Türk Mühendislik Araştırma ve Eğitimi Dergisi
Turkish Journal of Engineering Research and Education

2(2), 79-91, (2023)

RESEARCH ARTICLE

Effect of Partial and Full Replacements of Natural Aggregate with Bottom Ash in Pervious Concrete Pavement

Geçirimli Beton Kaplamada Doğal Agreganın Taban Külü ile Kısmi ve Tam İkamesinin Etkileri

Zeinab Nasser Eddine[1*] Firas Barraj [2] Jamal Khatib [1, 3] Adel Elkordi [1, 4]

[1] Dept. of Civil and Environmental Eng., Beirut Arab University. P.O. Box 11-5020 Beirut, Lebanon. Riad El Solh, Beirut 1107-2809, Lebanon.

[2] Department of Civil and Environmental Engineering, University of Balamand, P.O. Box 100, Al Koura 1304, Lebanon.

[3] Faculty of Science and Engineering, University of Wolverhampton, Wolverhampton WV1 1LY, United Kingdom.

[4] Dept. of Civil and Environmental Engineering, Faculty of Engineering, Alexandria university, Alexandria,21511, Egypt.

Received / Geliş: 15.05.2023
Accepted / Kabul: 16.06.2023
***Corresponding Author: Zeinab Nasser Eddine,** zaynab.naserddyne@gmail.com

ABSTRACT: Shrinkage is a main criterion of durability. Its control is essential for the long-term serviceability of concrete, especially pervious concrete (PC). This study examines the autogenous shrinkage and expansion of pervious concrete pavement (PCP), including municipal solid waste incineration bottom ash (BA) from a Lebanon source as a partial and full replacement of natural aggregate (NA). Five pervious concrete mixes were produced with various BA replacement ratios of 0, 25, 50, 75, and 100% BA (by volume), with comparable particle sizes to those of the natural aggregate. The study also investigates the compressive strength and total porosity of pervious mixes and analyzes the correlations between them. Results showed that the increase in BA content decreased the autogenous shrinkage, expansion, and compressive strength of PC mixes. However, it increases the total porosity of the mix. Results also present the correlations between compressive strength and autogenous shrinkage, expansion, and porosity at various curing days. A negative correlation was shown between expansion and total porosity, as well as between compressive strength and total porosity.

Keywords: Pervious, bottom ash, autogenous shrinkage, expansion, compressive strength, porosity.

ÖZ: Büzülme, dayanıklılığın ana kriterlerinden biridir. Betonun, özellikle de geçirimli betonun (PC) uzun süreçte hizmet verebilmesi için kontrol edilmesi gereklidir. Bu çalışma, doğal agreganın (NA) kısmi ve tam ikamesi olarak Lübnan kaynaklı belediye katı atık yakma taban külü (BA) içeren geçirgen beton kaplamanın (PCP) otojen büzülmesini ve genleşmesini incelemektedir. Doğal agreganınkine yakın parçacık boyutlarında, %0, 25, 50, 75 ve %100 BA (hacimce) olmak üzere çeşitli ikame oranlarına sahip beş ayrı geçirimli beton karışımı üretilmiştir. Çalışmada geçirimli betonların basınç dayanımı ve toplam gözenekliliği incelenmiş, bunlar arasındaki korelasyonlar analiz edilmiştir. Sonuçlar, BA içeriğindeki artışın, PC karışımlarının otojen büzülmesini, genleşmesini ve basınç dayanımını azalttığını göstermiştir. Bununla birlikte, BA içeriğindeki artış betonların toplam gözenekliliğini artırmıştır. Sonuçlar ayrıca çeşitli kürleme günlerinde basınç dayanımı ile otojen büzülme, genleşme ve porozite arasında ilişki olduğunu da ortaya koymuştur. Genleşme ile toplam porozite arasında ve basınç dayanımı ile toplam porozite arasında negatif bir korelasyon olduğu gösterilmiştir.

Anahtar Kelimeler: Geçirgen, dip külü, otojen büzülme, genleşme, basınç dayanımı, gözeneklilik.

Zeinab Nasser Eddine, Orcid: 0009-0001-3205-2310 / Firas Barraj , Orcid: 0000-0002-5946-9239 / Jamal Khatib, Orcid: 0000-0002-4393-6728/ Adel Elkordi, Orcid: 0000-0002-1487-8469

1. INTRODUCTION

The construction sector has recognized the ongoing need to develop PCP due to its numerous benefits, such as mitigating the negative impacts of population growth and addressing water runoff problems, in addition to its various environmental advantages [1]-[3]. PC is characterized by a low or negligible amount of fine aggregate, creating sufficient voids that facilitate the passage of air and water from the surface to the underlying layers [4]However, alongside these benefits, PC presents certain challenges, including the determination of appropriate mix proportions, workability, as well as durability characteristics [5]-[10].

The primary constituent of PC structures is natural aggregate, accounting for approximately 70% of their total volume [11]. However, due to urban expansion and the rising demand for natural aggregate, this resource has become increasingly scarce. As a result, there is a persistent need for alternative resources. Municipal solid waste, which requires huge landfill space demands and poses chronic problems, particularly in densely populated countries like Lebanon, has led to an increased exploration of utilizing MSWIA as a replacement for natural aggregates. Thus, the need for disposal methods and landfill spaces for these wastes will diminish with their recycling and reusing, which is very advantageous, especially for this country where about 7,500 tons of MSW are produced each year. Part of these ashes will be incinerated. Bottom ash (BA) is the predominant component, constituting approximately 80% of the total municipal solid waste incineration ashes, making its utilization crucial within the circular economy. Numerous previous studies have investigated the effects of partially or fully replacing natural aggregates with bottom ash in concrete, focusing on its mechanical and structural properties [12]-[14].

In addition to considering and evaluating the engineering properties, it is crucial to evaluate the durability characteristics of concrete due to the development of cracks that pose a threat to its durability. Shrinkage serves as a fundamental criterion for durability, as excessive shrinkage results in the formation of cracks. Drying shrinkage occurs when the free water in concrete evaporates due to the low external humidity and temperature of the cement paste [15]. Autogenous shrinkage, shares a similar mechanism with drying shrinkage but is internally induced, resulting from desiccation [16]. Expansion, in contrast, occurs when the specimen is exposed to water or excessive moisture [17].

Controlling shrinkage is of utmost importance in the construction industry, particularly for PC pavement, given its porous structure that exposes a large surface area to various environmental factors. While previous studies have explored this topic in PC [18]-[20], Few studies have been conducted on the shrinkage of PC pavement, specifically those containing bottom ash. This paper investigates the autogenous shrinkage, expansion, compressive strength, and total porosity of a PC pavement incorporating different amounts of bottom ash as a partial or full substitute for natural aggregate. Additionally, it explores the correlations between these factors.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

Portland cement 52.5 with a density of 3.15 g/cm^3 was employed. Silica fume (SF) was also utilized with a density of 2.3 g/cm^3 to improve the PC mechanical properties, while superplasticizer was applied to improve its workability. The employed natural aggregates ranged in size from 2.36 to 9.5 mm. The chemical compositions of the cement and SF can be found in Table 1. In the case of PC mixes incorporating waste, the bottom ash (BA) was submerged in water for one week for treatment. Both the natural aggregate (NA) and BA possessed identical particle sizes. The specific gravities and water absorptions were recorded as 2.51 and 1.62% for NA, and 1.8 and 12.49% for BA, respectively.

Table 1: Cement and SF chemical compositions.

	Cement	SF
SiO_2	21.6	90.8
Al_2O_3	4.05	0.56
Fe_2O_3	0.26	0.38
CaO	65.7	0.79
MgO	1.3	2.45
Na_2O	0.3	0.15
K_2O	0.35	0.15
SO_3	3.3	0.9
LOI	1.3	2.7

2.2 Mix Design

Five different mixes were produced. The ratio of water to binder in the control mix was 0.15, and the ratio of aggregate-binder was 4. The binder content was 400 kg/m^3 and was composed of 90% cement and 10% silica fume. In the other four mixes, NA was only replaced by volume with 25%, 50%, 75%, and 100% BA. All other mixes were kept constant across all mixes. Also, the superplasticizer remained at a constant level for all mixes and was determined and added based on the binder weight. The details of the mixes are listed in Table 2.

Table 2: Mix proportions of PC.

	kg/m^3					
Notation	**NA**	**BA**	**Cement**	**SF**	**Water**	**Superplasticizer**
0BA	1600	0	360	40	57	4
25BA	1200	288	360	40	57	4
50BA	800	575	360	40	57	4
75BA	400	862	360	40	57	4
100BA	0	1150	360	40	57	4

2.3 Sample Preparation and Testing

50 mm × 50 mm × 250 mm prism specimens were produced for the shrinkage measurement as well as the expansion measurement. After 24 hours, the specimens were taken out of the molds, and two demec points were positioned at 200 mm on each side of the samples, as represented in Figure 1 (a). A dial gauge (illustrated in Figure 1 (b)) was used to measure the length once a day for the first week, and then once a week for the next 28 days. Equation (1) was then used to calculate the length change, which was then reported as the average readings for two samples for each mix.

$$LC = \frac{L_0 - L_i}{200} \times 10^{-6} \quad (1)$$

Where,
LC represents the length change (με);
L_0 stands for the initial length that the dial gauge recorded (mm); and
L_i represents the length recorded by dial gauge on various days (mm).

Figure 1: (a) Sample with two demec points; (b) Dial gauge machine.

The autogenous shrinkage and expansion of mixes were determined according to ASTM C192 [21]. Specimens of both are shown in Figure 2. For autogenous shrinkage, the samples were placed in plastic bags to prevent exposure to environmental conditions from the outside. For expansion, specimens were submerged in water at a constant temperature of (20±1°C). In addition, compressive strength and total porosity experiments were carried out on 70 mm cubes. Compressive strength was evaluated at 1-, 7-, and 28-days post-curing according to ASTM C39 [22]. The compressive strength value was determined by averaging the results of three replicates samples. The average of three specimens was recorded as the compressive strength value. The total porosity of the concrete was determined using ASTM C 1754 [23]. To assure the saturation of pores, the specimen was initially submerged in water. After that, the weight of the samples (W_1) that were immersed was measured.

After the specimen had dried in the oven, its weight (W_2) was also obtained. Using equation (2), the specimen's total porosity (P) was calculated as follows:

$$P = \left[1 - \frac{W_2 - W_1}{\rho V}\right] x\ 100\% \quad (2)$$

Figure 2: (a) Specimens of autogenous shrinkage; (b) Specimens of expansion.

3. RESULTS AND DISCUSSION

3.1 *Autogenous Shrinkage*

Figure 3 presents the evolution of autogenous shrinkage in PC mixes containing different BA contents during the 28 days of curing. The mixes containing BA showed a small expansion in the first few days. After that, autogenous shrinkage for all mixes began and rose with curing time. For example, the autogenous shrinkage of the 0BA mix increased from 3με at day 1 to 437 με at day 28. This increase is attributable to the low water-to-cement ratio used, resulting in a low internal humidity that leads to the self-desiccation of the cement paste and automatically to autogenous shrinkage [1, 24, 25]. From the figure, we can also notice that the autogenous shrinkage increased faster in the first two weeks. This agrees with the results of conventional concrete with low w/c [26] and especially with the use of silica fume, where it has an effect on increasing the autogenous shrinkage [27], also, the early-age shrinkage [28].

The autogenous shrinkage of mixes containing BA diminished as BA content increased. For example, the autogenous shrinkage for 25BA mix at day 14 was 287με and for 100BA mix at the same day was 114με. This decrease is attributed to the role of water in BA in improving the relative humidity of cement paste, resulting in a decrease in self-desiccation [29, 30].

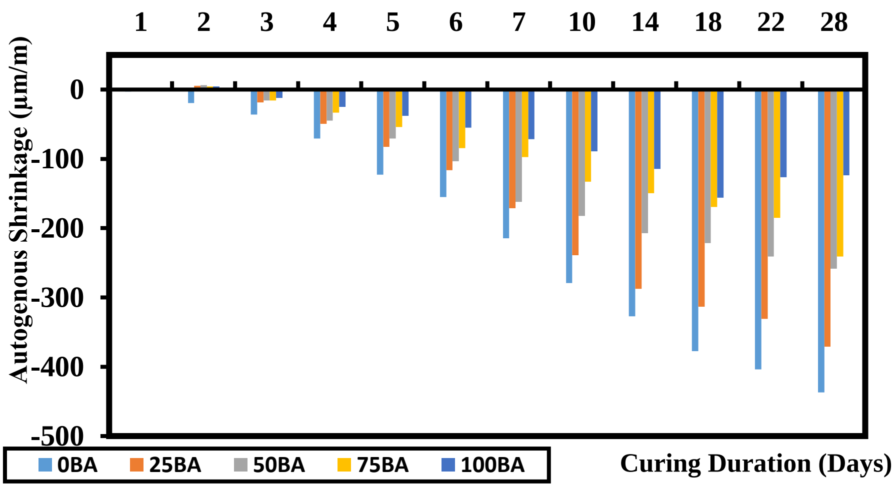

Figure 3: The evolution of autogenous shrinkage for PC mixes during 28 days.

Figure 4 displays the obvious difference in autogenous shrinkage between the control mix and the mixes containing BA. As mentioned before, autogenous shrinkage diminished as BA content increased. On day 7, the decrease was 21%, 25%, 55%, and 67% for mixes containing 25, 50, 75, and 100% BA, respectively. This reduction changes with time in a non-uniform way with the increase in BA, due to the effect of heterogeneous pores on the formation of cement paste and consequently of shrinkage, to achieve values of 20%, 40%, 54%, and 71% observed for mixes with 25, 50, 75, and 100% BA, respectively, after 28 days.

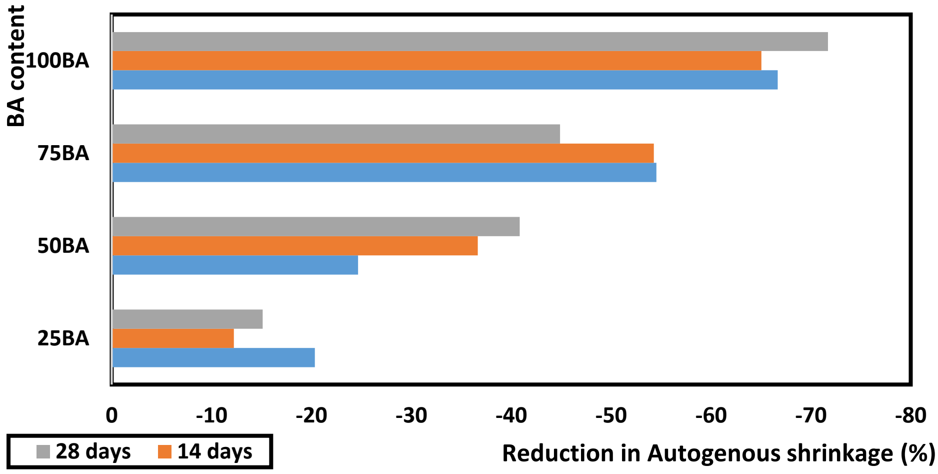

Figure 4: Difference between the autogenous shrinkage of the control PC (0BA) and mixes containing BA over 28days.

3.2 Expansion

Figure 5 shows the evolution of expansion of PC mixes containing various amounts of BA during 28 days of curing. All mixes revealed continuous expansion with time due to the high relative humidity. For the control mix (0BA), the expansion behavior might be attributed to the gel expansion when exposed to high humidity [31] and it might also be due to the alkali-silica reaction (ASR) in aggregates [32]. The expansion value for 0BA at day 28 was 585 με. It decreased as BA content increased to reach a value of 309 με at the same day for the mix containing 100BA. This decrease in expansion values as BA content increased is owing to the porous structure of BA aggregate, which leads to high porosity in mixes containing BA (Table 3) helping to accommodate the volume of expansion caused by the increasing relative humidity [30], the chemical reactions of the contaminants in BA [33] and the formation of expansion stresses [34].

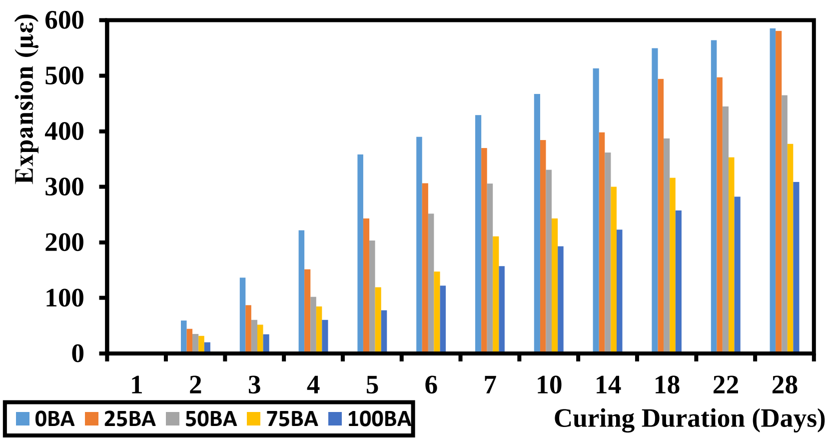

Figure 5: The evolution of expansion of PC mixes during 28 days.

Figure 6 presents the significant difference in expansion between the control mix and the mixes containing BA. Expansion decreased as BA increased. This decrease was 13%, 29%, 51%, and 63% at day 7 for mixes containing 25, 50, 75, and 100% BA, respectively. Due to the increase in porosity with BA content, the reduction in expansion continued to register values of 1%, 21%, 36%, and 48% for mixes containing 25, 50, 75, and 100% BA, respectively, after 28 days.

3.3 Compressive Strength

Table 3 presents the development of compressive strength of PC mixes containing different BA content at 1, 7, 14, and 28 curing days. for all curing time, there was a noticeable decrease in compressive strength as the BA content increased. For instance, at 7days, relative compressive strength of mixes containing BA to control mix (0BA) achieved values of 92.67%, 16.7%, 8.04%, and 7.39% for 25BA, 50BA, 75BA, and 100BA, respectively. This decrease in compressive strength was due to the porous nature and the low strength of bottom ash particles which weaken the whole concrete.

Additionally, it is possible that the bonding between the cement paste and BA aggregates weakened due to the rounded shape of bottom ash compared to natural aggregate, further contributing to the reduction in compressive strength. These findings align with the research conducted by Tijani et al. [35] who examined the influence of aggregate type on the PC properties.

At 28days, the relative compressive strength of mixes containing BA to control mix (0BA) achieved values of 84.11%, 35.7%, 31.3%, and 29.7% for 25BA, 50BA, 75BA, and 100BA, respectively. The compressive strengths for all concrete mixes increased with the curing time. This increment of compressive strength between 7 and 28 days of curing was obvious as BA content increased due to the pozzolanic activity of bottom ash particles [36].

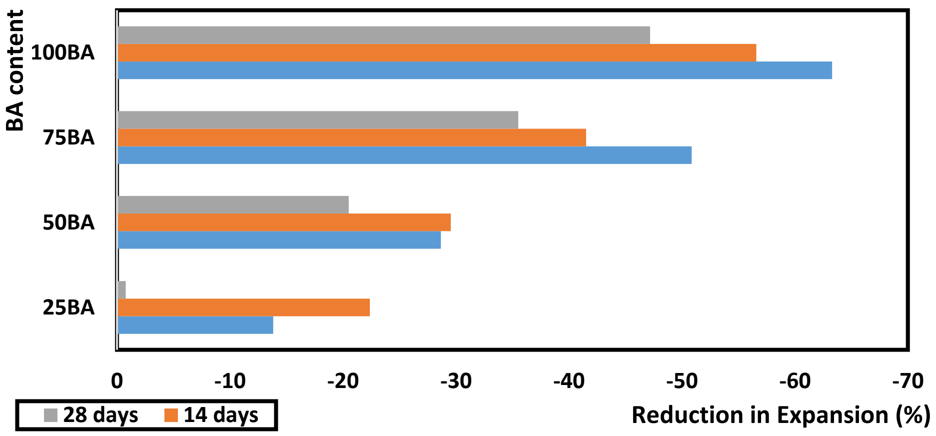

Figure 6: Difference between the expansion of the control PC (0BA) and mixes containing BA over 28days.

Table 3: Results of compressive strength and total porosity of PC mixes containing different BA percentages.

	Compressive Strength (MPa)				Total Porosity (%)
Notation	**1 day**	**7 day**	**14 day**	**28 day**	**28 day**
0BA	2.28	13.93	20.13	25.62	31.84
25BA	1.19	12.91	16.37	21.55	33.57
50BA	0.72	2.34	3.56	9.15	35.17
75BA	0.33	1.12	2.95	8.03	35.27
100BA	0.22	1.03	2.44	7.63	38.44

3.4 Porosity

Table 3 also displays the total porosity results of PC mixes containing varying percentages of BA. For the control mix, the total porosity was 31.8%. It increased to achieve a value of 38.4% for the 100 BA mix. With an increase in BA content, the total porosity of mixtures increased. This increase in porosity is mainly caused by of the BA particles' porous structure. Another potential factor could be the presence of aluminum in the BA, which could lead to the formation of H2 [37][38]. Consequently, the incorporation of BA into the mixes exhibited a higher porosity.

Furthermore, the results of total porosity emphasized that the decline in compressive strength observed as BA content increased was directly related to the porous nature of the BA aggregates.

3.5 Correlation between Autogenous Shrinkage and Expansion

In Figure 7, the relationship between autogenous shrinkage and expansion at days 1,7, 14, and 28 is illustrated. The control mix (0BA) exhibited a significantly high coefficient of determination, reaching a value of 0.99, where this value fluctuates between 0.8 and 0.97 for the mixes containing BA because of the non-uniform distribution of BA particles between the NA aggregates and consequently non-homogenous pore structures. However, it displayed a non-uniform decrease as the BA content increased. Interestingly, the increase in humidity, attributed to the higher BA content, had a positive influence on both autogenous shrinkage and expansion. Nevertheless, both autogenous shrinkage and expansion decreased as the BA content increased.

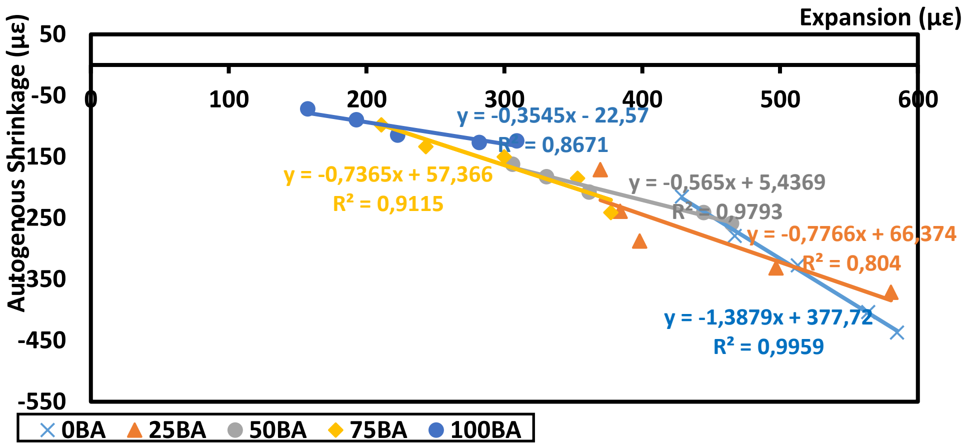

Figure 7: Correlation between autogenous shrinkage and expansion of PC mixes containing different percentages of BA.

3.6 Correlation between Autogenous Shrinkage and Compressive Strength

Figure 8 presents the correlation between autogenous shrinkage and compressive strength for all PC mixes. As observed, the correlation of control mix has a high coefficient of determination for the control mix (0BA) equal to 0.99, where this value fluctuates between 0.67 and 0.97 for the mixes containing BA. This coefficient of determination decreased in a non-uniform way as BA content increased due to non-homogenous pore structures of mixes containing BA particles. Additionally, the figure shows that even though the presence of BA helps enhance the relative humidity of concrete and consequently the self-desiccation and autogenous shrinkage of mixes incorporating BA. The compressive strength of the control mix recorded the highest values at various curing days. This is due to the fact that the strength of concrete does not only depend on the cement paste itself. It also relates to the aggregate strength and the strength of the bonding between the aggregate and the cement paste.

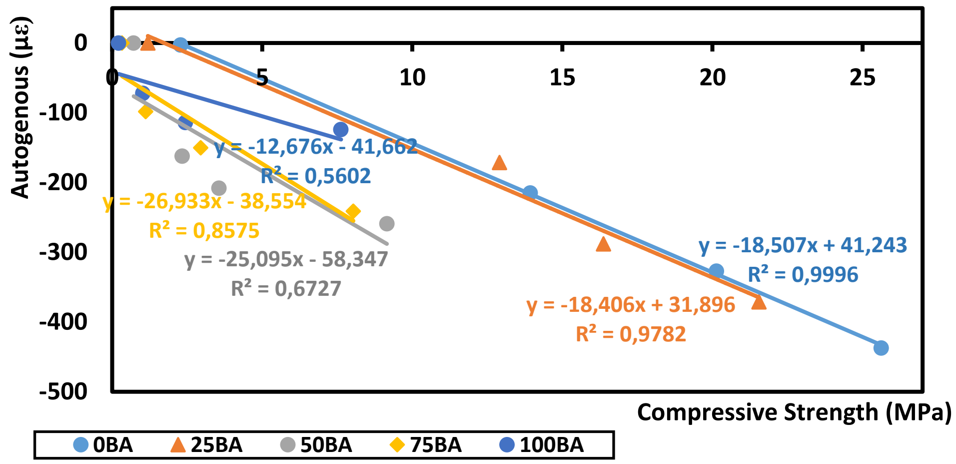

Figure 8: Correlation between autogenous shrinkage and compressive strength of PC mixes with varying amounts of BA.

3.7 Correlation between Expansion and Compressive Strength

Figure 9 illustrates the correlation between expansion and compressive strength for various PC mixes. A positive correlation was observed across all mixes. The coefficient of determination (R^2) for the 25BA mix exhibited the highest value of 0.98, surpassing other mixes, including the control mix, which has a coefficient of determination of 0.93. The varying coefficient of determination highlights the significant impact of BA particles on pore formation within PC mixes and, consequently, on compressive strength. This correlation aligns with findings from previous studies [6][39]. Additionally, even though the compressive strength of all mixes increased with curing days, the control mix recorded the highest values for both expansion and compressive strength. As a result, the fluctuation in coefficients of determination is due to the heterogenous nature of PC, especially with the presence of porous aggregate as bottom ash, leads to non-homogenous pore structures.

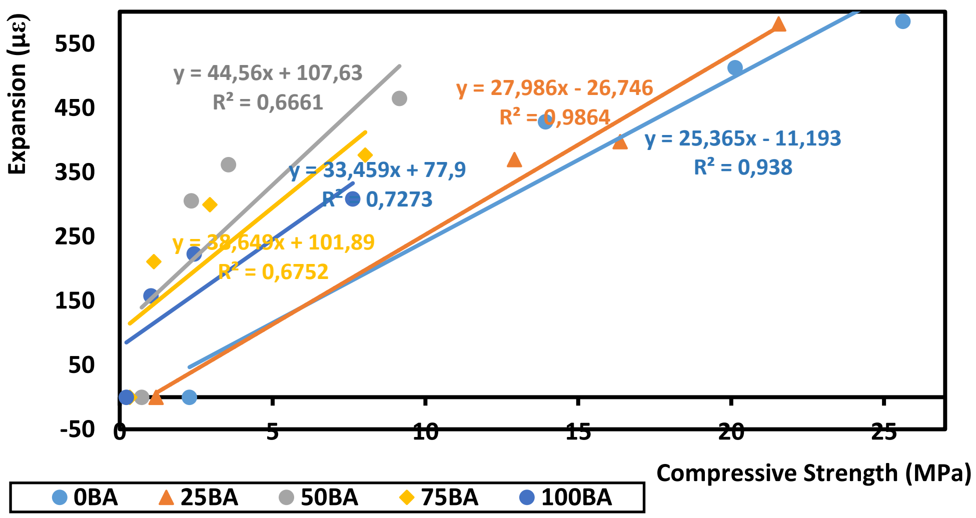

Figure 9: Correlation between expansion and compressive strength of PC mixes with varying amounts of BA.

3.8 Correlation between Autogenous Shrinkage and Total Porosity

Figure 9 displays the relationship between autogenous shrinkage and total porosity. A remarkable correlation between the two variables is observed. This relation is approximately linear, with a high coefficient of determination (R^2) of 0.97. In the 0BA mix, the autogenous shrinkage value is 437 με with a total porosity of 31.8%. On the other hand, the 100BA mix exhibits an autogenous shrinkage value of 124 με and a total porosity of 38.4%. These values indicate that the presence of porous aggregates which increase the total porosity and improves the moisture content and overall humidity of the mix, leading to a reduction in autogenous shrinkage as the bottom ash content increases.

3.9 Correlation between Expansion and Total Porosity

Figure 10 depicts the correlation between expansion and total porosity. A negative correlation is observed between these factors, with a coefficient of determination (R^2) of 0.85. In the 0BA mix, the expansion value is 585 με, accompanied by a total porosity of 31.8%. Conversely, the 100BA mix exhibits an expansion value of 309 με and a total porosity of 38.4%.

It was initially anticipated that mixes containing BA would yield the highest expansion values due to the presence of expansive materials and the reactions of contaminants within the BA, as mentioned earlier. However, the increase in porosity within PC mixes resulting from the addition of BA allows for the accommodation of this expansion volume. This relationship is clearly depicted in the figure, as expansion values decrease with an increase in total porosity (Figure 11). These findings align with similar observations reported elsewhere [39].

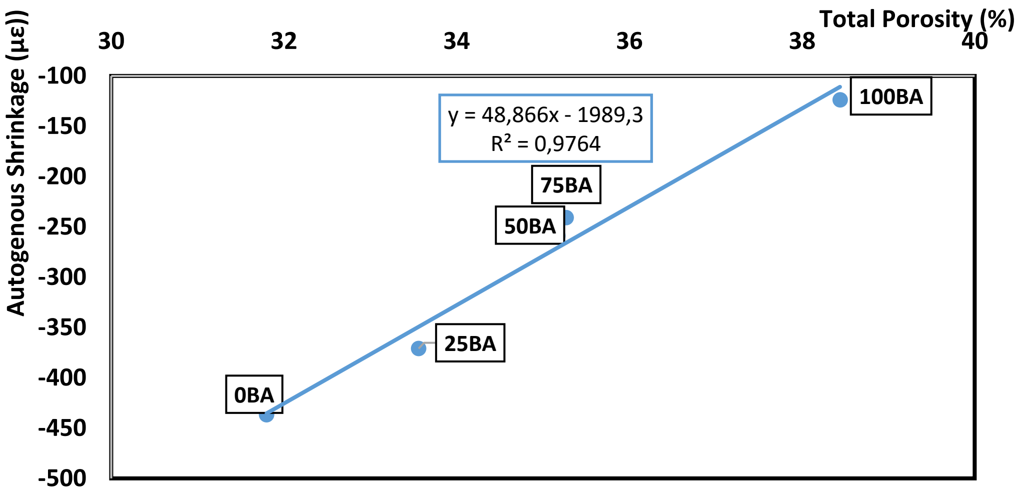

Figure 10: Correlation between autogenous shrinkage and total porosity of PC mixes with varying amounts of BA.

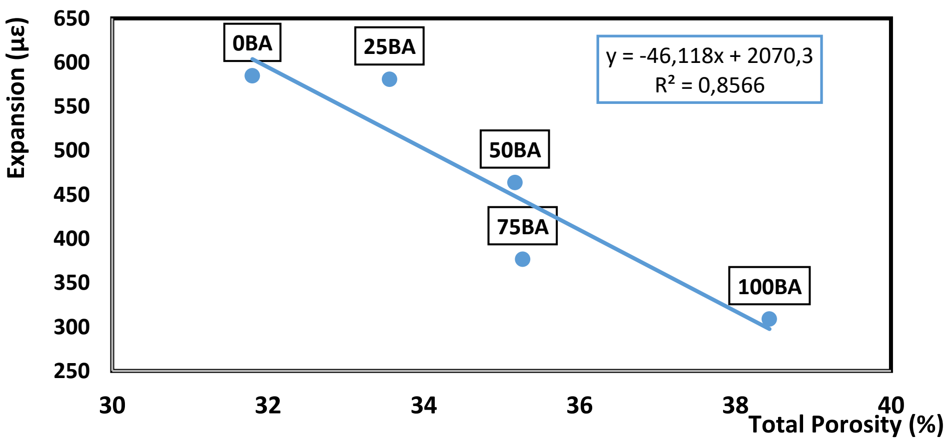

Figure 11: Correlation between expansion and total porosity of PC mixes containing different percentages of BA.

3.10 Correlation between Compressive Strength and Total Porosity

Figure 12 displays the relationship between compressive strength and total porosity for different PC mixes. A negative correlation is evident between these two factors, indicating that the compressive strength decreases with the increase in the total porosity. The control mix (0BA) exhibited compressive strength and total porosity values of 25.6 MPa and 31.8%, respectively. On the other hand, the 25BA, 50BA, 75BA, and 100BA mixes displayed compressive strength values of 21.5, 9.15, 8, and 7.6MPa, and total porosity values of 33.6, 35.1, 35.3, and 38.4%, respectively. The reduction in compressive strength might be due to the BA particles porous structure [40], which inherently diminishes the concrete strength. This finding agrees with the research findings reported by Sandoval et al. [39], highlighting the significance of aggregate nature in influencing the strength properties and porosity.

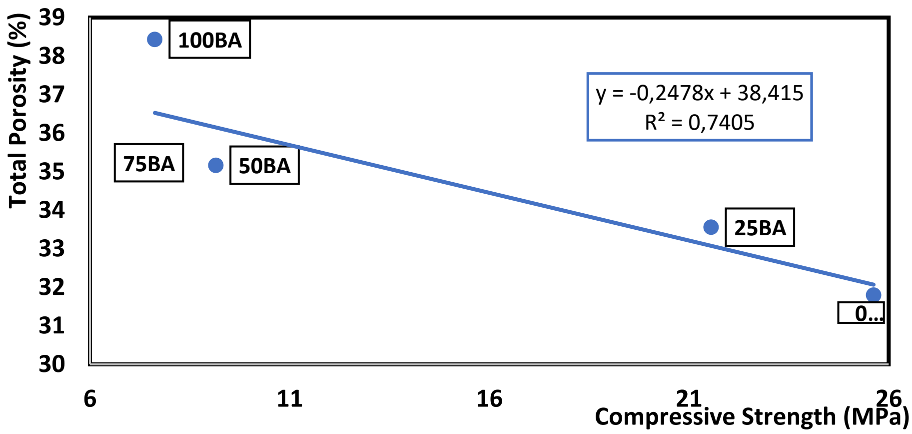

Figure 12: Correlation between Total porosity and Compressive Strength.

4. CONCLUSIONS

From the findings of this research, the following conclusions can be made:

- The expansion values of various mixes decrease as the percentage of bottom ash increases, due to the increase in porosity, which can accommodate the expansion volume. Expansion of mixes containing 0, 25, 50, 75, and 100% BA achieved values of 585, 581, 465, 377, and 309 $\mu\varepsilon$, respectively.

- Autogenous shrinkage decreased with the increase in BA content caused by the fact that the water in BA particles improves the overall humidity of the mix. Autogenous shrinkage of mixes containing 0, 25, 50, 75, and 100% BA achieved values of 437, 371, 259, 241, and 124 $\mu\varepsilon$, respectively.

- The porous structure of BA weakens the strength of PC, resulting in a low compressive strength with 100BA. Thus, the compressive strength of various mixes decreased with the increase in total porosity. The control mix (0BA) exhibited compressive strength and total porosity values of 25.6 MPa and 31.8%, respectively. However, the 25BA, 50BA, 75BA, and 100BA mixes displayed compressive strength values of 21.5, 9.15, 8, and 7.6 MPa, and total porosity values of 33.6, 35.1, 35.3, and 38.4%, respectively.

- Expansion decreased as the porosity of PC mixes increased. This fact is due to the increase in pores associated with the increase in BA content. Thus, mixes with a high content of BA can accommodate the volume expansion.

- Across all mixes, a positive correlation between compressive strength and expansion was found. The variance of values for the coefficient of determination fluctuates with the variation of BA content. This variable coefficient highlights the considerable influence of BA particles on pore formation in PC mixes and, subsequently, on compressive strength.

- The coefficient of determination of the correlation between autogenous shrinkage and compressive strength of the control mix recorded a high value for the control mix (0BA) equal to 0.99, where this value fluctuates in a non-uniform way, ranging between 0.67 and 0.97 for the mixes containing BA. This is explained by the fact that PC is a very heterogeneous material with high variability depending on the aggregate distribution and pore structure.

Author Contributions: Zeinab Nasser Eddine carried out the experiment and analyzed the findings of this work. She wrote and analyzed the manuscript with support from Firas Barraj. Jamal Khatib and Adel Elkordi helped supervise the project and conceived the original idea. All authors discussed the results and contributed to the final manuscript.

Acknowledgments: The SICOMO incineration plant is thanked for providing the necessary bottom ash for this research.

Conflict of Interest: The authors state that they have no conflicts of interest.

5. REFERENCES

[1] P. D. Tennis, M. L. Leming and D. J. Akers, Pervious concrete pavements (No. PCA Serial No. 2828). Skokie, IL: Portland Cement Association, 2004.

[2] N. Neithalath, J. Weiss and J. Olek, “Characterizing enhanced porosity concrete using electrical impedance to predict acoustic and hydraulic performance,” Cem. Concr. Res., vol. 36, no. 11, 2074-2085, Nov. 2006.

[3] J. X. Lu, X. Yan, P. He and C. S. Poon, “Sustainable design of pervious concrete using waste glass and recycled concrete aggregate,” J. Clean. Prod., vol. 234, 1102-1112, Oct. 2019.

[4] American Concrete Institute. Concrete Technology, ACI CT-13, 2013.

[5] O. Deo and N. Neithalath, “Compressive response of pervious concretes proportioned for desired porosities,” Constr. Build. Mater., vol. 25, no. 11, 4181-4189, Nov. 2011.

[6] O. Deo and N. Neithalath, “Compressive behavior of pervious concretes and a quantification of the influence of random pore structure features,” Mater. Sci. Eng. A, vol. 528, no. 1, 402-412, Nov. 2010.

[7] R. Zhong and K. Wille, “Material design and characterization of high performance pervious concrete,” Constr. Build. Mater., vol. 98, 51-60, Nov. 2015.

[8] S. Arifin, “Influence of Ash and Coconut Shell Against Compressive Strength and Permeability Characteristics of Pervious Concrete,” TURCOMAT, vol. 12, no. 3, 4129-4138, Apr. 2021.

[9] V. Yamin, D. G. S. Nivedha, K. Cheran and G. Indhumathi, “Structural behaviour of pervious concrete by using synthetic glass fibre as reinforcement,” TURCOMAT, vol. 12, no. 7, 582-588, Apr. 2021.

[10] K. Cheran, “Strengthening of permeable concrete using bitumen coated bamboo rods,” TURCOMAT, vol. 12, no. 7, 600-607, Apr. 2021.

[11] Y. Mao, J. Liu and C. Shi, “Autogenous shrinkage and drying shrinkage of recycled aggregate concrete: A review,” J. Clean. Prod., vol. 295, 126435, May 2021.

[12] H. Ghanem, M. Machaka, J. Khatib, A. Elkordi and O. Baalbaki, “Effect of partial replacement of cement by MSWIBA on the properties of mortar,” AJCE, vol. 37, no. 2, 82-89, June 2019.

[13] M. H. Wu, C. L., Lin, W. C. Huang and J. W. Chen, “Characteristics of pervious concrete using incineration bottom ash in place of sandstone graded material,” Constr. Build. Mater., vol. 111, 618-624, May 2016.

[14] H. Ghanem, J. Khatib, and A. Elkordi, “Effect of partial replacement of sand by mswi-ba on the properties of mortar,” BAU Journal-Science and Technology, vol. 1, no. 2, 4, June 2020.

[15] L. Wu, N. Farzadnia, C. Shi, Z. Zhang and H. Wang, “Autogenous shrinkage of high performance concrete: A review,” Constr. Build. Mater., vol. 149, 62-75, Sept. 2017.

[16] H. Chen, M. Wyrzykowski, K. Scrivener and P. Lura, “Prediction of self-desiccation in low water-to-cement ratio pastes based on pore

structure evolution," Cem. Concr. Res., vol. 49, 38-47, July 2013.

[17] J. Khatib, R. Ramadan, H. Ghanem and A. Elkordi, "Volume Stability of Cement Paste Containing Limestone Fines," Buildings, vol. 11, no. 8, 366, Aug. 2021.

[18] R. S. Ravindrarajah, and A. Yukari, Environmentally friendly pervious concrete for sustainable construction. In 35th Conference on Our World in Concrete & Structures, Singapore August, 2010, pp. 25 - 27.

[19] G. Xu, W. Shen, X. Huo, Z. Yang, J. Wang, W. Zhang and X. Ji, "Investigation on the properties of porous concrete as road base material," Constr. Build. Mater., vol. 158, 141-148, Jan. 2018.

[20] H. Fujiwara, R. Tomita, T. Okamoto, A. Dozono, and A. Obatake, "Properties of high-strength porous concrete," Spec. Publ., vol. 179, 173-188, Jan. 1998.

[21] ASTM C 192. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory; ASTM International: West Conshohocken, PA, USA, 2014.

[22] ASTM International. ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, 2014.

[23] ASTM International. ASTM C1754: Standard Test Method for Density and Void Content of Hardened Pervious Concrete, 2012.

[24] D. Youssef, "The use of lightweight sand for internal curing and its effect on performance of HPC used for concrete infrastructures," Ph. D., Université de Sherbrooke, 2013.

[25] C. Rößler, D. D. Bui, and H. M. Ludwig, "Rice husk ash as both pozzolanic admixture and internal curing agent in ultra-high performance concrete," Cem. Concr. Compos., vol. 53, 270-278, Oct. 2014.

[26] P. Shen, H. Zheng, D. Xuan, J. X. Lu and C. S. Poon, "Feasible use of municipal solid waste incineration bottom ash in ultra-high performance concrete," Cem. Concr. Compos., vol. 114, 103814, Nov. 2020.

[27] E. Ghafari, S. A. Ghahari, H. Costa, E. Júlio, A. Portugal, and L. Durães, "Effect of supplementary cementitious materials on autogenous shrinkage of ultra-high performance concrete," Constr. Build. Mater., vol. 127, 43-48, Nov. 2016.

[28] M. H. Zhang, C. T. Tam and M. P. Leow, "Effect of water-to-cementitious materials ratio and silica fume on the autogenous shrinkage of concrete," Cem. Concr. Res., vol. 33, no. 10, 1687-1694, Oct. 2003.

[29] A. Gonzalez-Corominas and M. Etxeberria, "Effects of using recycled concrete aggregates on the shrinkage of high performance concrete." Constr. Build. Mater., vol. 115, 32-41, July 2016.

[30] J. Kerby, "Internal curing using lightweight fine aggregate," Civil Engineering Undergraduate Honors Theses, 2013, Retrieved from https://scholarworks.uark.edu/cveguht/3.

[31] S. Multon and F. Toutlemonde, "Effect of moisture conditions and transfers on alkali silica reaction damaged structures," Cem. Concr. Res., vol. 40, no. 6, 924-934, June 2010.

[32] B. S. Hamad, G. R. Khoury and H Khatib, "Petrographic, mechanical and chemical properties of major coarse aggregate resources in Lebanon, eastern Mediterranean," Bull. Eng. Geol. Environ., vol. 59, 297-305, Feb. 2001.

[33] D. Xuan, P. Tang and C. S. Poon, "Effect of casting methods and SCMs on properties of mortars prepared with fine MSW incineration bottom ash," Constr. Build. Mater., vol. 167, 890-898, Apr. 2018.

[34] D. Xuan and C. S. Poon, "Removal of metallic Al and Al/Zn alloys in MSWI bottom ash by alkaline treatment," J. Hazard. Mater., vol. 344, 73-80, Feb. 2018.

[35] M. A. Tijani, W. O. Ajagbe, A. A. Ganiyu, & O. A. Agbede, "Effect of aggregate type on properties of pervious concrete," J. Eng. Technol., vol. 4, no.1, 37-46, Apr. 2019.

[36] A. Abdulmatin, W. Tangchirapat and C. Jaturapitakkul, "An investigation of bottom ash as a pozzolanic material," Constr. Build. Mater., vol. 186, 155-162, Oct. 2018.

[37] N. Saikia, G. Mertens, K. Van Balen, J. , Elsen, T. Van Gerven and C. Vandecasteele, "Pre-treatment of municipal solid waste incineration (MSWI) bottom ash for utilisation in cement mortar," Constr. Build. Mater., vol. 96, 76-85, Oct. 2015.

[38] T. P. Huynh and S. H. Ngo, "Waste incineration bottom ash as a fine aggregate in mortar: An assessment of engineering properties, durability, and microstructure," J. Build. Eng., vol. 52, 104446, July 2022.

[39] G. F. Sandoval, I. Galobardes, N. Schwantes-Cezario, A. Campos and B. M. Toralles, “Correlation between permeability and porosity for pervious concrete (PC),” Dyna, vol. 86, no. 209, 151-159, Apr./June 2019.

[40] C. Lian, Y. Zhuge and S. Beecham, “The relationship between porosity and strength for porous concrete.,” Constr. Build. Mater., vol. 25, no. 11, 4294-4298, Nov. 2011.