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Rheology as a tool for technological advancements in self-compacting lightweight concrete mixes

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Abstract:
This paper outlines a methodology aimed at enhancing the technological performance of self-compacting concrete using lightweight expanded clay aggregate. One of the primary challenges encountered when employing concrete with lightweight aggregate involves displacing expanded clay grains within the solution's liquid phase to ensure necessary fluidity (workability) while upholding high stability (structural viscosity and segregation resistance). To achieve this objective, the rheological parameters of the self-compacting cement matrix have been regulated by deliberately adjusting the functional groups of additives and the microfine mineral filler, employing analytical methods from computer materials science. Through the analysis of rheometric results obtained from investigating various solution mixtures, the most suitable model that describes their rheological behaviour has been identified. The impact of finely dispersed fly ash excipient, a carboxylate superplasticiser, and a stabiliser additive on the rheological parameters of self-compacting lightweight concrete mixes has been established. The inclusion of these complex additives in the composition has enabled substantial alterations in the flow index across a wide range (0,030-0,798). This adaptability allows for the adjustment of the mortar mixture's rheological behaviour throughout a spectrum ranging from «abnormally viscous liquid» to «Newtonian liquid». This approach, examining the singular-factor dependencies' analysis on the coefficients of rheological behaviour models, aids in addressing the primary challenge encountered when using concrete with lightweight aggregate.

Keywords:
rheology; self-compacting lightweight concrete mixes

1 Introduction

Lightweight self-compacting concrete represents a highly efficient material that combines the merits of structural lightweight concrete (LWC), including reductions in permanent loads, excellent heat and sound insulation, enhanced durability, and resistance to temperature and chemical effects [1-4], with the attributes of self-compacting concrete mixtures (SCC). These characteristics manifest in improved formwork fillability, high permeability, and resistance to segregation [5-6]. The seemingly disparate properties of low-density «density» (indicative of low dynamic energy during flow) and self-compaction, reliant on dynamic characteristics, pose challenges in the production of self-compacting lightweight concrete (SCLWC) [7-9]. However, insights gleaned from international scientific endeavours [10-12] have demonstrated that appropriately designed and prepared SCLWC mixes can meet the full spectrum of requirements necessary for high-quality construction, marking a substantial advancement in the studied technology. For instance, research findings [10] indicate that self-compacting lightweight concrete finds applicability across a range of restoration and construction projects. Notably, one commendable aspect of this concrete lies in its aesthetically appealing surface coupled with robust resistance to freeze-thaw cycles [5].

It is essential to acknowledge the study [13], wherein the author formulated technological guidelines for manufacturing structural lightweight self-compacting tuff-concrete at the production facility of «Credo», LLC (located in Gelendzhik, Arkhipo-Osipovka). Furthermore, the developed compositions were successfully implemented in the production of reinforced concrete products at the Agroindustrial Building Complex «Gulkevichi», OJSC [13].

A comparative analysis between the traditional SCC mixtures and SCLWC, produced using the methodology developed at the University of Warmia and Mazury in Olsztyn (UWM) involving Prof. Koval S.V. [14-17], demonstrates a noticeable rise in the use of fly ash and sand (whether light, heavy, or their combinations) as identified in previous studies in this field. Furthermore, achieving high-strength concrete might entail an increase in cement consumption [18]. The data from studies [5-7, 14] indicate that as the quality indicators improve in lightweight self-compacting concrete, challenges arise in ensuring its uniformity, particularly in the context of using lightweight aggregates [8, 9, 15]. Several authors also acknowledge the absence of effective methods for evaluating this displacement indicator of lightweight aggregate grains [10, 13, 16].

Tests such as the L-box, slump, V-funnel, and Marsh cone are commonly employed to characterise the fresh state of cement-based materials, evaluating properties like consistency, flowability, and pumpability [19-22]. However, relying solely on these tests proves inadequate for a comprehensive understanding of the rheological behaviour of cement-based materials. A comprehensive assessment necessitates a series of rheometric tests [23-24] to evaluate the fundamental rheological parameters of the composite. Researchers have investigated various factors influencing the rheological properties of cement-based suspensions. These factors encompass the impact of chemical additives and mineral additions [25, 26], temperature effects [27], mixing methods [28], and aggregate morphology [29]. Yet, most studies have focused on a singular phase of the cementitious composite (paste, mortar, or concrete), employing diverse equipment, test protocols, and exploring varied chemical compositions and morphological characteristics due to the array of component materials available. Thus, this study aimed to investigate the influence of active mineral additives like fly ash, stabiliser, and polycarboxylate-type plasticiser on the rheological parameters of the SCLWC mortar matrix. The objective was to impart high plasticity and stability to these mixtures, potentially enabling them to maintain exceptional mobility and resolve the issue of displacing lightweight aggregate grains.

2 Methodology

2.1 Materials and methods

A number of rheological behavior models have been used to mathematically describe the deformation dependencies of diverse natures in solution compositions. Table 1 [27] lists some of these models.

Table 1. Comparison of rheological behaviour models

Name	Equation	Applicability	Limitations
Casson	$\tau^{\frac{1}{n}} = \tau_0^{\frac{1}{n}} + (\eta \cdot \dot{\gamma})^{\frac{1}{n}}$	For non-Newtonian fluids, especially those with yield stress and high viscosity	Applicable to materials with yield stress and viscosity-dominant flow
Ree-Eyring	$\tau = \mu_0 \cdot \dot{\gamma} \left[\frac{\sinh(k\tau)}{k\tau}\right]^{-1}$	For viscoelastic materials with a significant yield stress and complex flow behaviour	Not suitable for simple shear-thinning or shear-thickening fluids without pronounced viscoelasticity
DeHaven	$\mu_0 \cdot \dot{\gamma} = \tau(1 + k\lvert\tau\rvert^n)$	For materials with power-law shear-thinning behaviour	May not accurately describe materials with yield stress or viscoelastic properties
Herschel-Bulkley	$\tau = \tau_0 + k \cdot \dot{\gamma}^n$	For a wide range of non-Newtonian fluids, including both shear-thinning and shear-thickening materials, with or without yield stress	May insufficiently capture the complexity of some viscoelastic materials or extremely shear-thinning or shear-thickening fluids
Bingham	$\tau = \tau_0 + \eta \cdot \dot{\gamma}$	For materials with yield stress and behaving like solids until reaching the yield point	Limited to materials with clear yield behaviour and may not be suitable for viscoelastic or shear-thinning/shear-thickening materials
Ostwald–de Waele	$\tau = k \cdot \dot{\gamma}^n$	Widely applicable to various non-Newtonian fluids, including shear-thinning and shear-thickening materials	May not fully capture complex viscoelastic behaviours or underestimate yield stress in some materials
Cross	$\tau = \eta_\infty \cdot \dot{\gamma} + \frac{(\eta_0 - \eta_\infty)\dot{\gamma}}{1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_b}\right)^n}$	For viscoelastic materials like polymer solutions	Limited to viscoelastic materials and unsuitable for other types of non-Newtonian fluids

A preliminary analysis and some studies [31-33] showed that the rheological behaviour of SCC mixes can be described by the Herschel-Bulkley model, which is expressed as:

$$\tau = \tau_0 + k \cdot \dot{\gamma}^n \tag{1}$$

where τ_0 is the ultimate shear stress, Pa; k is a consistency coefficient = $1\mathrm{s}^{-1}$, $\mathrm{Pa \cdot s^{-1}}$; and n is the flow index, a model parameter of the flow function.

Providing a range of qualitative indicators related to processability (such as mobility and segregation) is achievable by regulating the previously mentioned parameters of rheological behaviour models (Fig. 1), specifically the viscosity coefficient k ($\mathrm{Pa \cdot s^{1/n}}$) and yield strength (Pa) [33, 34].

Hence, augmenting the mixture's plasticity, and consequently its mobility, is accomplished by elevating k while reducing the flow index n through an increase in the solid phase concentration in the solution (compactness achieved through a fine mineral additive). Achieving high stability of the mixture (thus mitigating the risk of expanded clay extrusion to the surface) can be attained by a controlled increment in the ultimate shear stress of the mortar phase, τ_0.

By striking a balance between these parameters of the coefficient k and τ_0, it is theoretically feasible to formulate a self-compacting concrete mix utilising lightweight aggregate, ensuring both mobility and uniformity.

Several studies [35-39] demonstrate that in managing the flow index within suspensions reliant on a Portland cement binder, diverse kinds of polymeric redispersible powders (such as polyvinyl acetate, ethylene vinyl acetate, etc.) are employed. These additives can markedly alter the rheological indicator by creating films around the particles within the cement mortar. Hence, to curtail expenses while upholding the enhanced properties of the mixtures, we substituted expensive additives with Sika ViscoCrete-20 Gold plasticiser, as mentioned earlier.

When formulating multicomponent compositions (based on mineral or organic binders, hardening naturally or during thermal processing, possessing structural or detachable characteristics, etc.), it becomes imperative to address issues related to quantitative analysis. Ensuring properties at various stages of the material's existence, encompassing the characteristics of the emerging structure and functional properties of the composite, is crucial concerning the multicomponent composition and the parameters of the processes.

The parameters of the composition and technology, encompassing operational conditions, whose levels can be designated and established, form the vector of prescription-technological (PT) factors $x = (x_1, ..., x_k)$. The quality criteria Y, along with the technological and structural characteristics of the material at distinct stages, operational properties, and any other responses to alterations in controlled inputs x, collectively constitute what can be termed as properties.

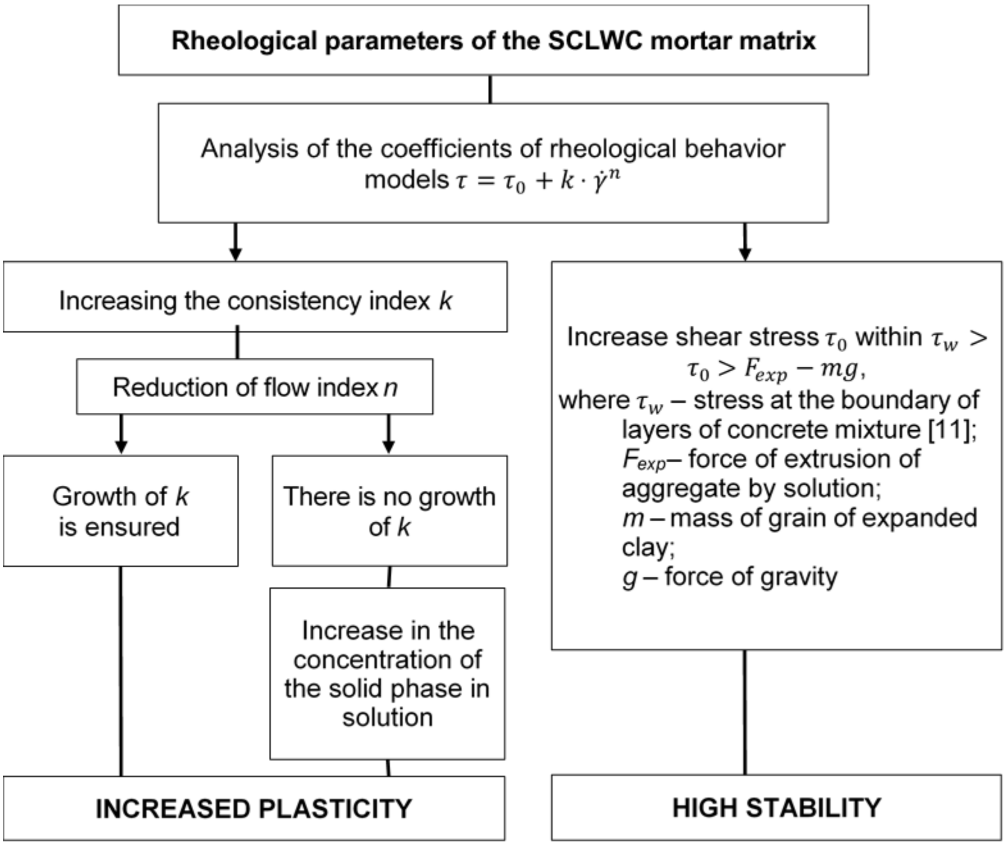

Figure 1. Schematic of the relationship between workability and the rheological parameters of the mortar matrix in SCLWC

It is evident that to conduct a quantitative analysis of the relationship between factors x and Y and to ensure «high quality in a project» (which involves determining the composition and modes that will provide specified or enhanced levels of a range of properties), mathematical models describing these relationships are essential. These models facilitate addressing both direct material science issues (such as forecasting and estimating Y) and inverse problems (involving design, determining admissible and optimal x) [40].

To address this issue, an experiment was conducted at the cement matrix level employing a D-optimal three-factor plan encompassing 15 experimental points [41]. The factors were normalised to $-1 \leq x_i \leq +1$. The transformation to dimensionless normalised variables $-1 \leq x_i \leq +1$ was executed using a standard formula: $x_i = (X_i - X_{oi})/\Delta X_i$. The levels of the variable factors and the experimental planning matrix are detailed in Table 2.

For the preparation of cement pastes, CEM I 52,5 R (EN-197-1) (C) served as the binder. It exhibited a specific surface area of 3850 cm²/g and a fineness of 8,1 %. The following prescription factors varied within the composition of cement pastes:

- Content of fly ash from Olsztyn TPP (FA), $X_1 = 15 \pm 15$ %. Specific surface area - 2700 cm²/g. Composition: SiO_2—59,2 %, Al_2O_3—24,3 %, Fe_2O_3—8,1 %, MgO—0,5 %, CaO—2,6 %, K_2O—2,3 %, TiO_2—1,0 %, MnO—0,1 %, Na_2O—0,63 %.
- Plasticising additive Sika ViscoCrete-20 Gold based on polycarboxylate esters (SP) $X_2 = 0{,}15 \pm 0{,}15$ %. Density 1,06 g/cm³, Cl content of 0,10 %, Na_2O equivalent of 1,50 %, pH of 4.
- CX ISOSTAB 6003 mixture stabiliser based on natural polysaccharide (ST) $X_3 = 0{,}03 \pm 0{,}03$ %. Density 1,01 ± 0,02 g/cm³; Cl content ≤ 0,10 %; Na_2O equivalent ≤ 0,50 %.

3 Results

The experiment was conducted at the University of Warmia and Mazury in Olsztyn, Poland, employing state-of-the-art equipment, notably the absolute rheometer Rheotest RN 4. This equipment facilitates the construction of viscosity and flow curves across extensive deformation ranges in both measurement modes (CS/CR) and enables complex rheological analysis. The device is equipped with multiple measuring systems, including a cone-plate, plate-plate, concentric cylinders, and a Peltier temperature control module.

Table 2. Experiment design and levels of factors variation

№	X_1	X_2	X_3	FA (%)	SP (%)	ST (%)	FA (g)	SP (ml)	ST (ml)	C (g)	W (ml)
1	-1	-1	-1	0	0,00	0,00	0	0,0	0,0	3000	1140
2	-1	-1	1	0	0,00	0,06	0	0,0	1,8		
3	-1	0	0	0	0,15	0,03	0	4,5	0,9		
4	-1	1	-1	0	0,30	0,00	0	9,0	0,0		
5	-1	1	1	0	0,30	0,06	0	9,0	1,8		
6	0	-1	0	15	0,00	0,03	450	0,0	0,9	2550	
7	0	1	0	15	0,30	0,03	450	9,0	0,9		
8	0	0	-1	15	0,15	0,00	450	4,5	0,0		
9	0	0	1	15	0,15	0,06	450	4,5	1,8		
10	0	0	0	15	0,15	0,03	450	4,5	0,9		
11	1	-1	-1	30	0,00	0,00	900	0,0	0,0	2100	
12	1	-1	1	30	0,00	0,06	900	0,0	1,8		
13	1	0	0	30	0,15	0,03	900	4,5	0,9		
14	1	1	-1	30	0,30	0,00	900	9,0	0,0		
15	1	1	1	30	0,30	0,06	900	9,0	1,8		

The rheological behaviour indicators of the solution mixtures were mathematically described using a second-order polynomial experimental statistical model (ES model). This model can be generally expressed as follows:

$$\hat{Y} = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} {x_i}^2 + \sum_{i<j} b_{ij} x_i x_j + \cdots \qquad (2)$$

where b_0 is the free member of the regression equation, bi is the linear effects, b_{ii} is the quadratic effects, b_{ij} is the interaction effects.

4 Discussion

The obtained flow index values (*n*) for 15 samples were utilised to construct a 3-factor experimental-statistical (ES) model of the 2nd order (3), as per the experimental design. The ES model proved to be suitable for the experiment, showing an error S_e = 0,18 and comprising four statistically significant coefficients:

$$\begin{array}{llll} n = 0{,}33 \pm 0x_1 & + 0{,}24x_1^2 & \pm 0x_1x_2 \pm 0x_1x_3 & \\ \quad - 0{,}23x_2 & \pm 0x_2^2 & \pm 0x_2x_3 & \\ \quad \pm 0_{x3} & - 0{,}11x_3^2 & & \end{array} \qquad (3)$$

The primary generalising indicators of the model in extreme coordinates for *n* are detailed in Table 3.

Table 3. Main generalising indicators of the model in extreme coordinates for *n*

n_{min}	0,01	n_{max}	0,798
x_1	0	x_1	-1
x_2	+1	x_2	-1
x_3	–1	x_3	0
absolute Δ {*n*}			0,80
relative differential δ {*n*}			80

From the estimates derived from the ES model and single-factor local fields (Fig. 2), it is evident that the addition of the plasticiser Sika Gold (reducing surface tension and the steric effect of the additive [42]), along with the presence of fly ash (forming layers that block cement grains) up to 15 %, notably decreases the flow index. This reduction ensures an increase in the viscosity coefficient, thereby enhancing the plasticity of the mixture. Further introduction of the solid phase becomes necessary only if an increase in *k* does not correspondingly decrease n, resulting in heightened viscosity of the system and consequently, reduced plasticity. This scenario necessitates substantial water addition to the mixture [43]. In this study, introducing fly ash beyond a specified dosage was deemed impractical.

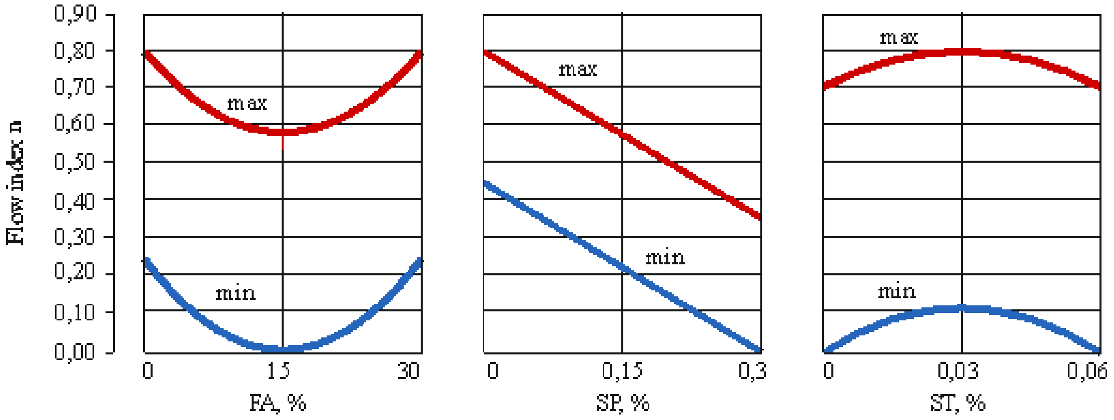

Figure 2. Influence of composition factors on the flow index *n* in the maximum and minimum zones

The impact of limiting shear stress on the mortar phase, τ0, is elucidated by the ES-model (4). This model was deemed appropriate for the experiment, featuring eight statistically significant coefficients:

$$\begin{aligned}\tau_0 = 85{,}29 + 17{,}14x_1 \pm 0x_1^2 \quad &- 9{,}26x_1x_2 \pm 0x_1x_3\\ - 99{,}5x_2 \quad + 44{,}32x_2^2 \quad &- 3{,}41x_2x_3\\ + 4{,}13x_3 \quad - 14{,}5x_3^2 \quad &\end{aligned} \tag{4}$$

The primary generalising indicators of the model in extreme coordinates for τ_0 are as follows: minimum τ_{0min} = 8,44 Pa (x_{min} when x_1=x_3=–1, x_2=0,98) and maximum τ_{0max} = 256,48 Pa (x_{max} when x_1=+1, x_2=–1, x_3=0,26) levels; showcasing an absolute Δ {τ_0} = 248 Pa and relative δ {τ_0} = 2,44 Pa difference. As depicted in the single-factor relationships in Fig. 3, the introduction of fly ash contributed to an increased resistance of the liquid phase of the solution against the pressure of aggregate grains, particularly those floating at a lower density. This was accomplished by compacting the cement matrix. Additionally, the inclusion of the ISOSTAB additive at 0,035 % displayed a notable stabilising effect.

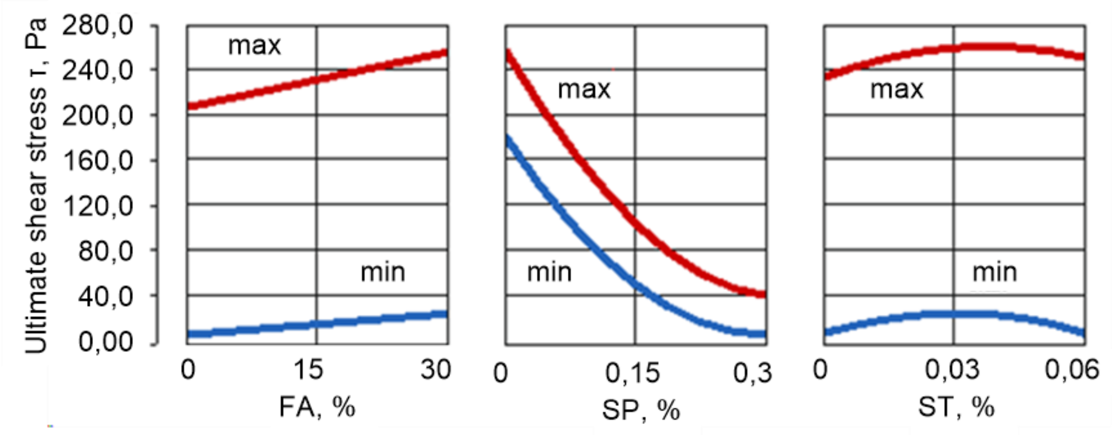

Figure 3. Effect of composition factors on the ultimate shear stress τ_0 in the maximum and minimum zones

Based on data from the ES-models (3-4), diagrams were created in a cubic form, depicted in Figs. 4 and 5. Analysis of the flow index n (Fig. 4) revealed an observed increase in the flow index of the mortar mixture when subjected to the combined influence of all modifying additives, particularly at medium dosages of the stabilising additive ISOSTAB. This resulted in a reduction in the concentration of the plasticiser Sika ViscoCrete-20 Gold, which is based on polycarboxylate esters, along with a decrease in the density of the cement matrix. Such composition conditions have the potential to offer high plasticity to the mixture, consequently ensuring sufficient mobility under specific concrete working conditions. It is noteworthy that the use of this combination of modifying additives can significantly alter the flow index *n* over a wide range (0,030-0,798), thereby affecting the rheological behaviour of the mortar mixture across the spectrum from an «abnormally viscous liquid» to a «Newton liquid».

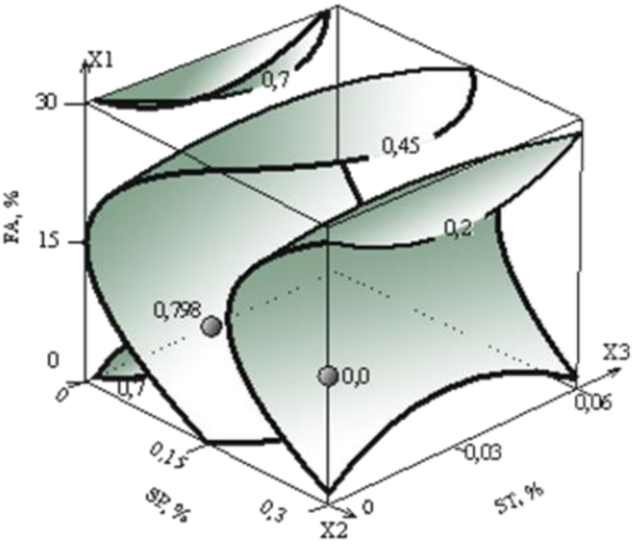

Figure 4. Influence of various factors on the flow index *n* of the solution phase

When examining the model illustrating the impact of variable factors on the limiting shear stress of the mortar phase τ_0 (Fig. 5), it becomes apparent that heightened stability in SCLWC mixtures, and consequently, increased segregation resistance, can be attained by elevating their density. This can be accomplished through the introduction of fine fly ash stabilising additives within the range of average dosages.

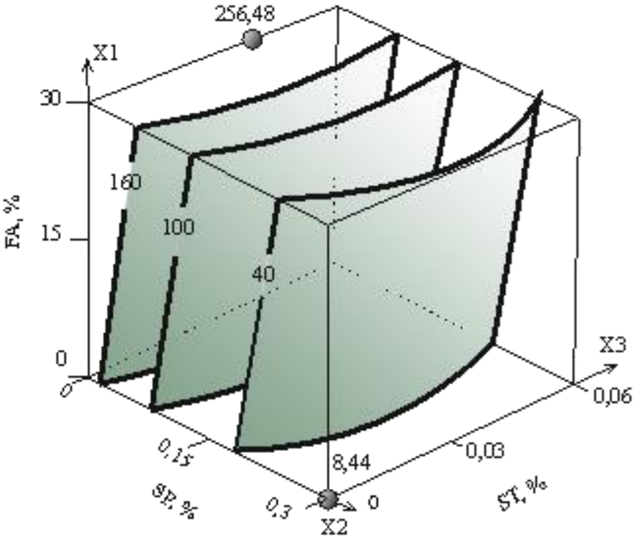

Figure 5. Influence of various factors on the ultimate shear stress of the mortar phase τ_0

Notably, the presence of polycarboxylate ester was minimal in this scenario. Subsequent analysis and exploration to identify the composition's «optimality zones» within combined models of the flow index n and the ultimate shear stress of the mortar phase τ0, considering known values of these indicators in specific working conditions, will facilitate the development of self-compacting concrete mixtures using lightweight aggregate, ensuring both high mobility and uniformity. In these instances, discussions revolve around attaining both optimal and pragmatic compositions while minimising the usage of the costliest components within the mixture.

5 Conclusions

Certain patterns regarding the impact of three variable factors (FA, SP, and ST) on the ultimate shear stress and flow index of cement suspensions were identified. It was determined that the content of superplasticiser in the composition holds the most substantial influence on the studied parameters. The use of this combination of modifying additives is sufficient to substantially alter the flow index over a broad range (0,03-0,798), essentially transforming the rheological behaviour of the mortar mixture from an "«abnormally viscous liquid» to a «Newton liquid». This illustrates the potential to produce self-compacting lightweight concrete on an expanded clay aggregate with enhanced mobility and stability by controlling the rheological parameters of the cement matrix in concrete mixes through targeted modification with Sika ViscoCrete-20 Gold plasticiser, CX ISOSTAB 6003 stabiliser, and the addition of active mineral fly ash to the composition. These rheological control methods can be utilised in the research and design of this concrete type while preserving high structural stability using lightweight aggregates. For future research evaluating the stability of lightweight self-compacting concrete, based on the obtained rheological behaviour results, it is recommended to estimate the optimum ratio within the «mobility-viscosity» system when selecting concrete mixes rationally.

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