44
Research paper
Doi 10.61892/STP202601068K
ISSN 2566-4484

STEPGRAD
СТЕПГРАД

Ehsan Kiana, University of Belgrade, kiana.ehsan@gmail.com
Aleksandar Radević, Građevinski materijali, aradevic@grf.bg.ac.rs
Aleksandar Savić, University of Belgrade, savic.alexandar@gmail.com
Mohsen Kiana, University of Belgrade, mohsen.kiana@kianfc.com
Gordana Broćeta, Civil Engineering, gordana.broceta@aggf.unibl.org
Nenad Ivanisevic, Civil Engineering, nesa@grf.bg.ac.rs
Mahdi Kiana, kian foam beton, Mahdi.kiana@kianfc.com

EXPERIMENTAL INVESTIGATION OF THE RELATIONSHIP BETWEEN BUBBLE MORPHOLOGY AND ABRASION RESISTANCE OF FOAMED CONCRETE

Abstract:

Abrasion resistance is a critical durability parameter of foamed concrete applied in floor screeds and wear - exposed surface layers. Owing to its cellular structure, abrasion performance depends on bubble morphology, including size, distribution and uniformity. This paper presents an experimental study combining high - magnification microscopy with standardized abrasion testing on mixtures with systematically varied composition. Statistical screening identified the governing parameters. Results demonstrate that foaming - agent properties and the resulting pore structure predominantly control abrasion resistance, while other mixture variables have secondary influence. Finer and more homogeneous pore systems significantly enhance surface durability.

Keywords: foamed concrete, abrasion resistance, bubble morphology, cellular structure.

ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ ОДНОСА МОРФОЛОГИЈЕ МЈЕХУРИЋА И ОТПОРНОСТИ ПЈЕНОБЕТОНА НА АБРАЗИЈУ

Резиме:

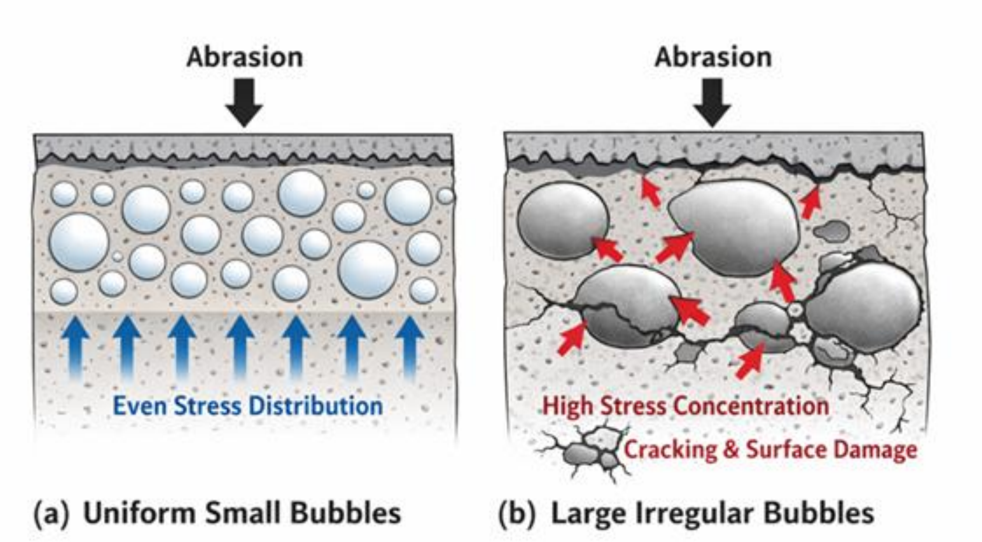
Отпорност на абразију представља кључни параметар трајности пјенобетона који се примјењује у подним естрисима и површинским слојевима изложеним хабању. Због ћелијске структуре, понашање при абразији зависи од морфологије мјехурића, односно њихове величине, расподјеле и уједначености. У раду је приказано сопствено експериментално истраживање које обједињује микроскопску анализу великог увећања и стандардизована испитивања отпорности на абразију на мјешавинама са систематски варираним саставом. Статистичком анализом идентификовани су доминантни фактори. Резултати показују да својства агенса за пјењење и формирана структура пора пресудно утичу на отпорност на абразију, док остали параметри имају секундарни значај. Финија и уједначенија порна структура значајно повећава површинску трајност.

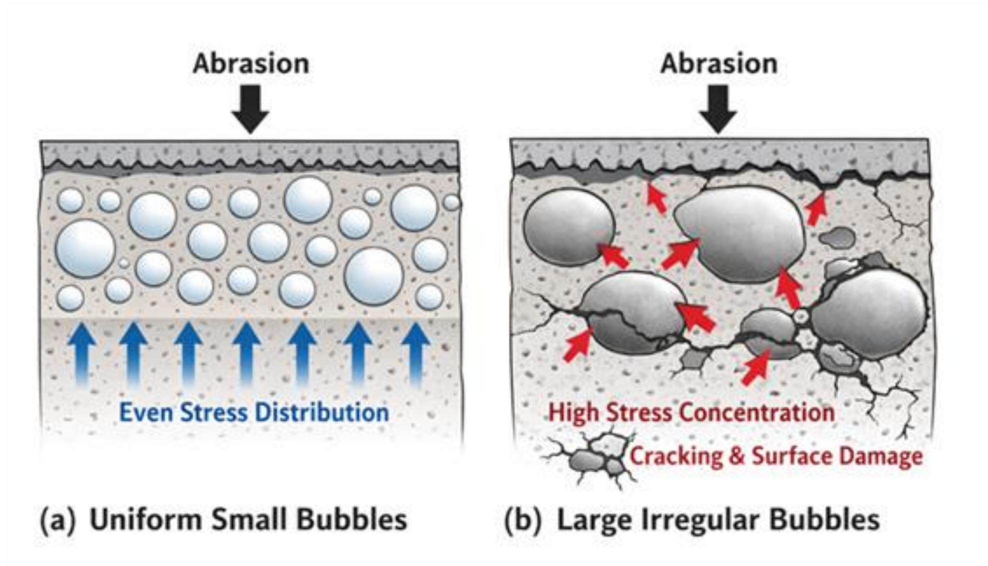
Кључне ријечи: пјенобетон, отпорност на абразију, морфологија мјехурића, ћелијаста стуктура.

1. INTRODUCTION

Foamed concrete is a lightweight, cellular cement - based material widely used for applications such as void filling, backfilling, floor leveling, and screeds [1], [2]. Its low density, pumpability, and thermal/acoustic performance make it attractive for modern construction [3]. However, the high porosity intrinsic to foamed concrete can reduce the integrity of the hardened matrix, leading to weaker surface layers and limited resistance to mechanical wear [4]. In service conditions where surfaces experience repeated friction, contact pressure, and micro - impact, inadequate abrasion resistance may result in surface degradation, dusting, and premature performance loss [5].

The mechanical and durability performance of foamed concrete is governed not only by its bulk density but also by the characteristics of its pore structure. Liu et al. reported that the thermal performance of foam concrete is strongly governed by pore morphology, including bubble size and uniformity, highlighting the critical role of microstructural optimization. Nevertheless, the relationship between bubble morphology and surface durability properties remains insufficiently explored [6]. The bubble network – defined by bubble size, size distribution, and spatial uniformity – controls stress concentration, crack initiation, and the likelihood of local wall collapse. Larger and less uniform pores can act as preferential sites for damage accumulation, whereas a refined and homogeneous bubble structure may reduce local stress peaks and improve the stability of the surface layer under abrasive actions (see





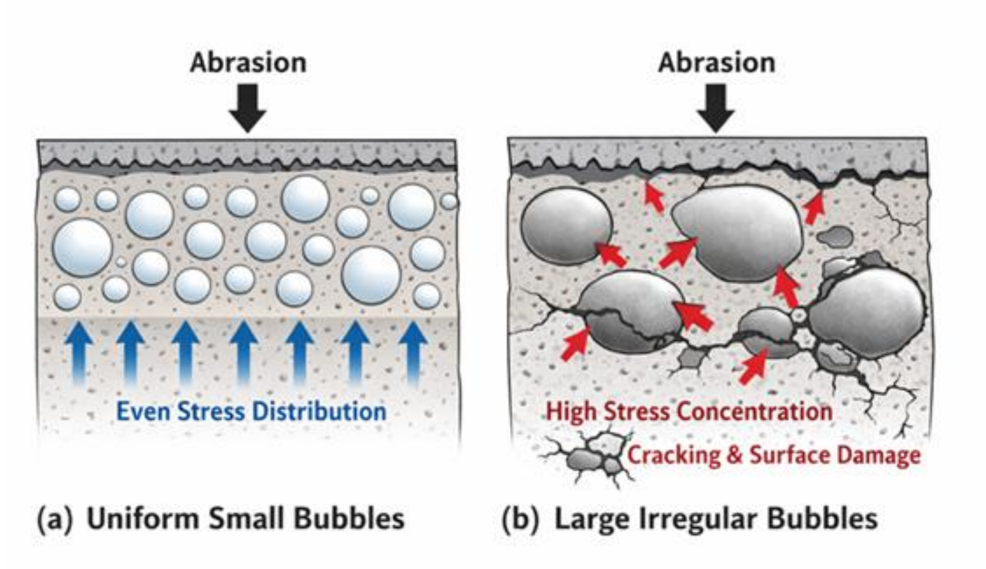


Figure 1. Schematic illustration of the influence of bubble size and uniformity on abrasion performance of foamed concrete (created by author).

Despite the increasing use of foamed concrete in floor - related applications, abrasion behavior has received less attention compared with other performance indicators. Moreover, the quantitative linkage between bubble morphology measured from high - magnification images and abrasion resistance measured by standardized tests remains insufficiently documented.

This paper aims to evaluate the relationship between bubble morphology and abrasion resistance of foamed concrete. Bubble sizes are quantified from 50 × microscopic images, and the abrasion resistance is assessed using the *Böhme* abrasion test (**Error! Reference source not found.**) [7]. The outcomes provide microstructure - based insights to guide practical improvements in foamed - concrete durability.

a) b)

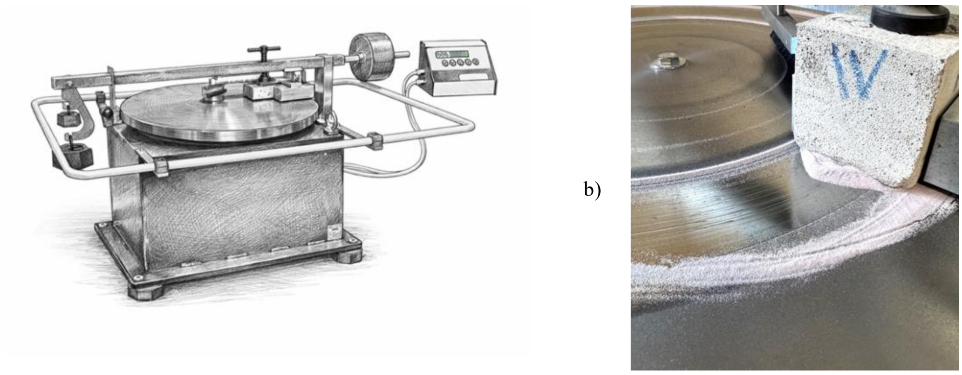


Figure 2. Böhme abrasion test used to evaluate abrasion resistance of foamed concrete:
(a) schematic illustration of the testing apparatus;
(b) experimental setup showing the foamed - concrete specimen during abrasion testing

In a previous study conducted by the authors, the physical and mechanical properties of foamed concrete were investigated with a particular focus on the influence of polypropylene fibers on parameters such as density, compressive strength, and tensile strength. That study primarily addressed the improvement of the bulk mechanical performance of foamed concrete mixtures [8].

Building upon those findings, the present research extends the investigation toward surface durability aspects, specifically the abrasion resistance of foamed concrete. The aim is to better understand how the cellular structure and bubble morphology influence wear behavior under abrasive conditions. In this way, the current study represents a continuation of the previous research by shifting the focus from general mechanical and physical properties to the durability performance of the surface layer.

2. EXPERIMENTAL PROGRAM

A total of sixteen foamed - concrete mixes were produced (**Error! Reference source not found.**). The experimental matrix included variations in (i) foaming agent type (synthetic vs. protein - based), (ii) cement type (Portland vs. pozzolanic), (iii) the use of supplementary cementitious materials (SCM – fly ash: with vs. without), and (iv) polypropylene fiber addition (with vs. without). The water - to - cement ratio was set to 0.45 for Mix 1 and to 0.60 for Mixes 2–16. Specimens were prepared under controlled laboratory conditions, cast in molds, and cured for 28 days prior to testing.

Table 1. Matrix of foamed concrete mixtures and investigated parameters

Number	Machine	Foam Agent	Cement	SCM	Fiber PP 12 mm
1	Wind pressure	Synthetic	Portland	without SCM	without fiber
2					with fiber
3				with SCM	without fiber
4					with fiber
5			Pozzolanic	without SCM	without fiber
6					with fiber
7				with SCM	without fiber
8					with fiber
9		Protein	Portland	without SCM	without fiber
10					with fiber
11				with SCM	without fiber
12					with fiber
13			Pozzolanic	without SCM	without fiber
14					with fiber
15				with SCM	without fiber
16					with fiber

Abrasion resistance was evaluated using the *Böhme* abrasion test in accordance with the relevant standard. The abrasion loss was expressed as volume loss ($cm^3/50\ cm^2$) and adopted as the primary indicator of surface durability. For the sixteen investigated mixes, the measured abrasion values ranged from approximately 8.11 to 38.55 $cm^3/50\ cm^2$.

To quantify bubble morphology, fracture surfaces of the hardened foamed concrete were imaged using a digital microscope at 50 × magnification. Bubble diameters were measured directly on the micrographs. The images were acquired using a digital inspection microscope (ASH Omni, ASH Technologies, Ireland) equipped with adjustable magnification and integrated LED illumination. The system was connected to a computer for real - time visualization and image capture, allowing precise measurement of pore dimensions on the fracture surface. For each mix, multiple bubbles were measured to characterize the pore system, and the average bubble size was calculated. The average bubble size ranged from approximately 0.269 to 0.568 mm across the mixes. In the next stage of analysis, bubble - size dispersion will be derived from the individual measured diameters to evaluate the effect of bubble uniformity on abrasion resistance.

Representative micrographs are provided to illustrate the measurement procedure and the characteristic pore morphology. Figure 3(a) shows a side view of a selected specimen (Mix 16) captured at 20 × magnification, highlighting the general cellular structure and pore connectivity. Figure 3(b) presents a top - view micrograph of the same specimen acquired at 50 × magnification, where individual bubble diameters were directly measured on the image. In addition, Figure 4 presents top - view micrographs at 50 × magnification for all sixteen mixes, enabling a qualitative comparison of bubble size, spatial distribution, and pore uniformity across the entire experimental matrix.

a)

b)

Figure 3. Micrographs used for bubble size measurements: (a) side view at 20 × magnification; (b) top view at 50 × magnification with measured bubble diameters (created by author).

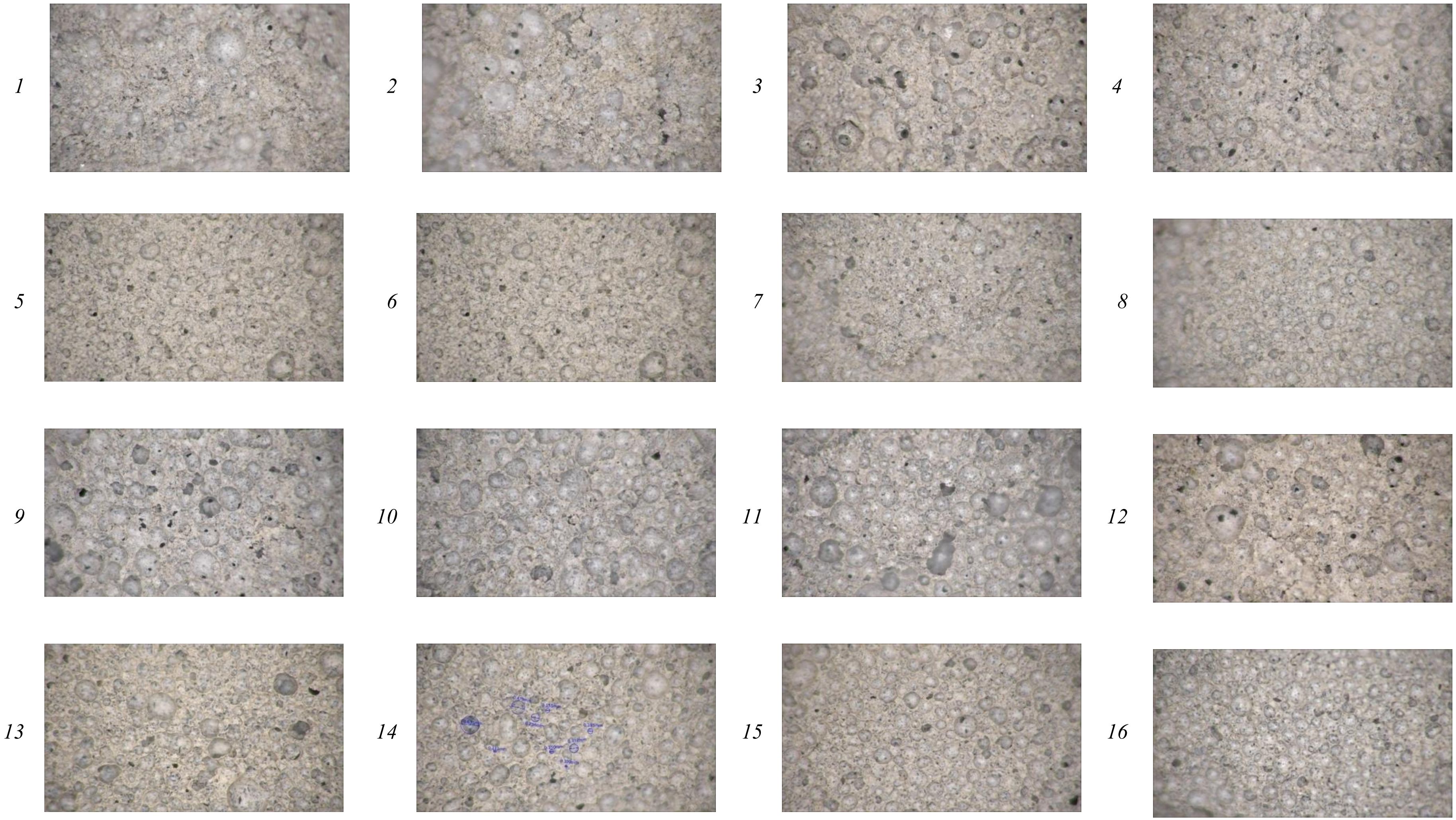
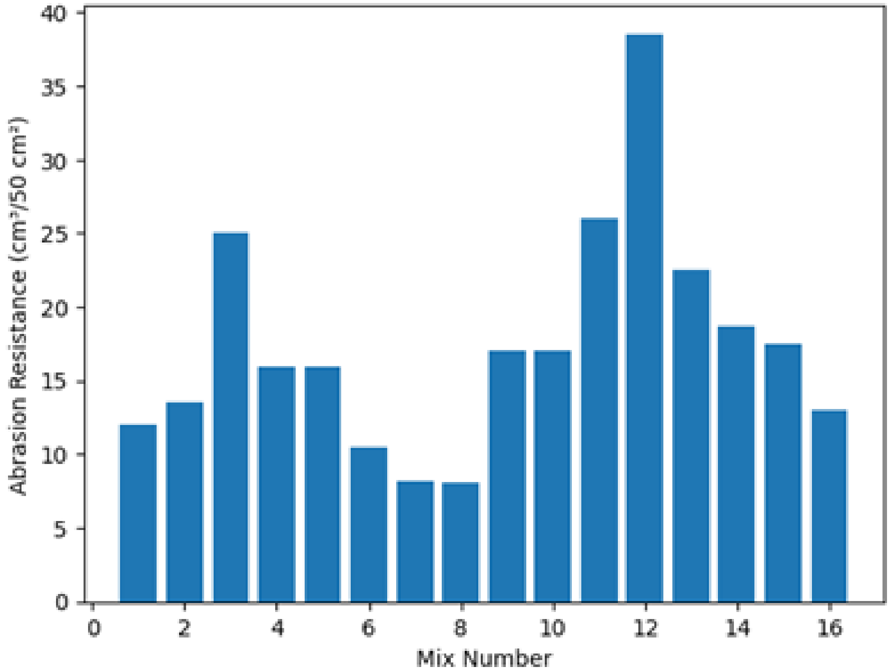


Figure 4. *Representative 50 × micrographs of foamed concrete for all sixteen mixes (Mixes 1–16), illustrating the variability in bubble size, distribution, and pore uniformity used for quantitative bubble morphology analysis (created by author).*

3. RESULTS AND EVALUATION

3.1. ABRASION RESISTANCE RESULTS

The abrasion resistance of the sixteen foamed - concrete mixtures was determined using the *Böhme* abrasion test. The measured abrasion volume loss values for all mixtures are summarized



in

. The abrasion results exhibit a wide range of variation among the investigated mixes.

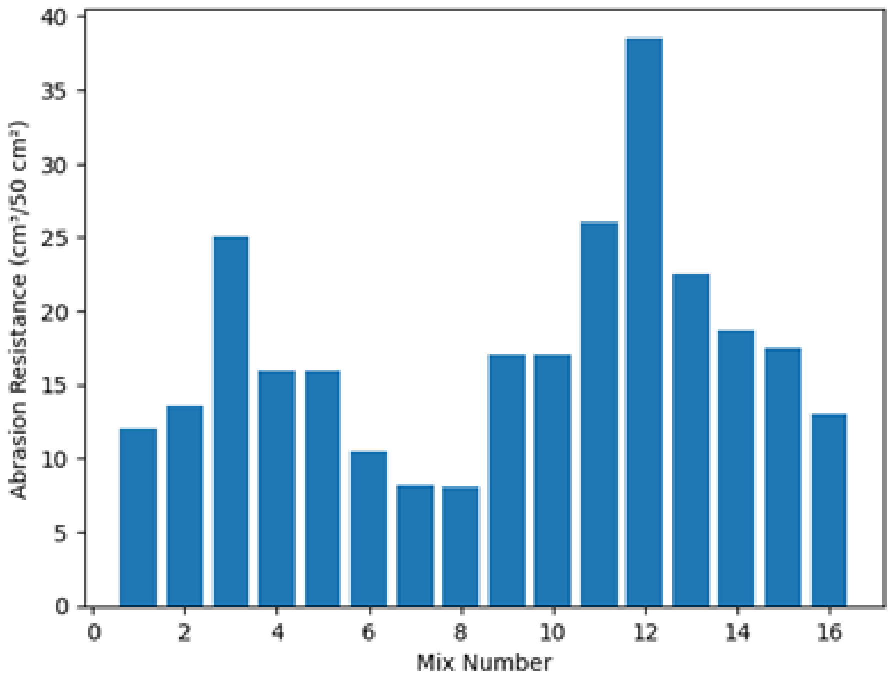


Figure 5. Abrasion volume loss of all foamed - concrete mixes measured by the Böhme abrasion test (created by author).

The lowest abrasion loss was obtained for Mix 8 (8.11 $cm^3/50\ cm^2$), followed closely by Mix 7 (8.14 $cm^3/50\ cm^2$). The highest abrasion loss was recorded for Mix 12 (38.55 $cm^3/50\ cm^2$). The remaining mixtures show intermediate abrasion values distributed across the investigated range.

When grouped according to foaming agent type, the synthetic - foam mixtures (Mixes 1–8) generally exhibit lower abrasion losses and smaller variability compared with the protein - based mixtures (Mixes 9–16), which show higher maximum abrasion values and greater scatter.

3.2. BUBBLE MORPHOLOGY RESULTS

The cellular structure of the foamed concrete was evaluated using fracture - surface micrographs obtained at 50 × magnification. Bubble diameters were measured directly from the images. Due to variations in image quality and pore density, the number of measurements per mixture ranged between 3 and 10 bubbles. Since such a limited number of measurements may be influenced by the presence of one or several large pores, the morphological analysis was not restricted to the mean bubble diameter alone. Instead, additional statistical indicators – including standard deviation (STD), coefficient of variation (CV = STD/Mean), and maximum bubble size (d_{max}) were calculated to more accurately characterize pore - structure heterogeneity.

Considering all measurements across the sixteen mixtures, individual bubble diameters ranged from 0.051 mm to 1.579 mm, indicating a considerable variability in cellular structure. The smallest mean bubble diameter was observed in Mix 14 (approximately 0.27 mm), whereas the largest mean value was recorded for Mix 2 (approximately 0.57 mm). However, closer examination reveals that the mean bubble size alone is insufficient to fully describe the cellular structure, as some mixtures with similar mean values exhibit markedly different dispersion and maximum bubble sizes, which may significantly influence mechanical and abrasion performance.

To ensure a coherent interpretation of the results and avoid fragmented analyses, an initial statistical screening was performed using Pearson correlation coefficients between abrasion resistance and the main mixture parameters. The results indicate that foam type exhibits the strongest correlation with abrasion resistance ($r \approx +0.51$), highlighting the dominant role of the foaming agent – and consequently the cellular structure – in governing abrasion behavior. Cement type also showed a noticeable negative correlation ($r \approx -0.43$), suggesting a relative improvement in abrasion resistance when pozzolanic cement is used. In contrast, the presence of SCMs ($r \approx +0.20$) and polypropylene fibers ($r \approx -0.07$) exhibited weak or negligible correlations. The correlation associated with the water - to - cement ratio ($r \approx +0.18$) should be interpreted with caution, since only one mixture was produced with a distinct w/c ratio (0.45), while all others were prepared at w/c = 0.60. Therefore, the dataset does not provide sufficient statistical variability to reliably assess the effect of this parameter.

Table 2. Pearson correlation screening between abrasion resistance and investigated parameters

Parameter	Definition / Encoding	Interpretation	Pearson r (vs. Abrasion)
Foam type	synthetic = 0, protein = 1	moderate positive	+ 0.51
Cement type	portland = 0, pozzolanic = 1	moderate negative	− 0.43
SCM	without = 0, with = 1	weak positive	+ 0.20
Water - to - cement ratio (w/c)	numerical value	weak	+ 0.18
Polypropylene fiber	without = 0, with = 1	negligible	− 0.07

3.3. ANALYSIS OF SYNTHETIC FOAM MIXTURES (MIX 1–8)

To obtain a more structurally consistent interpretation, Mixes 1 and 2 were excluded from the synthetic foam group, and the analysis was focused on Mixes 3–8. The evaluation was conducted using three complementary morphological parameters: mean bubble diameter, maximum bubble size (d_{max}), and coefficient of variation (CV), representing overall pore refinement, critical defect size, and structural heterogeneity, respectively.

Within this refined dataset, abrasion loss decreases generally with decreasing mean bubble size and, more distinctly, with decreasing maximum bubble size. Mix 3, which exhibits the highest abrasion loss (25.01 $cm^3/50\ cm^2$), is characterized by the largest d_{max} (1.132 mm) and the highest structural heterogeneity (CV = 0.761), indicating the presence of critical large pores that act as stress concentration sites under abrasive loading. In contrast, Mix 8 shows the lowest abrasion loss (8.11 $cm^3/50\ cm^2$) and simultaneously presents the smallest mean bubble size (0.321 mm) and the lowest maximum bubble size (0.640 mm), reflecting a refined and more homogeneous cellular structure.

However, the relationship is not strictly linear. For example, Mix 7 demonstrates excellent abrasion resistance (8.14 $cm^3 / 50\ cm^2$) despite exhibiting relatively high heterogeneity (CV = 0.751), suggesting that matrix characteristics and pore - wall integrity may partially compensate for structural dispersion. Overall, the results indicate that in synthetic foams, abrasion performance is primarily governed by the control of critical large pores (d_{max}), while mean bubble size and structural uniformity (CV) play supporting but non - negligible roles.

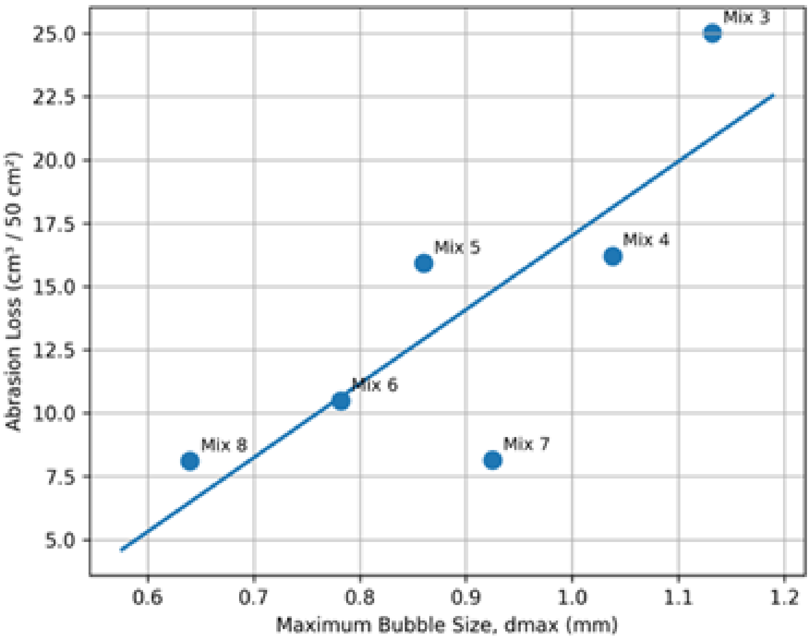


Figure 6. *Relationship between maximum bubble size (d_{max}) and abrasion loss for synthetic foamed - concrete mixes – Mixes 3–8 (points represent individual mixes; the line indicates the linear regression trend) (created by author).*

3.4. ANALYSIS OF PROTEIN - BASED FOAM MIXTURES (MIX 9–16)

In the protein - based foam group, abrasion loss exhibits a wide variation, ranging from 13.05 to 38.55 $cm^3 / 50\ cm^2$, indicating a higher sensitivity of this foam type to structural variations. Simultaneous analysis of mean bubble size, maximum bubble size (d_{max}), and coefficient of variation (CV) reveals that abrasion behavior in this group is primarily governed by the presence of critical large pores and the degree of structural heterogeneity.

The highest abrasion loss is observed in Mix 12, which exhibits both the largest d_{max} (1.457 mm) and the highest CV (0.74). This concurrence indicates that the presence of isolated large pores combined with high dispersion promotes localized stress concentration and accelerates surface degradation under abrasive loading. The behavior of Mix 11 and Mix 13 further supports this trend, as d_{max} values exceeding 1 mm are associated with a pronounced increase in abrasion loss.

In contrast, the lowest abrasion loss in this group corresponds to Mix 16, which presents a smaller d_{max}. Moreover, evaluation of the mean bubble size demonstrates that this parameter alone is insufficient to explain abrasion performance. For example, Mix 14, despite having the smallest mean bubble size (0.27 mm), still exhibits moderate abrasion resistance. This observation suggests that even when the overall cellular structure is refined, the presence of structural heterogeneity or relatively large local pores may adversely affect abrasion performance.

Overall, the results indicate that in protein - based foams, an increase in d_{max} beyond approximately 1 mm acts as a critical threshold, leading to a substantial increase in abrasion loss, while a higher CV further amplifies this effect. Therefore, in this foam type, controlling critical large pores and reducing structural heterogeneity is more influential than merely reducing the mean bubble size.

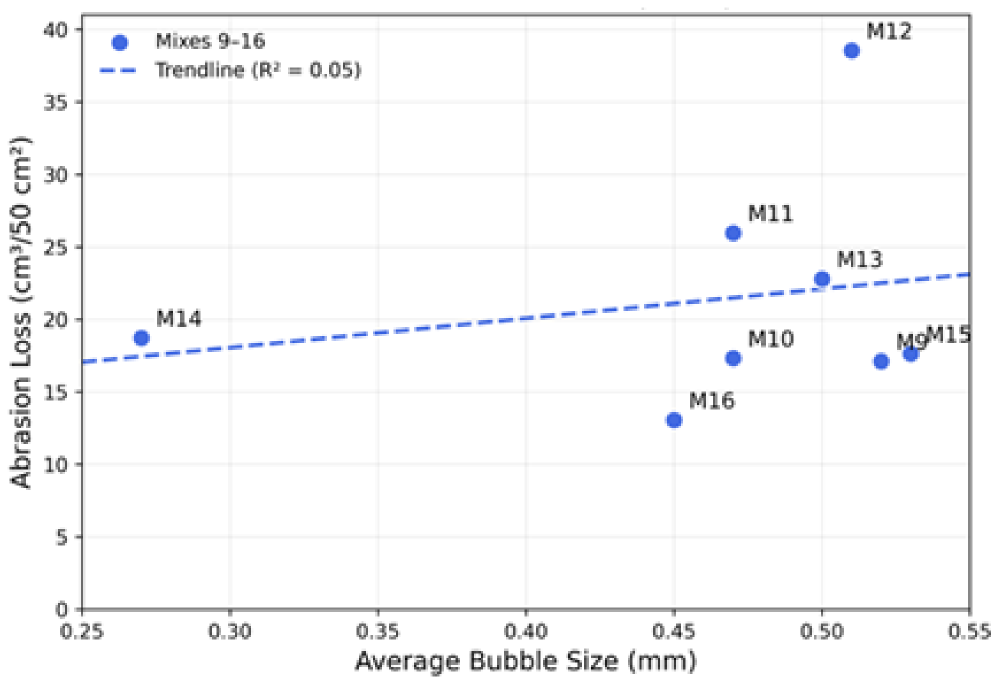


Figure 7. Maximum bubble size (d_{max}) versus abrasion loss for synthetic foam mixes – Mix 9–16 (points represent individual mixes; the solid line shows the linear regression trend) (created by author).

4. CONCLUSION

In this study, the relationship between bubble morphology and abrasion resistance of foamed concrete was investigated using fracture - surface microscopy and the standardized *Böhme* abrasion test. The results demonstrate that abrasion performance is governed not only by the mean bubble diameter, but more critically by the presence of isolated large pores (d_{max}) and the degree of structural heterogeneity (CV).

The findings indicate that cellular structures characterized by lower dispersion and limited critical large pores exhibit more stable abrasion behavior and improved resistance to surface degradation. In synthetic foams, abrasion resistance improves with the simultaneous reduction of mean bubble size and dispersion, although the relationship is not strictly linear. In contrast, protein - based foams show higher sensitivity to structural heterogeneity, where increases in maximum bubble size (d_{max}) are directly associated with significant increases in abrasion loss.

These results highlight that controlling bubble uniformity and minimizing large isolated pores are key parameters for enhancing the surface durability of foamed concrete. While foam type emerged as the most influential parameter within the investigated dataset, further studies incorporating a broader range of water - to - cement ratios and structural variables are necessary to establish more generalized predictive relationships.

ACKNOWLEDGEMENT

The authors gratefully appreciate support from the projects financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under Contract No. 200092. Also, the authors would like to express their sincere gratitude to Kian Foam Beton, based in Iran, for their generous financial support and technical assistance throughout the course of this research. This project would not have been possible without their commitment, provision of materials, and full funding.

LITERATURE

[1] K. Ramamurthy, E. K. Kunhanandan Nambiar, and G. Indu Siva Ranjani, “A classification of studies on properties of foam concrete,” *Cem. Concr. Compos.*, vol. 31, no. 6, pp. 388–396, Jul. 2009, doi: 10.1016/j.cemconcomp.2009.04.006.

[2] Y. H. M. Amran, N. Farzadnia, and A. A. A. Ali, “Properties and applications of foamed concrete; A review,” Dec. 30, 2015, *Elsevier Ltd*. doi: 10.1016/j.conbuildmat.2015.10.112.

[3] A. Raj, D. Sathyan, and K. M. Mini, “Physical and functional characteristics of foam concrete: A review,” Oct. 10, 2019, *Elsevier Ltd*. doi: 10.1016/j.conbuildmat.2019.06.052.

[4] A. Just and B. Middendorf, “Microstructure of high - strength foam concrete,” *Mater. Charact.*, vol. 60, no. 7, pp. 741–748, Jul. 2009, doi: 10.1016/j.matchar.2008.12.011.

[5] A. Warudkar and S. Elavenil, “A comprehensive review on abrasion resistance of concrete,” *International Journal of Applied Science and Engineering*, vol. 17, no. 1, pp. 29–43, 2020, doi: 10.6703/IJASE.202003_17(1).029.

[6] J. Liu, Y. Liu, X. Ma, H. Xu, X. Wu, M. Liu and Y. Zhuge, “Thermal performance optimization of foam concrete for energy - efficient construction: A state - of - the - art review,” Oct. 15, 2025, *Elsevier Ltd*. doi: 10.1016/j.jobe.2025.113899.

[7] EN 13892 - 3:2004. Methods of test for screed materials – Part 3: Determination of wear resistance – Böhme, European Committee for Standardization (CEN), Brussels, 2004.

[8] M. Kiana, A. Savić, G. Broćeta, A. Radević, E. Kiana, M. Aškrabić, and N. Ivanišević, “The Effect of Polypropylene Fibers on the Mechanical and Physical Properties of Foam Concrete,” *VI naučno - stručni simpozijum ENERGETSKA EFIKASNOST – ENEF 2025,* Banja Luka, 12–13 jun 2025, pp. 87–91. https://enef.etfbl.net/2025/resources/Radovi/15.%20THE%20EFFECT%20OF%20POLYPROPYLENE%20FIBERS%20ON%20THE%20MECHANICAL%20AND%20PHYSICAL%20PROPERTIES%20OF%20FOAM%20CONCRETE.pdf