R1* of FC samples ranges from 477.061 to 1036.860 kg/m$^3$ (Figure 4), which aligns with the target design density (<1000 kg/m$^3$), confirming that the proportioning method in Section 2.5.2 is effective. Figure 5 suggests that *R1* is sensitive to foam volume (*A*), w/c ratio (*B*), and maximum aggregate size (*C*). In CDEA (Figure 5a), increased *A* and *B* reduce *R1*, while *C* has a lesser impact. Liquid detergent's *R1* varies from 530.38 to 917.738 kg/m$^3$ with its perturbation plot (Figure 5b) indicating *A* primarily influences *R1*, while *B* and *C* have less effect. Dishwashing liquid's *R1* ranges between 486.276 to 935.400 kg/m$^3$ (Figure 5c) with *A* being the main influencing factor to R1 (see also [10, 11]). The dishwashing liquid's perturbation plot (Figure 5c) closely resembles the plot of liquid detergent, indicative of comparable formulations [28]. Overall, the values of *R1* for the 3 COTS alternative foaming agents have similar values. Table 8 details the *R1* models used in the desirability analyses.

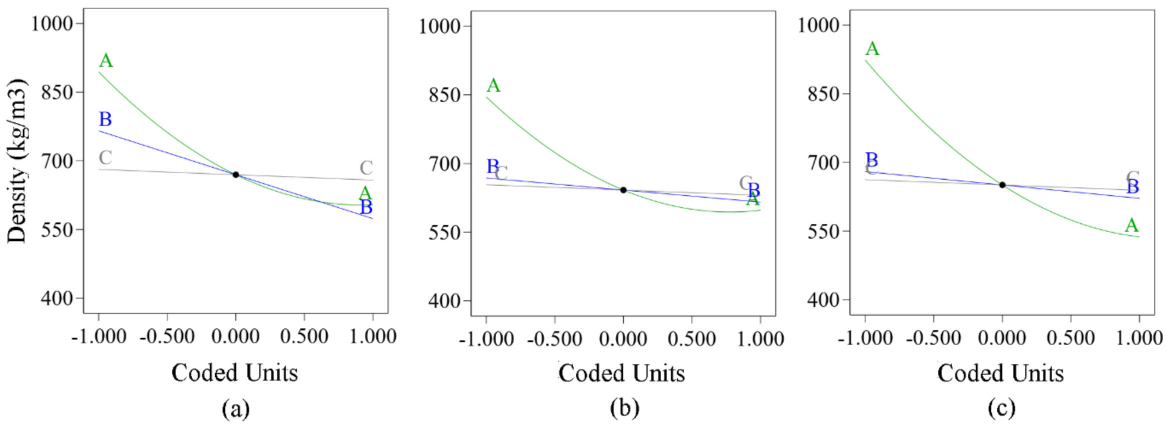



**Figure 5** Perturbation plots of *R1* for (a) CDEA, (b) liquid detergent, (c) dishwashing liquid

**Table 7** Response models for *R1*

| Foaming Agent | Response model | $R^2$ | Adj. $R^2$ |
|---|---|---|---|
| CDEA | $R1= +8065.89941-194.40051(A) -3452.39556(B) -23.26255(C) +26.66361(AB) +1.41783(A^2)$ | 0.95 | 0.92 |
| Liquid Detergent | $R1= +8868.89543-219.73150(A) -5661.32350(B) -23.26255(C) +89.27316(AB) +1.41783(A^2)$ | 0.95 | 0.92 |
| Dishwashing Liquid | $R1= +4124.89733 -136.62835(A) +6081.09656(B) -23.26255(C) -115.93677(AB) +1.41783(A^2)$ | 0.95 | 0.92 |

*3.3.2 $CO_2$ emission equivalence (R2)*

*R2* for all FC samples ranges from 243.231 to 528.2 kg $CO_2/m^3$ (Figure 6). In CDEA's (Figure 6a), *R2* spans 225.747 to 528.2 kg of $CO_2/m^3$ while liquid detergent's *R2* varies from 258.537 to 471.90 kg of $CO_2/m^3$ (Figure 6b). Dishwashing liquid's *R2* (Figure 6c) ranges from 233.776 to 479.78 kg of $CO_2/m^3$. *A* and *B* have a significant effect on *R2* in both CDEA and liquid detergent, while *C* has minimal impact. Across all COTS agents, increasing *A* and *B* decreases in *R2*, with *C* having minimal influence as shown in the perturbation plots. FCs produced with these alternative foaming agents have similar $CO_2$ emission equivalence values. Table 9 details the *R2* models used in the desirability analyses.

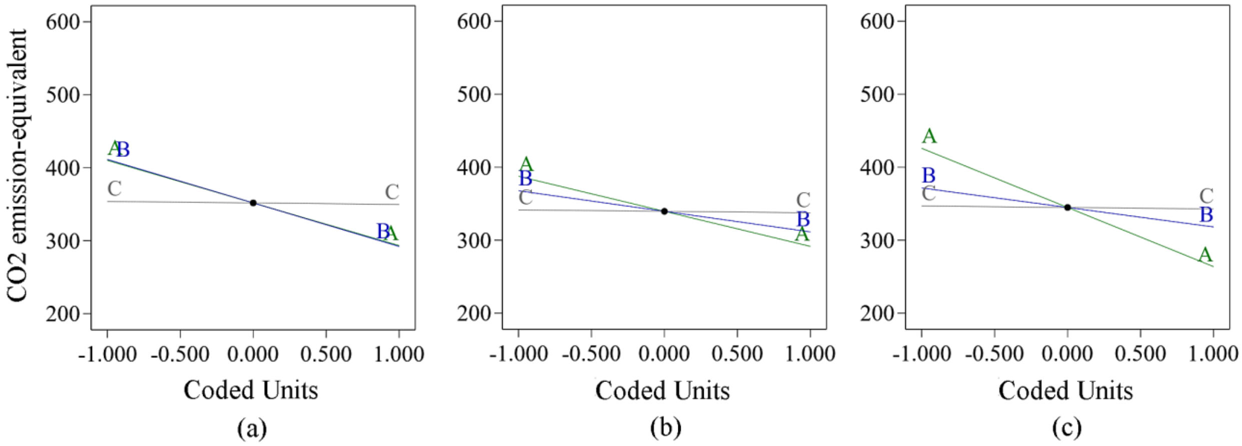



**Figure 6** Perturbation plots of *R2* for (a) CDEA, (b) liquid detergent, (c) dishwashing liquid

**Table 9** Response models for *R2*

| Foaming Agent | Response model | $R^2$ | Adj. $R^2$ |
|---|---|---|---|
| CDEA | *R2= +883.60916+1.31609(A) -1178.62786(B) +407.58543 (C) -7.82018(AC)* | 0.94 | 0.93 |
| Liquid Detergent | *R2= +528.32830+2.32521 (A) -546.89299(B) +407.58543 (C) -7.82018(AC)* | 0.94 | 0.93 |
| Dishwashing Liquid | *R2=+790.88024-1.69835 (A) -608.65247 (B) +407.58543(C) -7.82018(AC)* | 0.94 | 0.93 |

*3.3.3 Unit cost (R3)*

*R3* to produce 1 $m^3$ of FC ranges from 2108.39 to 5175.67 Php/$m^3$ (Figure 7). In CDEA (Figure 7a), *R3* spans 2126.23 to 4483.48 Php/$m^3$ with *A* and *B* notably having a significant influence on *R3*, while *C* minimally affects it. This is because increasing *A* and *B* reduces the amount of cement in the mix. Liquid detergent's *R3* (Figure 7b) varies from 3390.38 to 5208.23 Php/$m^3$ with its perturbation plot suggesting that *A* primarily influences *R3*, while *B* and *C* have similar but minimal impact. This is likely because liquid detergent is the most expensive among the COTS agents. Dishwashing liquid's *R3* (Figure 7c) ranges from 2666.11 to 4703.34 Php/ $m^3$ with its perturbation plot showing *A* significantly affecting *R3*, while *B* and *C* have a minimal influence. Comparatively, liquid detergent is the costliest, followed by dishwashing liquid, while CDEA's FC is the most economical. Table 10 shows the *R3* models used in the desirability analyses.

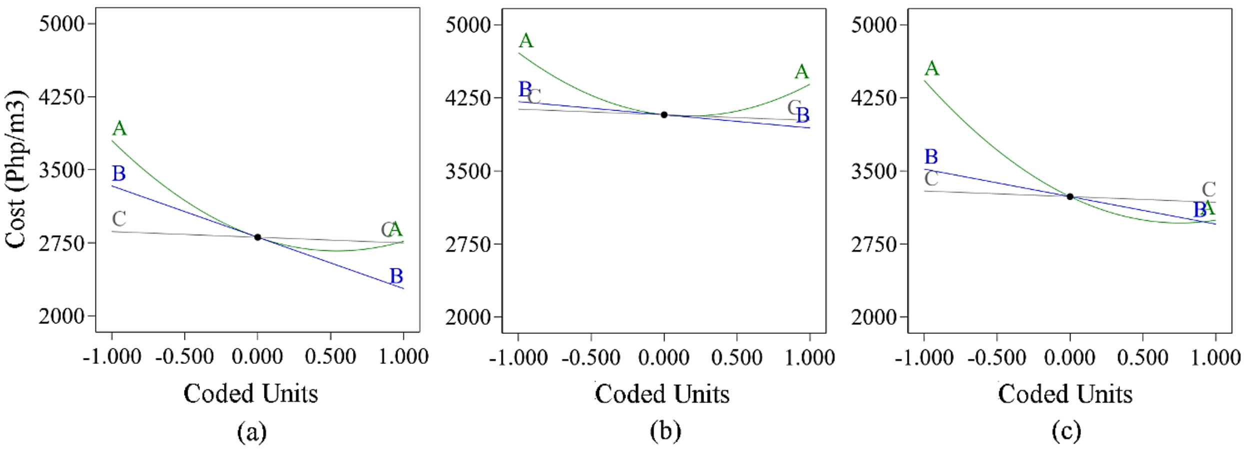



**Figure 7** Perturbation plots of *R3* for (a) CDEA, (b) liquid detergent, (c) dishwashing liquid

**Table 10** Response models for *R3*

| Foaming Agent | Response model | $R^2$ | Adj. $R^2$ |
|---|---|---|---|
| CDEA | *R3= +49354.39026-1185.35012(A)-35270.88514(B) -125.28623(C) +429.04641(AB) +8.04134(A²)* | 0.96 | 0.92 |
| Liquid Detergent | *R3= +64322.41330-1484.33194(A) -71716.38058(B) -125.28623(C) +1197.75579(AB) +8.04134(A²)* | 0.96 | 0.92 |
| Dishwashing Liquid | *R3= +34440.90003-956.77290(A) +2245.23637(B) -125.28623(C) -138.40625(AB) +8.04134(A²)* | 0.96 | 0.92 |

*3.3.4 Water absorption (R4)*

*R4* across FC samples ranges from 5.096 to 35.749% (Figure 8). Lower *R4* enhances durability by reducing permeability, moisture-related damage, chloride ion diffusion, and sulfate attack [37]. CDEA's *R4* values (Figure 8a) span 5.096% to 27.263%. Factor *A* primarily influences *R4* in CDEA, with *B* and *C* having minimal impact, aligning with Gökçe et al. [38]. Increasing *A* leads to an increase in voids, potentially increasing permeability. Liquid detergent's *R4* (Figure 8b) varies from 12.628 to 34.398%, influenced by factors *A*, *B*, and C. Decreasing *A* and *C* reduces *R4*, while *B* increases it. Dishwashing liquid's *R4* (Figure 8c) values range from 6.454 to 35.749% with the perturbation plot showing that *A* primarily influences *R4*, while *B* and *C* have a minimal influence. COTS alternative foaming agents impact *R4* differently, with liquid detergent and dishwashing liquid having similar *R4*, while CDEA has lower absorption. Table 11 details the *R4* models used as input in the desirability analyses.

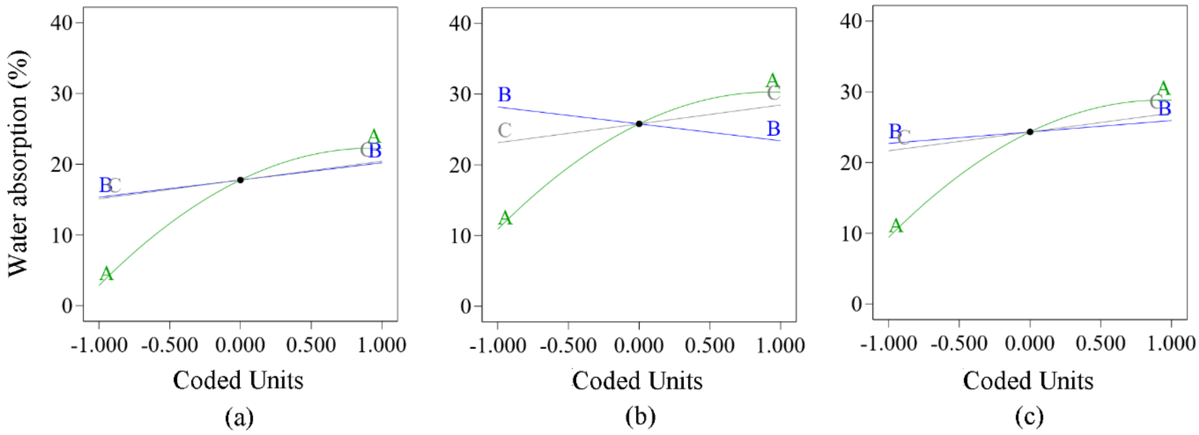



**Figure 8** Perturbation plots of *R4* for (a) CDEA, (b) liquid detergent, (c) dishwashing liquid

**Table 11** Response models for *R4*

| Foaming Agent | Response model | $R^2$ | Adj. $R^2$ |
|---|---|---|---|
| CDEA | *R4= -414.88311+12.88250(A) +53.30415(B) +5.50901(C) - 0.102331(A²)* | 0.85 | 0.80 |
| Liquid Detergent | *R4= -350.23349+12.68210(A) -47.74496(B) +5.50901(C) -0.102331(A²)* | 0.85 | 0.80 |
| Dishwashing Liquid | *R4= -433.0409 +13.56129(A) +21.30218(B) +5.50901(C) -0.102331(A²)* | 0.85 | 0.80 |

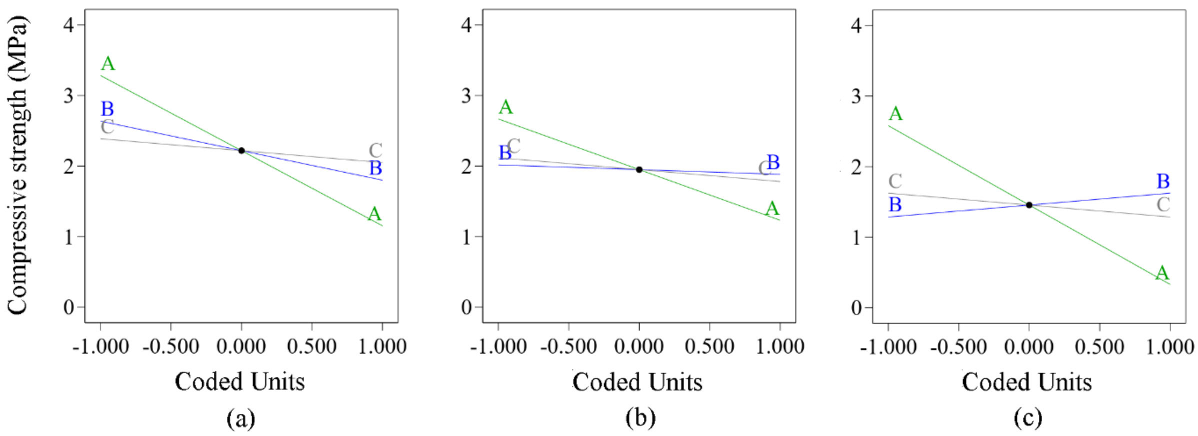



**Figure 9** Perturbation plots of *R5* for (a) CDEA, (b) liquid detergent, (c) dishwashing liquid

*3.3.5 Compressive strength (R5)*

CDEA's *R5* spans 0.852 MPa to 3.967 MPa (Figure 9a), with its perturbation plot showing that increasing *A*, *B*, and *C* leads to a decrease in *R5*. Liquid detergent's *R5* ranges from 0.841MPa to 3.042 MPa (Figure 9b), with its perturbation plot showing that an increase in *A* leads to a decrease in *R5*. However, the influence of *B* and *C* affects *R5* only minimally as with CDEA. Dishwashing liquid's *R5* ranges from 0.192MPa to 2.598 MPa (Figure 9c) and its perturbation plot illustrating that increasing *A* and *C* leads to a decrease in *R5*; however, *C* has only a minimal impact on *R5*. Interestingly, increasing B in dishwashing liquid, unlike typical concrete behavior, tends to raise R5, defying the usual water-cement ratio impact on strength. Comparatively, CDEA yields the highest compressive strength, followed by liquid detergent, and dishwashing liquid. Table 12 details the *R5* models used as input in the desirability analyses.

**Table 12** Response models for *R5*

| Foaming Agent | Response model | $R^2$ | Adj. $R^2$ |
|---|---|---|---|
| CDEA | *R5= +13.03726 -0.113875(A) -21.51752(B) +4.68768(C) +0.228741(AB) -0.087399(AC)* | 0.93 | 0.87 |
| Liquid Detergent | *R5= +13.90193 -0.188592(A) -29.94657(B) +4.68768(C) +0.497561(AB) -0.087399(AC)* | 0.93 | 0.87 |
| Dishwashing Liquid | *R5= -17.26132+0.385770(A) +45.14847(B) +4.68768(C)-0.726302(AB) -0.087399(AC)* | 0.93 | 0.87 |

### *3.4 Desirability analysis*

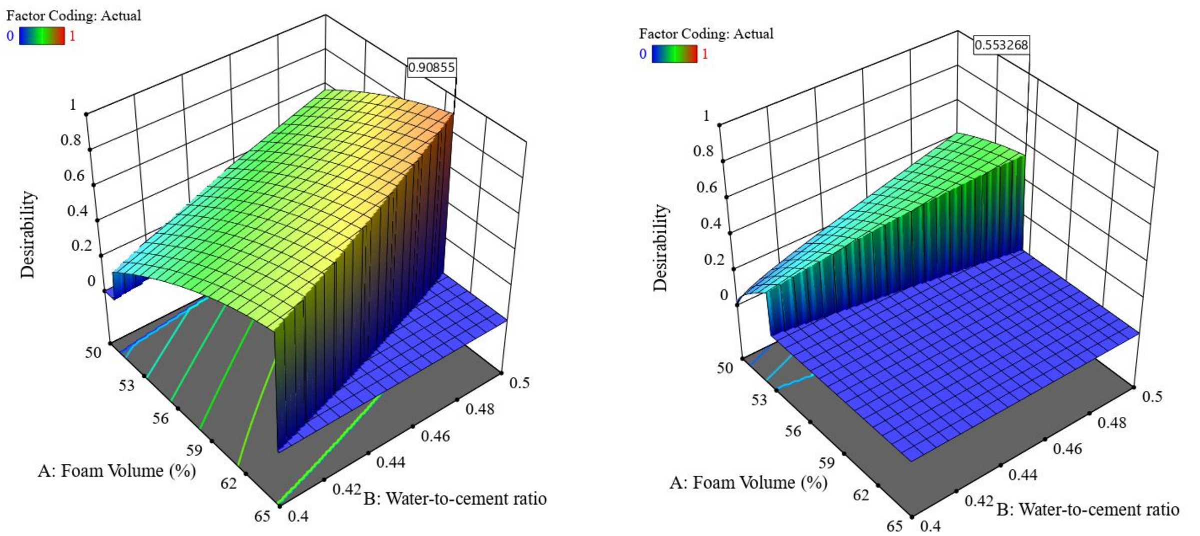
Analysis of FC samples reveals conflicts between inputs and responses, where improving one response may negatively affect another. For instance, enhancing *R1*, *R2*, and *R3* necessitates maximizing factor *A*, potentially conflicts enhancing *R4* and *R5* which requires minimizing factor *A*. Desirability analysis was performed to neutralize conflicts between the responses' behavior to find values of the inputs that could satisfy a pre-determined optimization criteria in Section 2.7 following ASTM C869 [35].

#### *3.4.1 Desirability analysis for CDEA*

Figure 10a summarizes CDEA's desirability analysis, revealing how water-to-cement ratio (*B*) and foam volume (*A*) impact the overall desirability score. The highest score is 0.906, which occurs when *A* = 60.073%, *B* = 0.50, and *C* = 1.611mm, and at 28-day curing period. Predicted response values are: *R1* = 541.501 kg/m$^3$, *R2* = 272.454 kg of $CO_2$/m$^3$ of FC, *R3* = 2199.526 Php/m$^3$, *R4* = 25%, and *R5* = 1.402Mpa. The point with the highest desirability score meets the minimum ASTM C869 requirement, indicating it exhibits favorable properties in terms of being lightweight, cost-effective, and having low $CO_2$ emission equivalence while meeting the standard for water absorption and compressive strength. However, it is worth noting that a deep valley can be observed in Figure 10a in the region where *A* is less than 52% and greater than 64%. *A* < 52% results in higher water absorption, while *A* > 65% yields FC with a compressive strength < 1.4MPa. This means that the values of the input factors within this region do not align with the desirability criteria.

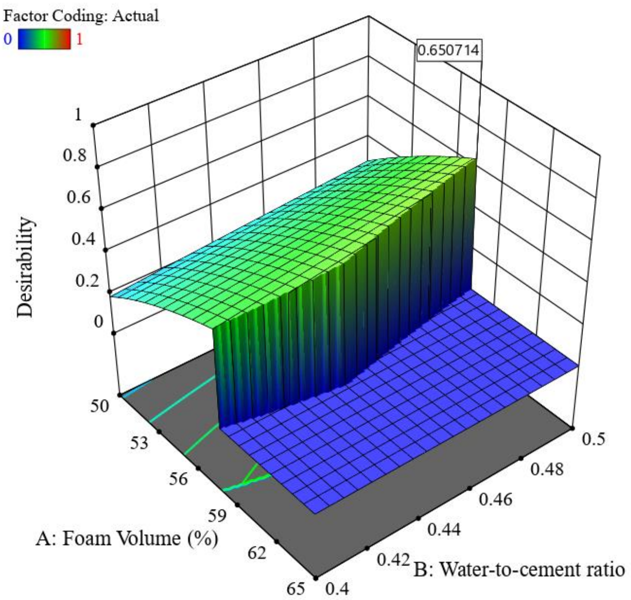
#### *3.4.2 Desirability analysis for liquid detergent*

Figure 10b summarizes the desirability analysis for liquid detergent, showing the influence of the water-to-cement ratio and foam volume on the overall desirability score. The highest score is 0.553, which is achieved when *A* = 55.749%, *B* = 0.50, and *C* = 2.00mm, and at the 28$^{th}$ day curing period. The predicted response values are: *R1* = 636.890 kg/m$^3$, *R2* = 322.246 kg of $CO_2$/m$^3$ of FC, *R3* = 3822.775 Php/m$^3$, *R4* = 25.00%, and *R5* = 1.915Mpa. Although this FC mix meets the minimum ASTM requirements for water absorption (*R4*) and compressive strength (*R5*), its desirability score is relatively low. This is mainly due to higher $CO_2$ emissions equivalence compared to other COTS alternative agents. The lower desirability score suggests that it may not be the most favorable choice when considering cost-effectiveness and environmental impact. Figure 10b also reveals limited workable regions to meet R5 > 1.4MPa and R4 < 25%.




(a) CDEA (b) liquid detergent

**Figure 10** 3D desirability plot showing the impact of foam volume and water-to-cement ratio for (a) CDEA (b) liquid detergent (c) dishwashing liquid




(c) dishwashing liquid

**Figure 10 (continued)** 3D desirability plot showing the impact of foam volume and water-to-cement ratio for (a) CDEA (b) liquid detergent (c) dishwashing liquid

*3.4.3 Desirability analysis for dishwashing liquid*

Figure 10c summarizes the dishwashing liquid's desirability analysis, considering the influence of the water-to-cement ratio and foam volume. The highest score is 0.651, which could be achieved when *A* = 57.689%, *B* = 0.50, and *C* = 1.00mm, and at the 28$^{th}$ day curing period. The predicted responses are: *R1* = 634.648 kg/m$^3$, *R2* = 350.26 kg of $CO_2$/m$^3$ of FC, *R3* = 2990.098 Php/m$^3$, *R4* = 25.00%, and *R5* = 1.766 Mpa. The FC mixture using dishwashing liquid complies with ASTM C869. However, caution is advised due to the predicted high absorption value. Although the desirability score is lower than that of CDEA, it surpasses that of liquid detergent, suggesting that dishwashing liquid is a viable COTS alternative foaming agent for FC production. Moreover, FC made with dishwashing liquid offers versatility, suitable for various applications such as thermal insulation, non-load-bearing partitions, lightweight cladding, and even for hollow block products.

## 4. Conclusions and recommendations

*4.1 Conclusions*

This study explores using commercial-off-the-shelf (COTS) alternative foaming agents for foamed concrete (FC) production via desirability analysis. It is found that CDEA, liquid detergent, and dishwashing liquid as COTS alternative foaming agents exhibit varying foam characteristics with respect to water-to-foaming agent ratio (*w/fa*). CDEA demonstrates significant variation in foam properties, such that when increasing *w/fa*, the stability and density decrease while capability increases. In contrast, liquid detergent shows limited variation in foam properties, while dishwashing liquid shows higher stability and capability with increasing *w/fa*. The desirability analysis optimal *w/fa* for CDEA is 16.59, whereas for liquid detergent and dishwashing liquid is 5.00. The FC produced using the COTS alternative agents considering the optimal *w/fa* was characterized in terms of density, $CO_2$ emission-equivalent, cost, water absorption, and compressive strength. Generally, it was found that the properties of FC are primarily influenced by the foam volume (*A*) and the water-to-cement ratio (*B*), with aggregate size (*C*) minimally affecting them. The type of foaming agent (*D*) minimally affects FC density (*R1*) with FC samples having similar values of 477.061 to 1036.860 kg/m$^3$, 530.38 to 917.738 kg/m$^3$, and 486.276 to 935.400 kg/m$^3$ for FCs using CDEA, liquid detergent, and dishwashing liquid, respectively. In terms of $CO_2$ emission equivalence (R2), regardless of COTS foaming agent used, the FCs produced have similar $CO_2$ equivalence values ranging from 243.231 to 528.2 kg $CO_2$/m$^3$. Comparing the unit cost (*R3*) of the FC samples, liquid detergent is found to be the costliest (3390.38 to 5208.23 Php/m$^3$), followed by dishwashing liquid (2666.11 to 4703.34 Php/ m$^3$), while CDEA's FC is the most economical (2126.23 to 4483.48 Php/m$^3$). FC samples' water absorption (*R4*) is also affected by varying COTS with FC using CDEA exhibiting lower absorption (5.096% to 27.263%) compared to liquid detergent (12.628 to 34.398%) and dishwashing liquid (6.454 to 35.749%). For compressive strength (*R5*), CDEA yields the highest compressive strength (0.852 MPa to 3.967 MPa), followed by liquid detergent (0.841MPa to 3.042 MPa), and dishwashing liquid (0.192MPa to 2.598 MPa). Further, the desirability analysis revealed that by careful manipulation of foam volume, water-to-cement ratio, and maximum aggregate size, FC could be produced using the COTS alternative foaming agents that comply with ASTM C869 standards. CDEA exhibit the highest desirability score with about 0.906, followed by dishwashing liquid of about 0.651, and last is the liquid detergent with 0.553. The optimum combinations of the input factors to have the most desirable FC therefore using CDEA is *A* = 60.073%, *B* = 0.50, and *C* = 1.611mm. The results of the research, therefore validated CDEA, liquid detergent, and dishwashing liquid as viable options as foaming agents for FC production.

*4.2 Recommendations*

To advance the exploration of commercial-off-the-shelf (COTS) alternative foaming agents, the following recommendations for future research are proposed:

1. Broaden the scope of performance parameters for foamed concrete by including additional factors such as thermal conductivity, sound insulation, and seismic resistivity, which were not addressed in this study.
2. Examine the impact of diverse curing conditions, such as steam curing, on the characteristics of foamed concrete, offering insights into how different curing processes influence its properties.
3. Undertake comprehensive life cycle assessment (LCA) to thoroughly evaluate the environmental impacts associated with the production of foamed concrete utilizing COTS alternative foaming agents. This would provide a holistic understanding of the sustainability aspects involved in the lifecycle of foamed concrete.

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