applied sciences

MDPI

Article

Recycling Waste Paver Blocks in the Manufacture of New Concrete Paver Blocks and Building Bricks

Jeonghyun Kim [1] and Namho Kim [2,*]

[1] Faculty of Civil Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] School of Industrial Design & Architectural Engineering, Korea University of Technology & Education, 1600 Chungjeol-ro, Byeongcheon-myeon, Dongnam-gu, Cheonan 31253, Chungnam, Korea
* Correspondence: nhkim@koreatech.ac.kr

Abstract: This study investigates the feasibility of recycling various waste paving blocks as raw materials for concrete. The recycling rate of waste blocks in Korea remains around 11%. Therefore, three types of waste paving blocks, i.e., recycled clay-, granite-, and concrete block, were used as partial replacements for sand in a concrete mixture at 10%, 20%, and 30% replacement ratios. According to the Korean standards for concrete pavers and building bricks, compressive strength, flexural strength, and water absorption tests were conducted. In addition, UPV and unit weight tests were performed. The results showed that the performance of concrete mixtures decreased with the increasing replacement ratio of waste clay and concrete, while the addition of waste granite improved the properties of the mixtures. All the prepared concrete mixtures met the requirements specified in the standards, demonstrating that concrete incorporating waste blocks can be used as paving blocks and building bricks under limited conditions.

Keywords: paving block; building brick; cementitious composite; waste paving block

check for updates

Citation: Kim, J.; Kim, N. Recycling Waste Paver Blocks in the Manufacture of New Concrete Paver Blocks and Building Bricks. *Appl. Sci.* **2022**, *12*, 10970. https://doi.org/10.3390/app122110970

Academic Editors: Alfonso Cobo, José Manuel Ruiz Román and María Isabel Prieto Barrio

Received: 27 September 2022
Accepted: 27 October 2022
Published: 29 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Waste paving blocks generated from construction projects are one of the major social and environmental issues in Korean society. Several municipalities have policies in place to provide citizens with demolished waste blocks of decent quality, but the recycling rate of blocks remains at around 11%. Additionally, waste blocks with a damaged or poor quality cause environmental issues and social costs such as landfilling and waste storage. Therefore, it is necessary to find an effective way to utilize the continuously generated waste paving blocks.

For sustainable development, extensive studies have been conducted on cement composites containing various types of waste. In general, cement composites with various wastes show lower workability and strength in comparison with ones without waste [1,2]. Leite et al. [3] reported that the slump of concretes with 50% and 100% recycled concrete aggregate was reduced by 45% and 85%, respectively, compared to natural aggregate concrete, and materials segregation was observed when natural aggregate was replaced with recycled aggregate at 100% replacement ratio. In a study using granite waste as a substitute for sand [1], a 10% replacement ratio of sand by granite waste reduced the slump by 50%, and at the 20% replacement ratio, the slump was zero. Schackow et al. [4] reported that about 6%, 12%, and 14% more water was required to achieve the same slump at replacement ratios of 10%, 25%, and 40% of the waste brick aggregate, respectively.

As can be seen from these previous studies, in many cases, regardless of type, when recycled materials are included, more free water is required to achieve adequate workability, however, an increase in the water-to-cement ratio is the crucial parameter that degrades the properties of cement composites [5]. Although some researchers have achieved their target slump by increasing the dosage of superplasticizers [6], the pronounced detrimental

effects of superplasticizers on the environment cannot be ignored. In this context, using various wastes for concrete products that do not require workability (i.e., zero-slump) can be considered a more environmentally friendly and viable option.

Many studies have focused on evaluating the effect of different types of waste on concrete paving blocks: crumb rubber [7,8], ceramic waste [9], recycled concrete aggregate [10], and various kinds of ashes [11,12]. However, little research has been conducted on the recycling of demolished waste paving blocks themselves in the production of new paving blocks and building bricks. Utilizing old waste blocks to make new blocks not only reduces the amount of waste generated but also offsets the slump loss that occurs when recycled materials are included in normal concrete. Therefore, in this study, three different waste paving blocks commonly used as paving materials in Korea were recycled as fine aggregates in a concrete mixture for the production of new pedestrian blocks and building bricks (Figure 1). The aim of this study is (i) to evaluate the applicability of old waste paving blocks for new concrete products; (ii) to propose an optimum replacement ratio that meets the industrial standards for practical application. For this aim, concrete mixtures containing different wastes were prepared, and the main characteristics (i.e., water absorption, flexural strength, and compressive strength) stipulated in the Korean Industrial Standards (KS) for concrete products were analyzed. In addition, other important properties such as density and ultrasonic pulse velocity (UPV) were investigated. The experimental results were compared with the requirements specified in the KS to discuss the use of concrete products containing recycled materials.

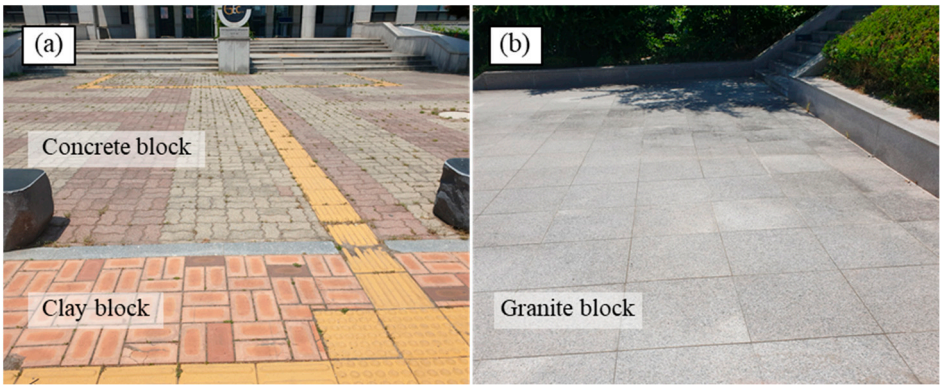


Figure 1. Pavement for pedestrians in Korea: (**a**) concrete and clay block; (**b**) granite block.

The significance of this study is to provide immediate and practical value on utilizing waste paving blocks in new concrete products for paving blocks and building bricks. The results of this study can help conserve natural resources by reducing the consumption of river sand and reduce landfill shortages by facilitating waste recycling.

2. Materials and Methods

2.1. Materials

Ordinary Portland cement (OPC) with a density of 3.15 g/cm^3 was used as the main binder throughout the experiment. The chemical composition of OPC is given in Table 1.

Table 1. Chemical composition of ordinary Portland cement.

	CaO	SiO_2	Fe_2O_3	Al_2O_3	SO_3	K_2O	MgO	TiO_2	SrO	ZnO	MnO
OPC	73.39	13.11	4.62	2.84	2.82	1.48	1.05	0.28	0.16	0.15	0.10

Natural river sand (NS) with specific gravity and water absorption of 2.59 and 1.48%, respectively, was used as fine aggregate. Crushed granite aggregate with a maximum nominal size of 13 mm in size was used as coarse aggregate (CA). The specific gravity

and water absorption of CA were 2.60 and 1.09%, respectively. A polycarboxylate-based plasticizer was used as an admixture.

Three types of demolished waste paving blocks made of clay, concrete, and granite were obtained from a building remodeling project. These blocks can commonly be found on pedestrian roads in Korea. These blocks have been used in outdoor environments for over 15 years. To remove impurities on the surface, the waste blocks were washed with tap water. After washing, the waste blocks were fed into a Los Angeles ball mill machine with 11 steel balls, approximately 48 mm in diameter and weighing approximately 400 g, and rotated 500 times at a speed of 30 rpm. Then, each crushed waste block with a size of 150 μm–4.75 mm was obtained through sieving. Dust fractions smaller than 150 μm were excluded, and fractions larger than 4.75 mm were re-crushed in the ball mill machine until they reached the desired size. The prepared recycled materials were named as follows: recycled brick (RB), recycled concrete (RC), and recycled granite (RG). Figures 2 and 3 show the waste blocks used in this study and their particle size distribution. The physical properties of the waste blocks are provided in Table 2.

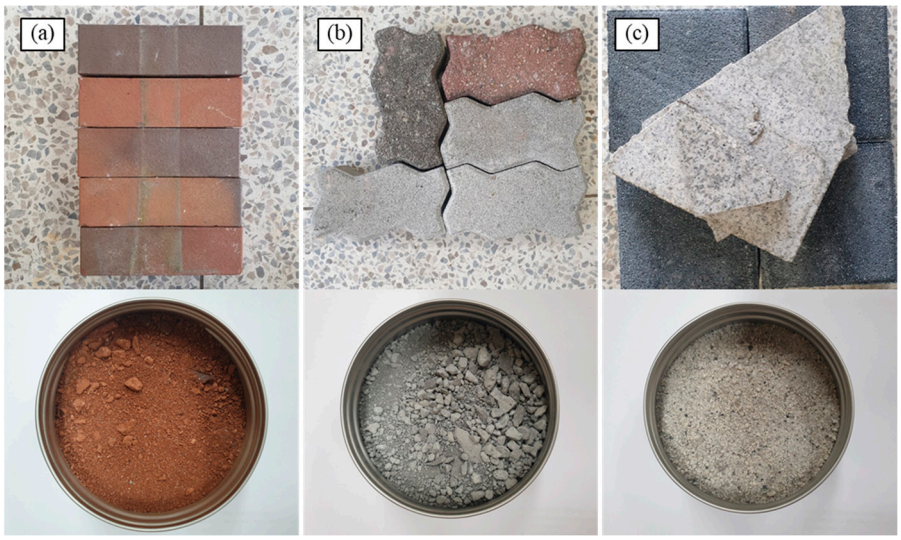


Figure 2. Different waste paving blocks used in the study: (**a**) clay block; (**b**) concrete block; (**c**) granite block.

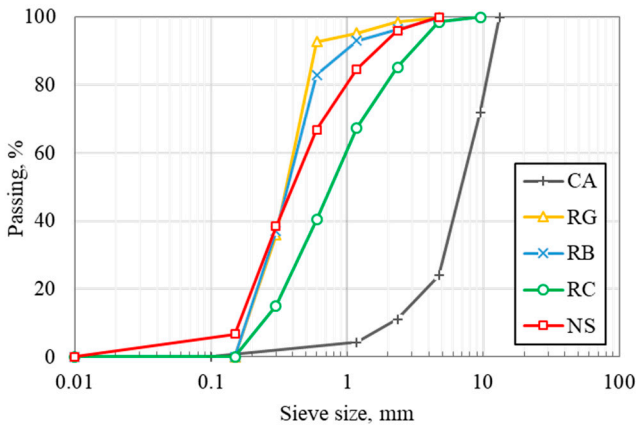


Figure 3. Particle size distribution of recycled materials.

Table 2. Characteristics of waste blocks.

	RB	RC	RG
Compressive strength, MPa	19.17	29.24	101.70
Flexural strength, MPa	4.20	6.70	10.26
Water absorption, %	7.70	5.63	0.58
Specific gravity	2.26	2.29	2.62

2.2. Mix Design and Specimen Preparation

Ten series of concrete mixtures, including a reference mixture, were made in a laboratory in accordance with KS F4419. The water-to-cement (w/c) ratio was 0.25, and the ratio of OPC, NS, and CA was set to be 1:1.6:3.2 by weight. NS was replaced by RB, RC, and RG in concrete mixtures at 10%, 20%, and 30% replacement ratios. The dosage of the plasticizer was kept constant at 1.8% of OPC in accordance with the recommendations provided by the manufacturer. Detailed mix proportions are given in Table 3.

Table 3. Mix proportions (kg/m^3).

Mix	w/c	Water	OPC	NS	RB	RC	RG	CA	Admixture
Reference	0.25	96	384	614				1229	6.91
RB10	0.25	96	384	553	61			1229	6.91
RB20	0.25	96	384	492	123			1229	6.91
RB30	0.25	96	384	430	184			1229	6.91
RC10	0.25	96	384	553		61		1229	6.91
RC20	0.25	96	384	492		123		1229	6.91
RC30	0.25	96	384	430		184		1229	6.91
RG10	0.25	96	384	553			61	1229	6.91
RG20	0.25	96	384	492			123	1229	6.91
RG30	0.25	96	384	430			184	1229	6.91

Specimens with a length of 200 mm, a width of 100 mm, and a depth of 60 mm were prepared (Figure 4). The mixing procedure was as follows: for homogeneity of the mixture, NS, CA, and OPC were mixed for 2 min in a mechanical pan mixer. Then, water was added and mixed for 3 min. The mixture was cast into molds and compressed by a universal testing machine with a load of 40 kN. After a day of casting, all specimens were demolded and cured in water until testing.



Figure 4. Prepared concrete samples.

2.3. Methods

The selected properties for the prepared concrete mixtures were evaluated on three specimens at 28 days of age.

The unit weight was determined by dividing the volume of the specimen by the dry weight. According to KS F4004, the water absorption was determined by the difference between the saturated weight and dry weight of a specimen. Each sample is immersed in water at 23 °C for at least 24 h, and after wiping the surface water with a damp cloth, the saturated surface dry weight was measured. The specimens were then oven dried at 110 °C for 24 h until a constant weight was reached, then cooled to room temperature and weighed.

UPV is considered an effective tool for the quality inspection of concrete and is closely related to various properties of concrete [13]. UPV was measured in accordance with ASTM C594 using a portable instrument consisting of a pair of a transmitter and a receiver. The time it takes for ultrasonic waves to pass through both ends of the specimen (about 200 mm) was measured. The UPV value was used to investigate the correlation with the properties of concrete.

Flexural strength was conducted according to KS F4419. A three-point bending test was performed on a 200 × 100 × 60 mm prism specimen A load corresponding to a stress of 0.1 MPa per second was applied. The flexural strength was determined by the following Equation (1).

$$\text{Flexural strength, MPa} = \frac{3Pl}{2bd^2} \quad (1)$$

where P = load at failure (N); l = span length (=140 mm); b = width of specimen (mm); d = depth of specimen (mm).

Compressive strength was carried out according to KS F4004. A load corresponding to a stress of 0.25 MPa per second was applied to the nominal area of the concrete mixture, and the strength was calculated by dividing the load at failure by the cross-sectional area of the concrete mixture.

3. Results

The test results for the concrete mixtures prepared in this study are presented in Table 4. The purpose of this study is to investigate the possibility of recycling waste blocks as a fine aggregate in the production of new concrete paving blocks and building bricks, thus, the requirements and applications for concrete paving blocks and building bricks specified in the KS are also provided.

Table 4. Summary of the test result of concrete mixtures.

Mix		Compressive Strength, MPa	Flexural Strength, MPa	Water Absorption, %	Unit Weight, kg/m^3	UPV, m/s	Remarks
Ref		25.87	7.61	5.02	2133	3630	-
RB-10		24.63	6.41	6.97	2120	3301	-
RB-20		23.44	6.16	7.29	2117	3267	-
RB-30		20.67	6.00	7.65	2114	3212	-
RC-10		24.96	7.24	6.03	2124	3405	-
RC-20		22.30	7.07	6.50	2114	3305	-
RC-30		21.24	6.37	7.35	2109	3194	-
RG-10		26.15	7.79	5.73	2139	3412	-
RG-20		27.67	7.95	6.19	2145	3439	-
RG-30		28.23	8.14	6.31	2149	3498	-
Building brick (KS F4004)	Type 1	Min. 13	N/A *	Max. 7	N/A	N/A	Outdoor or load-bearing structure
	Type 2	Min. 8	N/A	Max. 13	N/A	N/A	Internal and non-load-bearing structure
Paving block (KS F4419)	-	N/A	Min. 5	Max. 7	N/A	N/A	-

* N/A = not applicable.

3.1. Unit Weight

The unit weight was determined by dividing the dry weight of a concrete sample cured for 28 days by its volume. Figure 5 shows the unit weight of concrete mixtures containing 10%, 20%, and 30% of RB, RC, and RG as a replacement for fine aggregate, and the unit weight ranged from 2109 kg/m^3 to 2149 kg/m^3. The increase in the replacement ratio of RB and RC decreases the unit weight of mixtures, but the variation is negligible as it is from 0.43% up to 1.1%, while the addition of GP increased the unit weight from 0.28% to 0.75%, but this can also be considered insignificant. This change in unit weight can be elucidated by the difference in specific gravity between the recycled materials and NS. The specific gravity of RB, RC, and RG is 2.26, 2.29, and 2.62, respectively, while that of NS is 2.59. Therefore, the unit weight of the RB and RC series is lower, and that of the RG series is relatively higher compared to the mixture made with NS. These results are in good agreement with those reported in previous studies [14,15].

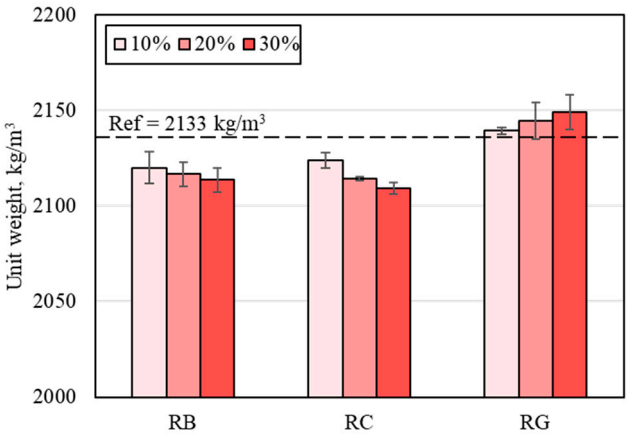


Figure 5. Unit weight of concretes.

3.2. Compressive Strength

The test results of the 28-day compressive strength of the concrete mixtures are shown in Figure 6, where each value represents the average of the strengths measured on three specimens. Except for RG, RB and RC showed a negative influence on the compressive strength of concrete mixtures with increasing replacement ratios. The compressive strengths of the RB and RC series were 20.67–24.63 MPa and 21.24–24.96 MPa, respectively, which were 4.8–20.1% and 3.5–17.9% lower than the reference mixture.

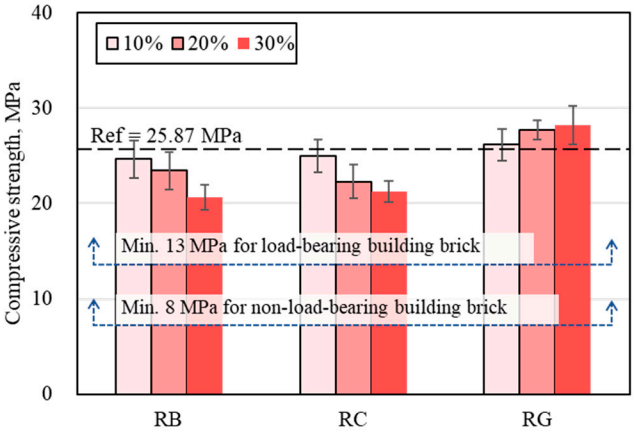


Figure 6. Compressive strength of concrete with different waste blocks.

The decrease in strength of concrete containing RB and RC can be associated with the characteristics of each material. RB and RC, which are porous materials, have many microcracks and micropores, which cause loose bonds and weak interfacial transition

regions in concrete, reducing strength [16]. Additionally, the low intrinsic strength and stiffness of RB and RC used as aggregates are the main factors contributing to the lowering of the compressive strength of concrete mixtures [17].

In contrast, the compressive strength of the RG series was 26.15–28.23 MPa, which was increased by 1.1%, 6.9%, and 9.1% compared to the reference sample at the given replacement ratios. The increase in compressive strength due to the addition of RG is consistent with the results reported in previous studies [18,19]. In a study conducted by Amani et al. [18], the compressive strength increased by 6.1% and 14.3% when RG was added at 20% and 30% replacement ratios. Some researchers have found that the addition of about 25% to 30% of RG improved the strength through better distribution and formation of C-S-H gels in a concrete matrix [20,21].

The test results of compressive strength for all concrete mixtures satisfied the KS requirements. According to the KS, compressive strength is not included in the quality requirements for concrete paving blocks, whereas building blocks are divided into two types based on their purpose of use. Bricks for external and load-bearing structures must have a compressive strength of not less than 13 MPa, and bricks for internal non-load-bearing must have at least 8 MPa. Since the compressive strength of all the mixtures exceeds 13 MPa, replacing the fine aggregate by 30% with RB, RC, and RG allows its use as a multi-purpose building brick.

3.3. Flexural Strength

The flexural strength test results at 28 days of age are shown in Figure 7, and the results were similar to those of compressive strength. The flexural strength decreases when replacing fine aggregate for the RB and RC series, and increases for the RG series. The flexural strengths of the RB and RC series were 6.0–6.41 MPa and 6.37–7.24 MPa, respectively, which were 15.8–21.2% and 4.9–16.4% lower than the reference mixture, respectively. However, up to the 30% replacement level of RG, the concrete mixtures showed improved flexural strength. The flexural strength of the RG series was 7.79–8.14 MPa, which was increased by 2.28%, 4.43%, and 6.94% at replacement ratios of 10%, 20%, and 30%. The rough, angular texture of RG may have improved flexural strength by increasing friction between aggregates and cement paste. Another cause of improved flexural strength is similar to the reasons described for compressive strength, i.e., better formation of C-H-S gels. The increase in flexural strength due to the addition of RG as a replacement for fine aggregate is consistent with the results reported in the literature [22,23].

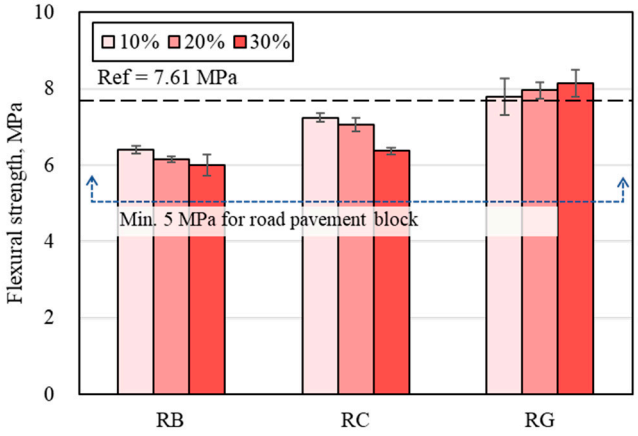


Figure 7. Flexural strength of concrete with different waste blocks.

The flexural strength for all concrete mixtures satisfied the KS requirements. According to the standards, flexural strength is not required for concrete building bricks, whereas it should exceed 5.0 MPa for concrete paving blocks. The lowest flexural strength observed was measured on RB-30, which was 6.0 MPa. Therefore, replacing 30% of fine aggregates

with RB, RC, and RG is a viable option to recycle old paving blocks into new paving blocks and building bricks.

3.4. Water Absorption

Water absorption is considered an indirect indicator of the durability of concrete mixtures as it measures the volume of permeable pores [24]. The water absorption of concrete mixtures containing RB, RC, and RG increased with an increasing replacement ratio. It seems obvious that the water absorption of mixtures is influenced by that of recycled materials (Figure 8). The water absorption of NS used in this study was 1.48%, and the water absorption of the reference mixture made with NS was 5.02%. The mixture using RB with a water absorption of 7.70% had the highest absorption in the range of 6.97–7.65%, followed by the RC-based samples (water absorption of 5.64%) at 6.03–7.35%. For the RG series, even though the material had the lowest absorption of 0.56%, the absorption of the mixture containing RG was 5.73–6.31%, which was higher than that of the reference mixture. This increase in absorption can be explained by the material geometry and particle size. Compared to NS, GP has rougher and more angular geometry, and more than 90% of its particle size is less than 75 µm. The increased specific surface area of RG increases the water demand due to increasing water absorption [1,25].

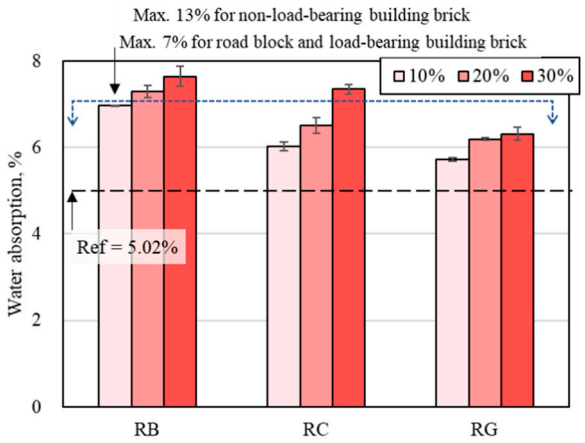


Figure 8. Water absorption of concrete with different waste blocks.

The water absorption test results for all concrete mixtures meet the standards for different applications. For concrete paving blocks and structural and exterior building bricks, the water absorption should be less than 7%. The non-load-bearing internal building bricks allow up to 13% water absorption. According to the standard, all concrete mixtures except RB-20, RB-30, and RC-30 can be used as paving blocks and building bricks for load-bearing structures. RB-20, RB-30, and RC-30 are not acceptable as paving blocks but are suitable internal building bricks with non-load-bearing structures.

3.5. Ultrasonic Pulse Velocity

UPV is a non-destructive testing technique that can predict various properties of concrete based on the time of ultrasonic waves passing through an object. Figure 9 shows the UPV test results. The measured UPV of the concrete mixtures with recycled materials was in the range of 3194 m/s to 3498 m/s, while that of the reference mixture was 3459 m/s. As the replacement ratio increased to 10%, 20%, and 30%, the UPV of the RB mixtures decreased to 3301 m/s, 3267 m/s, and 3212 m/s, and that of the RC series decreased to 3405 m/s, 3305 m/s, and 3194 m/s, respectively. Conversely, the UPV of the RG series gradually increased to 3412 m/s, 3439 m/s, and 3498 m/s, showing a trend opposite to that of the RB and RC.

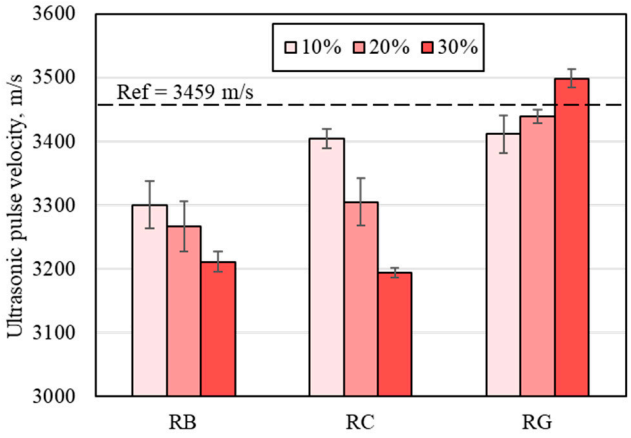


Figure 9. Ultrasonic pulse velocity of concrete with different waste blocks.

The UPV result can be related to various properties of the concrete mixture. As observed in Figure 10, UPV decreases with decreasing unit weight. In general, the low unit weight is due to the low density and porosity of the materials, and the pores in the concrete reduce the transmission rate of ultrasonic waves. Therefore, the UPV of denser concrete tends to be higher. The coefficient of determination (R^2) between the unit weight and UPV of the prepared mixtures was 0.8386, indicating a good correlation. Additionally, in Figure 10b, UPV shows a strong correlation with compressive strength (R^2 = 0.8748), indicating that UPV can be used for predicting the compressive strength of concrete mixtures containing RB, RC, and RG.

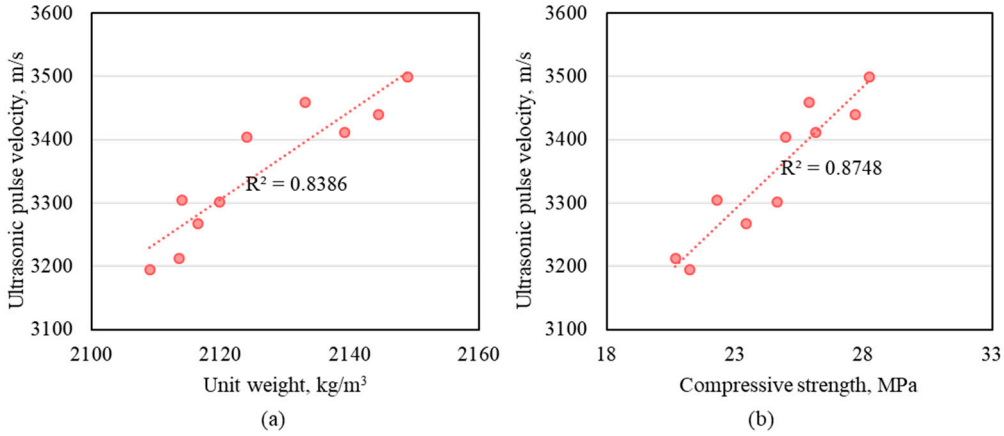


Figure 10. Correlation between ultrasonic pulse velocity and unit weight (**a**), compressive strength (**b**).

4. Discussion

The experimental investigations conducted in this study showed that different waste paving blocks had different effects on the properties of concrete mixtures. Within 30%, as the replacement ratio of RB and RC increased, the properties deteriorated, while the properties of mixtures with RG were gradually improved. The experimental results obtained in this study can be attributed to the characteristics of the old waste blocks used to manufacture the new concrete block and brick. Figure 11 shows the relationship between the properties of the waste blocks (x-axis and see Table 2) and the properties of new concrete products containing the waste blocks (y-axis, see Table 4). As provided in Table 2, specific gravity, compressive strength, and flexural strength increase in the order of brick block, concrete block, and granite block waste, while water absorption increases in the reverse order. It is obvious that the characteristics of these wastes affect the properties of the concrete containing them. For example, as shown in Figure 11a–c, the unit weight, compressive strength, and flexural strength of new concrete products increase in the order of RB, RC, and

RG. Moreover, when the replacement ratio of RB and RC increases, these three properties decrease, while when the replacement ratio of RG increases, the properties increase. The water absorption of concrete increases in the order of RG, RC, and RB, which is proportional to the absorption capacity of the waste blocks.

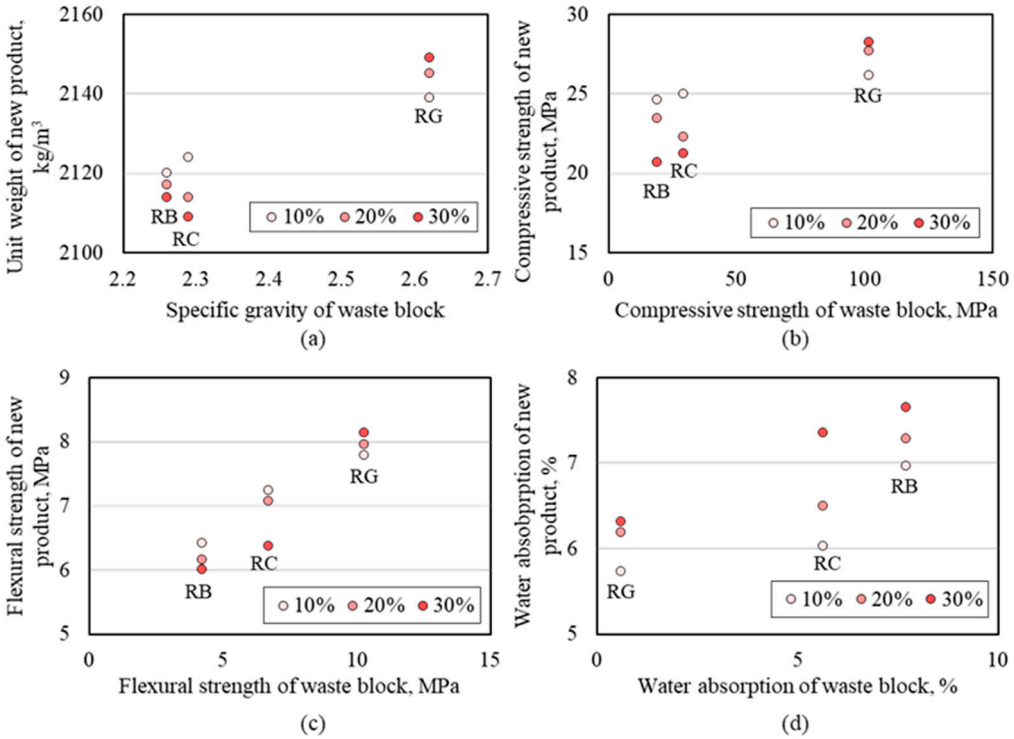


Figure 11. Correlation between properties of old waste blocks and properties of new concrete products: (**a**) unit weight; (**b**) compressive strength; (**c**) flexural strength; (**d**) water absorption.

The results obtained clearly showed that the characteristics of the recycled materials influence the properties of the new concrete, and therefore the 'average effect' arising from the centralized disposal of waste should be taken into account. The average effect of using different wastes has been observed in the literature. For example, in the study of Kechagia et al. [26], the 28-day compressive strength of concrete mixed with 20% marble dust and 20% recycled glass, respectively, was 51.5 MPa and 45.2 MPa, but when the given materials were mixed by 10% simultaneously (i.e., 10% marble dust and 10% recycled glass), the compressive strength was 50.7 MPa, showing an average effect. Kolawole et al. [27] reported that the mechanical and durability properties of concrete mixed with bamboo leaf ash and ground clay brick by 5% at the same time were lower than when the given materials were used individually by 10%. Therefore, if possible, it is necessary to prevent the 'average effect' through the selective demolition and treatment of waste.

5. Practical Application

Many previous studies have found that various types of waste can be recycled as raw materials for concrete, and concrete mixtures containing recycled materials are generally more economical and environmentally friendly than traditional concrete. Although these recycled concretes are used in actual structures, some societies are still reluctant to use recycled products [28]. Therefore, it is essential to constantly strive to find ways to reuse and recycle waste for various uses in real life. Figure 12a shows an example of the reuse of demolished paving blocks as retaining walls and steps. As in this example, where appearance is less important, waste paving blocks can be reused without recycling. This reuse has the advantage of saving the resources and energy consumed in the production of new blocks and recycling of old blocks, but waste blocks that are severely damaged cannot be utilized. Figure 12b is an example of using cut-concrete building bricks as a finishing

material in the form of a tile for internal columns. After construction, there is little external force, hence the strength and durability of concrete products are relatively less required. These concrete products can be considered one solution for applying large amounts of recycled materials.



Figure 12. Reusing (**a**) and recycling (**b**) wastes.

6. Conclusions

In this study, the feasibility of recycling waste paving blocks which are commonly used in Korea into new paving blocks and building bricks was investigated, and the following conclusions can be drawn:

- Partial replacement of natural sand with RB and RC reduced the properties of concrete mixtures (unit weight, compressive strength, flexural strength, water absorption) with the increased replacement ratios;
- At a replacement ratio limited to 30%, the addition of RG improved the properties of the concrete mixtures except for water absorption. Exceptionally, the water absorption increased with an increase in the RG replacement ratio, which appears to be due to the finer particle size of RG;
- UPV can be used to predict the compressive strength of concrete mixtures containing RB, RC, and RG, showing a coefficient of determination of 0.87;
- As a replacement for fine aggregate, all concrete mixtures made of RB, RC, and RG with a replacement ratio of up to 30% met Korean Industrial Standards under different conditions of use.

The main tests of concrete adopted in this study were limited to those specified in Korean Industrial Standards. Compared with recycled material-free concrete, concrete containing old recycled materials such as brick, granite, and concrete may have different behavior; thus, more comprehensive studies including durability performance are suggested for further research.

Author Contributions: Conceptualization, J.K. and N.K.; formal analysis, J.K.; investigation, N.K.; resources, N.K.; data curation, J.K. and N.K.; writing—original draft preparation, J.K.; writing—review and editing, N.K.; supervision, N.K.; funding acquisition, N.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study was conducted under Research Project (22POQW-C152690-04) funded by the Ministry of Land, Infrastructure, and Transport (MOLIT) and the Korea Agency for Infrastructure Technology Advancement (KAIA).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the members of our research team, MOLIT, and KAIA for their constant guidance and support throughout the whole project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vijayalakshmi, M.; Sekar, A.S.S.; Ganesh prabhu, G. Strength and Durability Properties of Concrete Made with Granite Industry Waste. *Constr. Build. Mater.* **2013**, *46*, 1–7. [CrossRef]
2. Aslani, F.; Ma, G.; Yim Wan, D.L.; Muselin, G. Development of High-Performance Self-Compacting Concrete Using Waste Recycled Concrete Aggregates and Rubber Granules. *J. Clean. Prod.* **2018**, *182*, 553–566. [CrossRef]
3. Leite, M.B.; Figueire do Filho, J.G.L.; Lima, P.R.L. Workability Study of Concretes Made with Recycled Mortar Aggregate. *Mater. Struct.* **2013**, *46*, 1765–1778. [CrossRef]
4. Schackow, A.; Stringari, D.; Senff, L.; Correia, S.L.; Segadães, A.M. Influence of Fired Clay Brick Waste Additions on the Durability of Mortars. *Cem. Concr. Compos.* **2015**, *62*, 82–89. [CrossRef]
5. Kou, S.C.; Poon, C.S. Properties of Concrete Prepared with Crushed Fine Stone, Furnace Bottom Ash and Fine Recycled Aggregate as Fine Aggregates. *Constr. Build. Mater.* **2009**, *23*, 2877–2886. [CrossRef]
6. Yang, S.; Lim, Y. Mechanical Strength and Drying Shrinkage Properties of RCA Concretes Produced from Old Railway Concrete Sleepers Using by a Modified EMV Method. *Constr. Build. Mater.* **2018**, *185*, 499–507. [CrossRef]
7. Da Silva, F.M.; Gachet Barbosa, L.A.; Lintz, R.C.C.; Jacintho, A.E.P.G.A. Investigation on the Properties of Concrete Tactile Paving Blocks Made with Recycled Tire Rubber. *Constr. Build. Mater.* **2015**, *91*, 71–79. [CrossRef]
8. Ling, T.-C.; Nor, H.M.; Hainin, M.R. Properties of Crumb Rubber Concrete Paving Blocks with SBR Latex. *Road Mater. Pavement Des.* **2009**, *10*, 213–222. [CrossRef]
9. Penteado, C.S.G.; Viviani de Carvalho, E.; Lintz, R.C.C. Reusing Ceramic Tile Polishing Waste in Paving Block Manufacturing. *J. Clean. Prod.* **2016**, *112*, 514–520. [CrossRef]
10. Chu, S.H.; Poon, C.S.; Lam, C.S.; Li, L. Effect of Natural and Recycled Aggregate Packing on Properties of Concrete Blocks. *Constr. Build. Mater.* **2021**, *278*, 122247. [CrossRef]
11. Koksal, F.; Gencel, O.; Sahin, Y.; Okur, O. Recycling Bottom Ash in Production of Eco-Friendly Interlocking Concrete Paving Blocks. *J. Mater. Cycles Waste Manag.* **2021**, *23*, 985–1001. [CrossRef]
12. Subashi De Silva, G.H.M.J.; Priyamali, M.W.S. Potential Use of Waste Rice Husk Ash for Concrete Paving Blocks: Strength, Durability, and Run-off Properties. *Int. J. Pavement Eng.* **2022**, *23*, 2265–2277. [CrossRef]
13. Kewalramani, M.A.; Gupta, R. Concrete Compressive Strength Prediction Using Ultrasonic Pulse Velocity through Artificial Neural Networks. *Autom. Constr.* **2006**, *15*, 374–379. [CrossRef]
14. Chen, J.J.; Li, B.H.; Ng, P.L.; Kwan, A.K.H. Adding Granite Polishing Waste as Sand Replacement to Improve Packing Density, Rheology, Strength and Impermeability of Mortar. *Powder Technol.* **2020**, *364*, 404–415. [CrossRef]
15. Dang, J.; Zhao, J. Influence of Waste Clay Bricks as Fine Aggregate on the Mechanical and Microstructural Properties of Concrete. *Constr. Build. Mater.* **2019**, *228*, 116757. [CrossRef]
16. Mistri, A.; Bhattacharyya, S.K.; Dhami, N.; Mukherjee, A.; Barai, S.V. Petrographic Investigation on Recycled Coarse Aggregate and Identification the Reason behind the Inferior Performance. *Constr. Build. Mater.* **2019**, *221*, 399–408. [CrossRef]
17. Poon, C.S.; Chan, D. Paving Blocks Made with Recycled Concrete Aggregate and Crushed Clay Brick. *Constr. Build. Mater.* **2006**, *20*, 569–577. [CrossRef]
18. Amani, A.; Babazadeh, A.; Sabohanian, A.; Khalilianpoor, A. Mechanical Properties of Concrete Pavements Containing Combinations of Waste Marble and Granite Powders. *Int. J. Pavement Eng.* **2021**, *22*, 1531–1540. [CrossRef]
19. Binici, H.; Aksogan, O. Durability of Concrete Made with Natural Granular Granite, Silica Sand and Powders of Waste Marble and Basalt as Fine Aggregate. *J. Build. Eng.* **2018**, *19*, 109–121. [CrossRef]
20. Singh, S.; Khan, S.; Khandelwal, R.; Chugh, A.; Nagar, R. Performance of Sustainable Concrete Containing Granite Cutting Waste. *J. Clean. Prod.* **2016**, *119*, 86–98. [CrossRef]
21. Arjun Siva Rathan, R.; Sunitha, V. Mechanical and Microstructural Study on Interlocking Concrete Block Pavers Using Waste Granite Dust. *Int. J. Pavement Eng.* **2022**, *23*, 358–371. [CrossRef]
22. Jain, A.; Gupta, R.; Chaudhary, S. Sustainable Development of Self-Compacting Concrete by Using Granite Waste and Fly Ash. *Constr. Build. Mater.* **2020**, *262*, 120516. [CrossRef]
23. Singh, S.; Nagar, R.; Agrawal, V.; Rana, A.; Tiwari, A. Sustainable Utilization of Granite Cutting Waste in High Strength Concrete. *J. Clean. Prod.* **2016**, *116*, 223–235. [CrossRef]
24. Shah, S.H.A.; Ali, B.; Ahmed, G.H.; Tirmazi, S.M.T.; El Ouni, M.H.; Hussain, I. Effect of Recycled Steel Fibers on the Mechanical Strength and Impact Toughness of Precast Paving Blocks. *Case Stud. Constr. Mater.* **2022**, *16*, e01025. [CrossRef]
25. Gencel, O.; Ozel, C.; Koksal, F.; Erdogmus, E.; Martínez-Barrera, G.; Brostow, W. Properties of Concrete Paving Blocks Made with Waste Marble. *J. Clean. Prod.* **2012**, *21*, 62–70. [CrossRef]
26. Kechagia, P.; Koutroumpi, D.; Bartzas, G.; Peppas, A.; Samouhos, M.; Deligiannis, S.; Tsakiridis, P.E. Waste Marble Dust and Recycled Glass Valorization in the Production of Ternary Blended Cements. *Sci. Total Environ.* **2021**, *761*, 143224. [CrossRef]
27. Kolawole, J.T.; Olusola, K.O.; Babafemi, A.J.; Olalusi, O.B.; Fanijo, E. Blended Cement Binders Containing Bamboo Leaf Ash and Ground Clay Brick Waste for Sustainable Concrete. *Materialia* **2021**, *15*, 101045. [CrossRef]
28. Kim, J. Construction and Demolition Waste Management in Korea: Recycled Aggregate and Its Application. *Clean Technol. Environ. Policy* **2021**, *23*, 2223–2234. [CrossRef]