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Research Article

Effects of Using Waste Glass Granular and Lightweight Pumice Granular on the Abrasion Resistance of Pervious Concrete

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Abstract

Pervious concrete is one of the concrete types that contain no or little fine aggregate to obtain the void between aggregate particles for permitting passage of water through and reducing the risk of flooding. This article deals with the preparation of two sets of sustainable pervious concrete by using waste glass granular, lightweight pumice aggregate as a partial replacement of single-size coarse aggregate with six different ratios, including 0, 5, 10, 20, 30, and 50%, for finding their effect on the mechanical properties, permeability, and abrasion resistance. The second group used waste glass granular as a partial replacement of coarse aggregate with the same rate of pumice aggregate to find their effect on the abrasion resistance ability of the previous concrete and compare them together. The obtained result showed that using lightweight aggregate as a partial replacement of coarse aggregate with a single size (9.5–12.5 mm) increased the mechanical properties and permeability of pervious concrete. The usage of LWA compared to the WGG in the previous concrete showed that LWA provided lower abrasion resistance ability (toughness) compared to the WGG.

1. Introduction

A decrease in the porous area due to the increase in the construction area and urbanization causes the collection of water over the land. It increases the probability of flooding with the increase in surface runoff [1–4]. Pervious concrete, gap-graded concrete, or void-enhanced concrete [5] is the type of concrete that can be used for ground covering, urban pavement, and permitting permeability of water since it does not contain fine aggregate, for that in many sources renamed by no fine concrete [6–10], and the rate of void content in the previous concrete is in the range 15–35% of the total volume of concrete [11]. Using pervious concrete can reduce ground runoff, flood risk, and traffic problems, solving the problem of urban drainage [12–14]. For the first time, previous concrete has been used before 1900, while its patented was in 1980

[15, 16]. The use of pervious concrete can not only reduce underground pollution but also reduce urban heat island effects [6]. The most important properties of the pervious concrete are permeability and abrasion resistance since its production target is to permit the water to pass through and stay stable against the friction that is subjected to for reducing the maintenance cost [17]. The compressive strength of pervious concrete without using any additional material falls in the range of three to twenty-eight cubic MPa [18, 19]. In most cases, coarse aggregate in the previous concrete preferred to be a single size to guarantee the required void content and provide the required amount of permeability [20, 21].

Owing to the increase in the population and development of communities, the requirement of life increases, which causes an increase in the produced waste materials [22–24]. Many researchers try to produce sustainable pervious concrete by using waste material as a partial replacement for one of the pervious concrete components, which are cement (C.C.), water, and coarse aggregate (NCA) [18, 25–27].

One of the waste materials that have been used by researchers as a partial replacement of coarse aggregate in pervious concrete is waste demolished concrete granular [28, 29]. Construction waste quantity, including waste demolished concrete granular quantity, increases with time passing [29, 30]. In the European Union, about nine hundred million tons of waste construction materials are produced annually [31, 32].

Pervious concrete can also be considered a type of lightweight concrete since its density varies in the range of 1600–1900 kg/m3 [33]. For this reason, many researchers tried to use lightweight aggregate (LWCA) as a partial replacement for coarse aggregate and produce lighter-weight coarse aggregate [34]. Used lightweight aggregate may be artificial aggregate such as pumice, which is obtained from volcanic areas, or artificial aggregate such as perlite [35].

Also, much research has been done on the use of waste glass powder or granular in previous concrete [36–38], since the waste glass is non-biodegradable and has a high amount that is not recycled and put in the land [39, 40]. Much research has been done on using waste glass as cement, sand, or coarse aggregate in concrete production [41–43].

In 2015, one investigation used recycled lightweight aggregate, which is obtained from demolished autoclaved concrete blocks. The result obtained was that the usage of recycled lightweight aggregate reduces the density and thermal conductivity [35]. In 2013, there was a publication that used three types of lightweight aggregate, including pumice, diatomite, and recycled concrete aggregate with 100% as replacement of coarse aggregate in previous concrete, and obtained that using each type of these types of lightweight aggregate decreased the density and thermal insulation three to four times compared to the pervious concrete, which contains natural aggregate [44]. An investigation in 2016 used palm oil kernel shells as a partial replacement of coarse aggregate with three differential rates, including 0.25, 0.5, and 75% [45]. In 2024, scientific research used single-size waste glass granular with six different ratios as a partial replacement of coarse aggregate, investigating their effect on the mechanical properties of pervious concrete [38]. This article deals with the usage of pumice as a partial replacement of coarse aggregate, investigating its effect on the compressive, flexural, tensile strength, permeability, and abrasion resistance of pervious concrete and also comparing the obtained result of abrasion resistance to the ability of pervious concrete, which was modified with six different rates of single-size waste glass granular (WGG).

This article deals with the investigation of the usage of lightweight pumice aggregate in single-size partial replacement of coarse aggregate in pervious concrete to find its effect on the mechanical properties, permeability, and abrasion resistance of pervious concrete, comparing the abrasion resistance ability of pervious concrete modified with waste glass granular as partial resistance of coarse aggregate to the abrasion resistance ability of pervious concrete modified with single-size waste glass granular.

2. Materials and Methods

In the experimental work, lightweight pumice aggregate has been brought in a single size (9.5–12.5 mm) to be used as partial replacement of coarse aggregate in pervious concrete with six different ratios (0, 5, 10, 20, 30, and 50%) to find their effect on the compressive, flexural, tensile strength, permeability, and abrasion resistance of pervious concrete. In the second stage, single-size waste glass granular (with the same ratio and percentages as used for lightweight pumice aggregate) has been used as a partial replacement of coarse aggregate to investigate its effect on the abrasion resistance of pervious concrete. In the final step, the effects of using waste glass granular and lightweight pumice granular on the abrasion resistance have been compared together.

2.1. Experimental Work

The experimental work is divided into three parts: at the first, the required properties of the used materials have been investigated and found; based on the founded properties of the materials, in the second step, the concrete mix design has been completed; and finally, at the last step, the required samples for the selected properties of the concrete have been prepared and tested.

2.1.1. Cement

The used cement was produced by the Tasluja company, as shown in Figure 1, which has the chemical composition as expressed in Table 1. The cement exhibited specific properties outlined in Table 2, all of which fall within the specified ranges stipulated by the ASTM C150 standard [46].

Figure 1. Used cement in the experimental work

Table 1. Chemical composition of used cement

Chemical compositions	Cement composition (%)
Al_2O_3	4.54
Fe_2O_3	4.56
CaO	62.53
MgO	3.76
SO_3	2.43
K_2O	0.47
Na_2O	0.13
CO_2	2.54
SiO2	19.12
MnO_2	-
TiO2	-

Table 2. Physical properties of used cement.

Tests name	Tests results (Cement)
Fineness (ASTM, C115) [47]	3000 cm^2/gr
Normal consistency (ASTM, C187) [48]	26.9 %
Initial setting time (ASTM, C191) [49]	140 Minute
Final setting time (ASTM, C191) [49]	190 Minute
Specific Gravity (ASTM, C188) [50]	3.14
Density (ASTM, C188) [50]	1.44 gr/cm^3

2.1.2. Natural Coarse Aggregate

The coarse aggregate employed in the study underwent sieving according to the specifications outlined in ASTM C33 [51]. Its size range was adjusted to fall within 9.5 – 12.5 mm as shown in Figure 2, to ensure the desired void ratio in the design. The physical characteristics of the coarse aggregate have been determined, and its oven-dry specific gravity was 2.5 based on ASTM C127 [52], dry compacted density was 1464 kg/m^3 based on ASTM C29 [53], and its water absorption was 0.36% based on ASTM C127 [52].

Figure 2. Used coarse aggregate in the experiment

2.1.3. Light-Weight Pumice Aggregate

The aggregate acquired originated from volcanic sites and displayed a dark brown color, as depicted in Figure 3. Following the transportation to the laboratory, the material underwent a sieve analysis test, satisfying the specifications outlined in ASTM C330 [54], C127 [52], and C29 [53]. The resulting physical properties are outlined when its oven-dry specific gravity was 0.93 based on ASTM C127 [52], dry compacted density was 865 kg/m^3 based on ASTM C29 [53], and its water absorption was 13.5 % based on ASTM C127 [52].

Figure 3. Volcanic lightweight aggregate

2.1.4. Waste Glass Granular

The waste glass granules as shown in Figure 4, were utilized as a partial substitute for coarse aggregate; they were sieved to pass through a 12.5 mm sieve while being retained on a 9.5 mm sieve. Additionally, various essential properties of the waste glass granules have been assessed, and its oven-dry specific gravity was 2.65 based on ASTM C127 [52], dry compacted density was 1517 kg/m^3 based on ASTM C29 [53], and its water absorption was 0.045 % based on ASTM C127 [52].

Figure 4. Waste glass granular

2.1.5. Water

The paramount characteristic of the water employed in this study is its pH value, determined by the procedures outlined in ASTM D1293 [55]. The obtained pH value was recorded at 7.3, indicating that the water is suitable for use in concrete and mortar applications.

2.2. Concrete Mix Design

In accordance with the guidelines presented in ACI 522R-10 [56], the composition of the concrete mix was devised and is detailed in Table 3 and Table 4. The mixing process was carried out following the preparation of the control mix. Subsequently, ten additional mixtures were prepared, five mixes involving the partial replacement of coarse aggregate with waste glass granules, while the other involved replacing coarse aggregate partially with pumice coarse aggregate. The water-to-cement (w/c) ratio was held constant at 0.34, with a consistent cement content of 305 kg/m³ across all eleven mixtures. Moreover, the targeted void ratio for all mixtures was set at 20%.

Table 3. Mix compositions modified with LWA

Mix Name	Replacement percent (%)	w/c	Cement content (kg/m^3)	Pumice coarse aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
Mix-1	0	0.34	305	0	1455
Mix-2	5	0.34	305	28.2	1382.2
Mix-3	10	0.34	305	56.4	1309.5
Mix-4	20	0.34	305	112.8	1164
Mix-5	30	0.34	305	169.2	1018.5
Mix-6	50	0.34	305	282	727.5

Table 4. Mix compositions modified with WGG

Mix Name	Replacement percent (%)	w/c	Cement content (kg/m^3)	Waste glass granular (kg/m^3)	Coarse aggregate (kg/m^3)
Mix-1	0	0.34	305	0	1455
Mix-2	5	0.34	305	77.115	1382.2
Mix-3	10	0.34	305	154.23	1309.5
Mix-4	20	0.34	305	308.46	1164
Mix-5	30	0.34	305	462.69	1018.5
Mix-6	50	0.34	305	771.15	727.5

2.3. Pervious Concrete Properties

After finalizing the mix design, the mix compositions will be blended following the procedure outlined in ASTM C192 [57]. This process involves three distinct steps: Initially, all the cement and half of the water are added to the mixture and mixed for one minute. Subsequently, the remaining half of the water is incorporated and mixed for an additional one minute. In the final stage, the coarse aggregate is introduced and mixed for three minutes. Required samples for measuring the following properties have been prepared:

2.3.1. Compressive Strength

This test is regarded as a crucial assessment of the mechanical properties of pervious concrete, as it involves determining the average compressive strength using cylindrical samples (three samples measuring 10*20 cm each, as shown in Figure 5) after a curing period of 28 days. The testing is conducted at a loading rate of 0.25 MPa/sec, following the procedures specified in ASTM C39 [58].

Figure 5. Compressive strength test samples

2.3.2. Indirect Tensile Strength

This test is regarded as a crucial assessment of the mechanical properties of pervious concrete, as it involves determining the average tensile strength using cylindrical samples (three samples measuring 10*20 cm each, as shown in Figure 6) after a curing period of 28 days. The testing is conducted at a loading laterally, following the procedures specified in ASTM C496 [59]. The used loading rate must be in the range of 0.7 to 1.4 MPa/min based on the same specification.

Figure 6. Tensile strength test samples

2.3.3. Permeability Test

In alignment with the principles outlined in ASTM C1701 [60] and further elaborated upon by Wang et al. [61] and Ahmad et al. [38], previous concrete cubes measuring 10 x 10 x 10 cm were prepared. A cylindrical component was embedded within one layer of the cube, with its surroundings appropriately sealed to prevent water from escaping, as illustrated in Figure 7. A precise quantity of water was introduced into the cylinder, and the time required for this water to traverse a specific path was measured. This allowed for the determination of the coefficient of permeability. This allowed for the determination of the coefficient of permeability using Eq. 1:

$$k = \frac{Volume\ of\ water\ passed\ through\ pipe}{Area\ of\ pipe * time\ required\ for\ water\ to\ pass} \quad (1)$$

Figure 7. Permeability test samples

2.3.4. Flexural Test

This particular test was conducted in accordance with the guidelines outlined in ASTM C78 [62]. Samples were prepared with dimensions measuring 10 x 10 x 40 cm, and the testing involved applying a load rate of 1.2 MPa/min. For each mix, three samples, as illustrated in Figure 8, were prepared, and their average values were considered as the flexural strength of the respective mix.

Figure 8. Flexural test samples

2.3.5. Abrasion Resistance

Based on the given idea from ASTM C944 [63], since the requirement equipment was not available, for each mix, three samples were prepared with dimensions equal to 74*65*65 mm, and by the procedure [64]. The abrasion resistance ability test has been done. After putting the samples under an axial load and putting abrasive grain on the task table, passing the sample through twenty-two cycles, the weight losses were determined for each sample. Figure 9 shows the samples.

Figure 9. Abrasion test samples

3. Result and Discussions

After the testing process for the prepared samples following results have been obtained as expressed in different parts below:

3.1. Compressive Strength

From six mixes that contain lightweight aggregate as partial replacement of coarse aggregate (0, 5, 10, 20, 30, and 50%), for each mix, three cylindrical samples have been prepared and tested with a load rate of 0.25 MPa/sec after 28 days. The obtained result showed that with the increase of the usage of lightweight aggregate up to 30%, the compressive strength value increased, as shown in Figure 10 since increasing the filled void ratio with pastes caused an increase in the bond between paste and granules that increased the compressive strength value, while increasing the replacement rate to 50% decreased the compressive strength value but remained higher than the control mix. This decrease in the compressive strength when LWA is used more than thirty percent may be caused by the effect of the toughness between the used aggregates becoming higher than the voids that were filled with paste, while [38] used waste glass granular as a partial replacement of coarse aggregate with the same ratios in the previous concrete, which decreased the compressive strength value due to the smooth surfaces that were provided by the waste glass granules, which decreased the obtained bond that was obtained between paste and granules that caused the decrease in the obtained compressive strength.

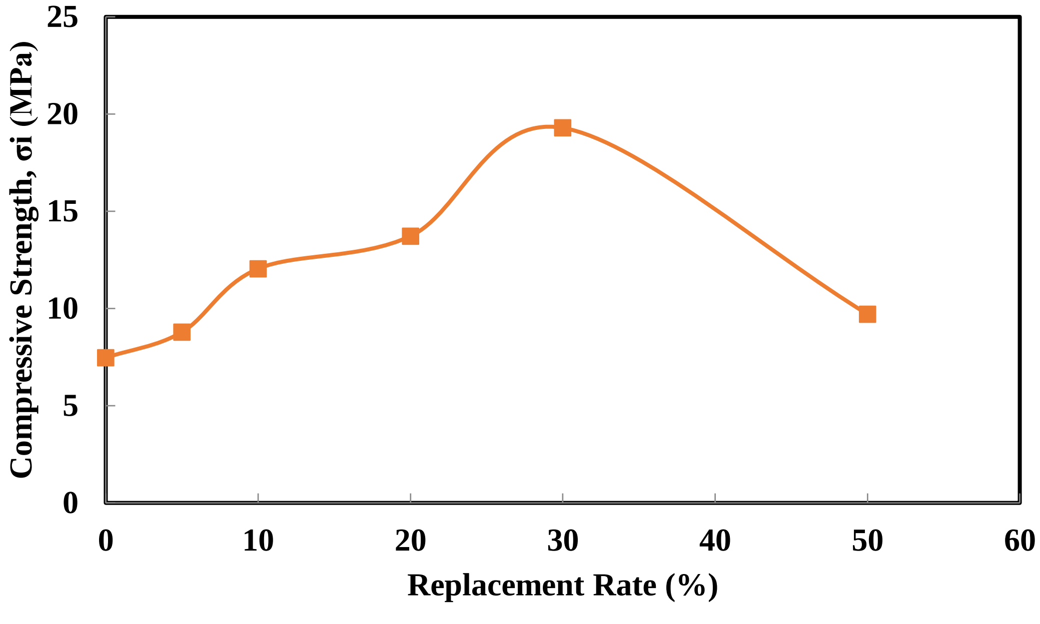

Figure 10. Compressive strength value based on the lightweight aggregate replacement ratio

3.2. Indirect Tensile Strength

The tensile strength represents the ability of the concrete to withstand the tensile stress that is put over the concrete and is measured based on the standard procedure and sample size that was prepared with the ASTM C496 [59]. Based on the obtained result from experimental work as expressed in Figure 11, the usage of the lightweight aggregate will cause an increase in the tensile strength until the usage of 20% as a partial replacement of coarse aggregate in the previous concrete that provided the optimum value of tensile strength due to the availability of the voids in the lightweight aggregate that were filled with the paste and increased the bond between the paste and granules that caused the increase in the tensile strength. The obtained result approved the result obtained by [38] when using waste glass granular with the same rates as LWA and decreasing the tensile strength gradually with the increase of the used rate of waste glass granular due to the decrease in the obtained bond between waste glass granular surfaces and the available paste due to the smooth surfaces that have been coated by waste glass granular.

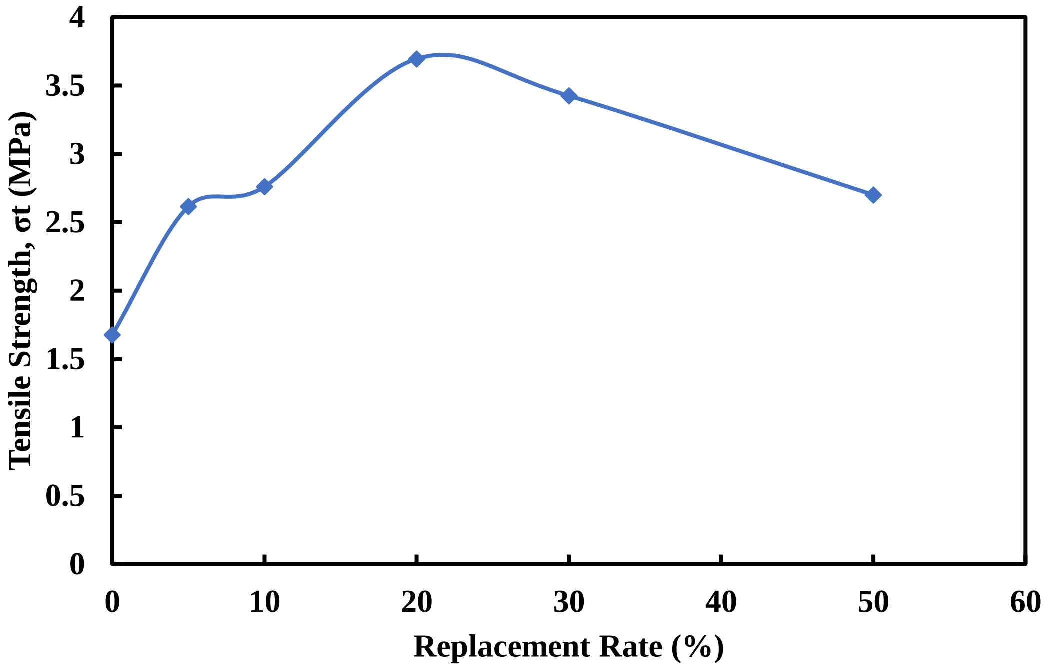

Figure 11. Tensile strength value based on the LWA replacement ratio

3.3. Flexural Strength Test

After considering the given procedure as in ASTM C78 [62], samples were prepared with dimensions measuring 10x10x40 cm, and the testing involved applying a load rate of 1.2 MPa/min. The obtained results are shown in Figure 12. The obtained result showed that with the usage of the LWA until 10%, the flexural strength increased compared to the control samples since with the usage of pumice lightweight aggregate, its voids would fill with the paste and increase the bond strength, which caused the increase in the flexural strength. With the increase in the used rate of LWA, the bond decreased due to the increase in the toughness effect by a higher rate compared to the void filling, which caused the decrease in the flexural strength.

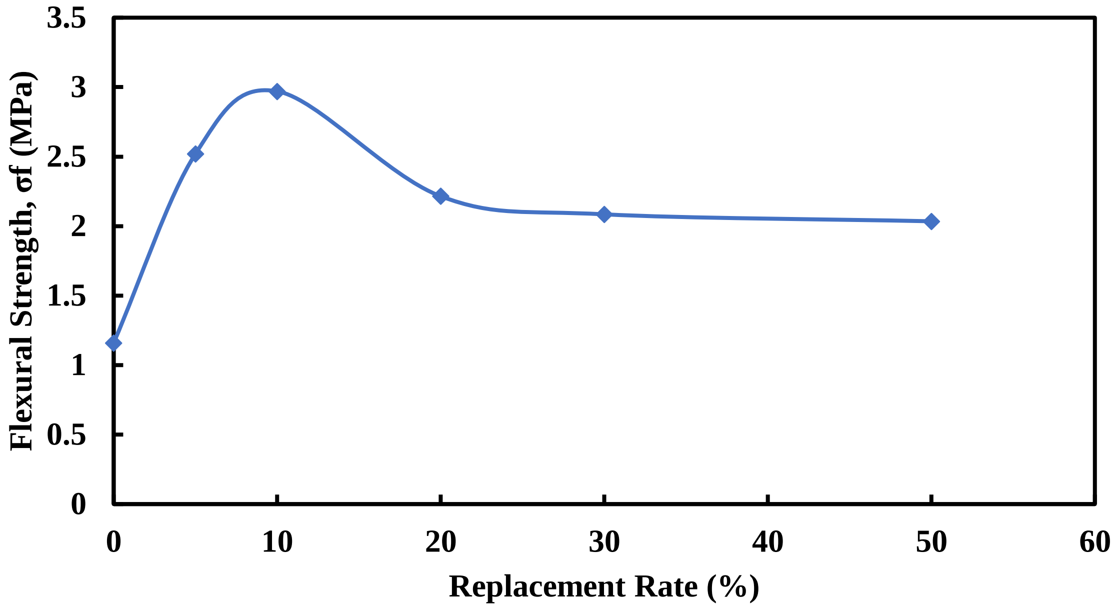

Figure 12. Flexural strength value based on the LWA replacement ratio

3.4. Permeability Test

After passing a constant volume of water through prepared samples as shown in Figure 7 and measuring the time of passing, the obtained result showed that with the increase of the replacement rate of coarse aggregate by lightweight aggregate, the coefficient of permeability increased, which means the increase in the permeability value as shown in Figure 13. Ahmad et al. [38] obtained that the usage of waste glass granular with a single size as a partial replacement of coarse aggregate increased the permeability value of the previous concrete.

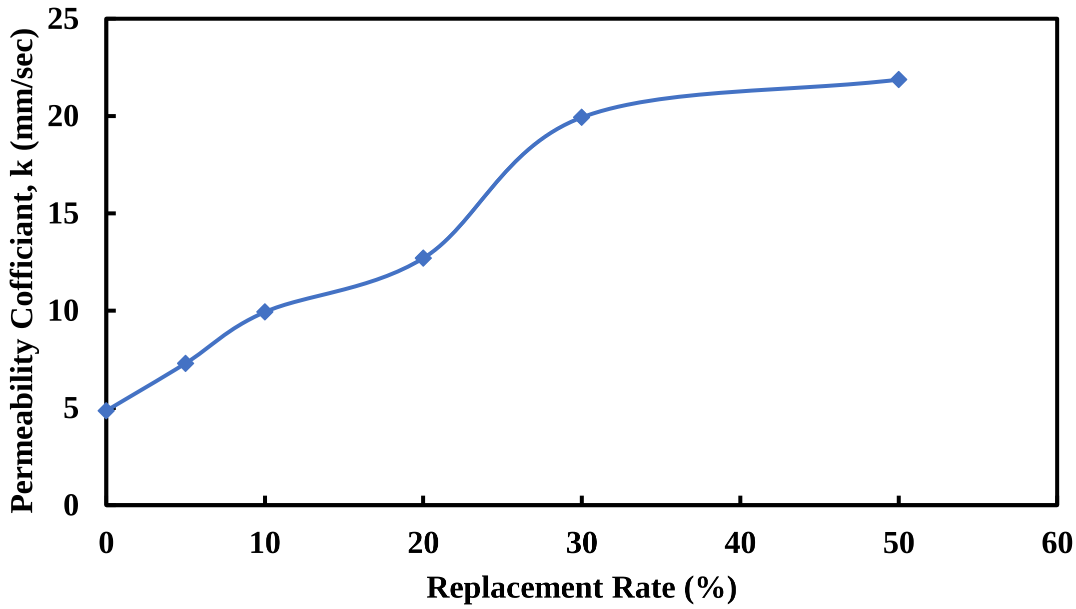

Figure 13. Permeability value based on the LWA replacement ratio

3.5. Abrasion Resistance of Pervious Concrete Modified with LWCA

After passing the samples under the stated cycles, the following results have been obtained for the previous concrete, which was modified with the lightweight aggregate and waste glass granular as shown in Figure 14. Based on the obtained result, the previous concrete which contains lightweight concrete provides the same abrasion resistance ability compared to the previous concrete which was modified with waste glass granular as a partial replacement of coarse aggregate until the usage of 5% of each material but with the increase of the used rate of used material increases the difference in the abrasion resistance ability between the pervious concrete which modified with lightweight aggregate and the pervious concrete which contain waste glass granules, with the usage of 50% of LWA as partial replacement of coarse aggregate provide abrasion resistance with about 30% of the mix which contains 50% of WGG as partial replacement of coarse aggregate.

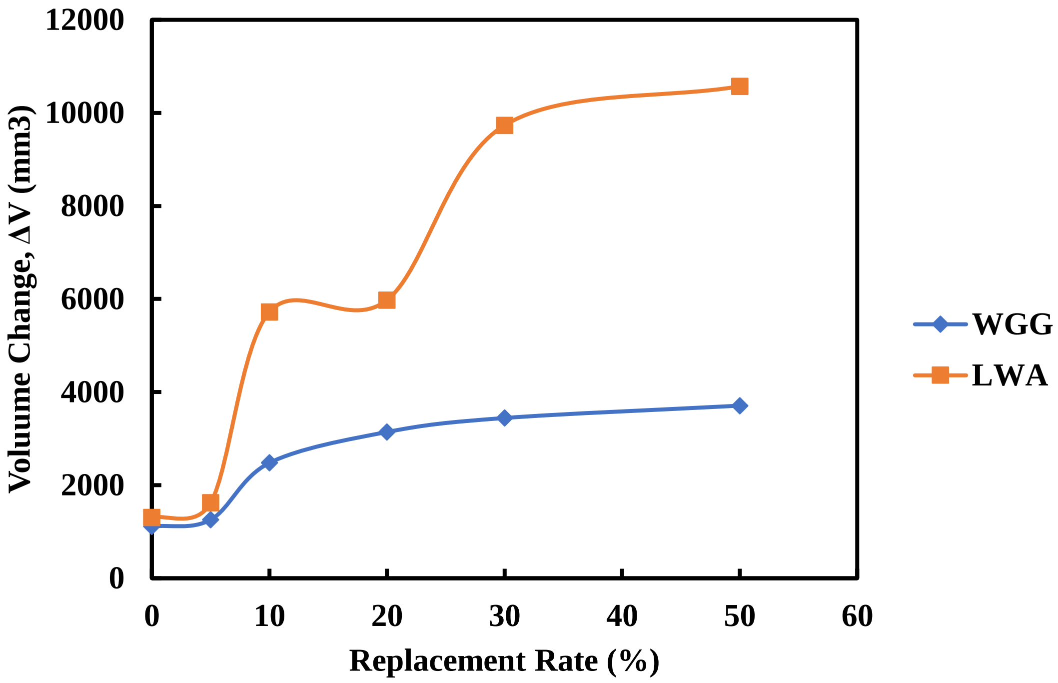

Figure 14. Abrasion resistance test value based on the LWA, WGG replacement ratio

4. Conclusions

After using lightweight aggregate (LWA) as a partial replacement for coarse aggregate in the previous concrete and comparing its effects on mechanical properties and abrasion resistance with a mix that contained waste glass granular (WGG) as a replacement, the following conclusions were drawn: The incorporation of LWA in the concrete up to 30% increased the compressive strength of the designed mix. Additionally, up to 20% LWA improved the tensile strength, while the flexural strength increased with up to 10% LWA. However, as the LWA content in the concrete increased, the permeability coefficient also increased. In terms of abrasion resistance, the combination of LWA and WGG as partial replacements of coarse aggregate revealed that WGG exhibited superior resistance to abrasion compared to both the control mix and the mix containing LWA. This is because WGG has higher toughness, allowing it to withstand greater loads and stresses than LWA.

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