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Recycled Surgical Mask Waste as a Resource Material in Sustainable Geopolymer Bricks

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Abstract: With the advent of the COVID-19 pandemic, the global consumption of single-use surgical masks has risen immensely, and it is expected to grow in the coming years. Simultaneously, the disposal of surgical masks in the environment has caused plastic pollution, and therefore, it is exigent to find innovative ways to handle this problem. In this study, surgical masks were processed in a laboratory using the mechanical grinding method to obtain recycled surgical masks (RSM). The RSM was added in doses of 0%, 1%, 2%, 3%, and 4% by volume of geopolymer bricks, which were synthesized with ground granulated blast furnace slag (GGBS), rice husk ash (RHA), sand, and sodium silicate (Na_2SiO_3) at ambient conditions for a duration of 28 days. The developed bricks were tested for compressive strength, flexural strength, density, water absorption, efflorescence, and drying shrinkage. The results of the study reveal that compressive strength and flexural strength improved with the inclusion of RSM in the bricks. The highest values of compressive strength and flexural strength were 5.97 MPa and 1.62 MPa for bricks with 4% RSM, respectively. Further, a reduction in the self-weight of the bricks was noticed with an increase in RSM. There was no pronounced effect of RSM on the water absorption and efflorescence properties. However, the RSM played a role in reducing the drying shrinkage of the bricks. The sustainability analysis divulges the catalytic role of RSM in improving material performance, thereby proving to be a potential candidate for low-carbon material in the construction industry.

Keywords: strength; durability; sustainability; geopolymer bricks; recycled surgical masks

Citation: Thoudam, K.; Hossiney, N.; Lakshmish Kumar, S.; Alex, J.; Prakasan, S.; Chandra, S.; Urs, Y.; Arunkumar, A.S. Recycled Surgical Mask Waste as a Resource Material in Sustainable Geopolymer Bricks. *Recycling* **2023**, *8*, 93. https://doi.org/10.3390/recycling8060093

Academic Editors: Domenico Asprone and Dariusz Mierzwiński

Received: 22 August 2023
Revised: 5 October 2023
Accepted: 16 November 2023
Published: 19 November 2023

1. Introduction

The emergence of the COVID-19 pandemic has led to an escalation in the consumption of single-use surgical masks due to better healthcare expenditure and an increase in respiratory protection. According to a recent market analysis report, the trade of surgical masks is expected to expand at a compound annual growth rate of 5.1% from 2022 to 2030 [1], which is an indication of the growing use of surgical masks in the coming years. The use of surgical masks greatly reduced the spread of COVID-19 disease; however, its negative environmental impact due to improper handling and disposal is becoming a widespread concern. Surgical masks are typically made of polypropylene (PP) and other plastic products, which are manufactured by chain-growth polymerization and processed thermally to fit the required products [2]. The PP masks are made of three fabric layers, which are the outer non-woven fabric, a middle melt-blown fabric, and an inner soft fiber layer similar to the outer layer [3]. According to Prata et al. [4], during the COVID-19 pandemic, approximately 129 billion single-use face masks were disposed of every month across the globe, and as per Nghiem et al. [5], all these PP masks represent more than half a million tons of PP waste in the world. Further, in the first two years of the pandemic, at least 4 million tons of improperly handled PP waste from personal protective equipment would have been released into the environment. The PP waste released from surgical masks will cause a serious ecological hazard [6,7] because PP masks are made of fibers [8], and these materials disintegrate into secondary microplastics at a higher rate compared to other plastic products such as bags and boxes [9,10]. Additionally, PP mask microplastics can persist in the environment for up to 450 years [5], and this can cause serious ill effects on living organisms [11]. Therefore, it is exigent to explore different ways to handle the waste from surgical masks and mitigate its ill effects on the environment.

The use of plastic waste such as polystyrene (PS), polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyethylene terephthalate (PET) have shown potential in construction applications [12]. Arulrajah et al. [13] utilized LDPE and HDPE, along with demolition waste, as road construction material. The results of their study showed that adding 3 to 5% of plastic waste in the pavement base and subbase provides sufficient resilient modulus for pavement application. Grady [14] reviewed the possibilities of waste plastic in asphalt concrete. Accordingly, LDPE and HDPE can be utilized in asphalt concrete at an optimum dose to improve the tensile properties and rutting resistance of asphalt concrete. Salim et al. [15] investigated the use of PET waste in reinforcing building plaster; the study's results showed improvement in the mechanical performance of plaster material in bending, resulting in better flexure strength for the plaster. Almohana et al. [16] reviewed the sustainable production of concrete with plastic waste. The authors shared an interesting perspective on using plastic waste to replace natural aggregates in concrete to enhance its sound and thermal insulation. Additionally, the lower density of plastic waste, when compared to natural aggregates, reduced the overall weight of the concrete and encouraged the production of lightweight green concrete for various non-structural applications in building applications.

Akinwumi et al. [17] investigated the suitability of shredded plastic waste in compressed earth bricks. The results of this study showed bricks with 1% plastic waste exhibited the highest compressive strength, with an increase of 244% when compared to control bricks. Additionally, at an optimum plastic waste of 1%, the durability properties of the bricks were not adversely affected, and thus, the practice of using plastic waste in bricks provides an opportunity for affordable housing with reduced environmental nuisance.

Similar to the problem of plastic waste, one of the preferred ways to handle the issues of surgical masks is to recycle them in construction materials, thus reducing their impact on the environment. To do so, recent research studies have investigated the use of surgical mask fibers in construction materials [18–20]. Kilmartin-Lynch et al. [21] investigated the use of surgical mask fibers in concrete. The concrete specimens with mask fibers of 0.20% by volume improved the compressive strength and indirect split tensile strength by 18% and 12% when compared to control specimens, respectively. The study showed that the addition of surgical mask fibers in an optimum dose improves the overall quality of concrete. Koniorczyk et al. [22] reported that the addition of processed masks in concrete did not affect the durability properties of the concrete, and further, it showed the possibility of processing and reusing these waste masks with a high recycling capacity, such that, in 1 m^3 of concrete, approximately 1000 masks will be consumed. Castellote et al. [23] showed that the addition of 5% of shredded mask waste by weight of cement did not affect the characteristics of the cement mortar. The strength and durability properties of the cement mortar mixes with waste masks were maintained at reasonable levels for practical application. Ahmed and Lim [24] utilized disposable medical face mask fibers and basalt fibers in concrete. The study showed the benefit of recycling disposable face masks in improving the mechanical performance of concrete, and such concrete can be used in buildings and structural applications. Saberian et al. [25] proposed the recycling of surgical face masks with recycled concrete aggregate in pavement applications. The results of the study showed that the blend of waste mask and recycled aggregates provides sufficient stiffness and strength for application in the pavement base/subbase. Further, the study showed the benefits of recycling millions of tons of face masks in the pavement base and preventing such waste from being dumped into landfills. Wang et al. [26] used shredded face mask fibers as an additive in hot mix asphalt to improve its rutting performance. The results of the study showed improved performance for modified mixes with 1.5% shredded mask fibers. The modified mixes with mask fibers reduced the rut depth values by as much as 69% when compared to control mixes without mask fibers.

From the existing literature, it is clear that processed surgical face masks can be used as a constituent in construction materials. It also shows the benefits of improving the properties of construction materials without affecting their performance. However, most of the studies are quite limited and have been explored in the past few years. Moreover, there have been only a few studies that have explored the potential of waste surgical masks in bricks. Since bricks are in high demand due to the multitude of housing projects in developing countries [27], they can play a crucial role in the consumption of waste surgical masks and further reduce their harmful effects on the environment. Therefore, the primary goal of this study is to utilize recycled surgical masks (RSM) in geopolymer bricks synthesized with ground granulated blast furnace slag (GGBS), rice husk ash (RHA), and sodium silicate (Na_2SiO_3) at ambient curing conditions. It is believed that the proposed method will help to improve the circularity rate in the construction industry since it substantially reduces the need for extraction of primary raw materials, as most of the binders used are waste derived from other industries; furthermore, this will create opportunities for effective resource management in the construction industry.

2. Significance of Research

The construction sector should make a great effort to contribute towards the goal of carbon neutrality set by the nations of the world [28]. At the same time, the shift from a linear to a circular economy model has provided an opportunity to recycle plastic waste in the construction industry [29]. One of the approaches for low-carbon emissions is to improve the performance of construction materials [30], and plastic waste can play a catalytic role in improving the material's properties and performance [31]. However, the use of waste surgical masks in alternative geopolymer bricks has not been extensively studied, and there are many gaps in terms of the properties of such construction materials, as discussed by the authors in their recently published article [32]. Therefore, this study is undertaken to further enhance the understanding of such materials from a sustainability perspective and contribute towards circular economy approaches in the construction industry.

3. Materials and Methods

To prepare geopolymer bricks, the materials used were GGBS, RHA, sand, and RSM as the solid fraction, while the liquid fraction consisted of Na_2SiO_3 sol. and water. GGBS was procured from JSW Cement Limited, and RHA was obtained from waste landfills close to Ramanagara City in Karnataka. In the present study, unused surgical face masks were utilized. Prior to the mix proportion selection, surgical face masks were processed in the laboratory to obtain RSM. The RSM, GGBS, and RHA were characterized using physical and chemical tests. The obtained results on the raw materials complied with the recent study published by the authors [32].

3.1. Mix Proportion for Bricks

The effective use of RHA in the construction industry can achieve sustainable practice [33]. Recently, several studies have reported its positive influence in developing alkali-activated binders [34]. According to Mehta and Siddique [35], the inclusion of 5–15% RHA in GGBS improved the compressive and tensile properties of alkali-activated binders. Similarly, Venkatesan and Pazhani [36] reported improved strength and durability properties for 10% RHA replacement with GGBS. Therefore, in this study, the geopolymer binder was proportioned with 85% GGBS and 15% RHA of the total binder content. Further, manufactured sand was used to improve the workability and to reduce the shrinkage in the mix [37]. The total quantity of sand was decided based on initial laboratory trials and it was fixed at 30% by the total weight of the solid fraction. To activate the solid precursors, Na_2SiO_3 sol. was added, and the total quantity was fixed at 8% based on the previous study [38]. There was a need for additional water to achieve the desired consistency for the mix, and this was set at 10% based on initial laboratory trials. The RSM was added based on the volume fraction of the mix, and it ranged from 0% to 4% in increments of 1%. The types of bricks evaluated are presented in Table 1. The respective densities (i.e., GGBS = 1340 kg/m^3, RHA = 620 kg/m^3, sand = 1955 kg/m^3, RSM = 100 kg/m^3, Na_2SiO_3 = 1593 kg/m^3, and water = 1000 kg/m^3) were used to determine the final weight fractions of each constituent, as presented in Table 2. For example, the determined unit weight of RSM was 100 kg/m^3, and to obtain 4% RSM in the bricks, the calculation was ($\frac{4}{100} \times 100$), which resulted in 4 kg/m^3 of RSM in the bricks. As seen, most of the constituents remained constant, except for RSM, which varied from 0% for RMGB0 to 4% for RMGB4; here RMGB denotes recycled surgical mask geopolymer bricks.

Table 1. Types of bricks evaluated.

Brick Type	GGBS	RHA	Sand	RSM	Na_2SiO_3	Water
	Wt.%					
RMGB0	59.5	10.5	30	0	8	10
RMGB1	59.5	10.5	30	1	8	10
RMGB2	59.5	10.5	30	2	8	10
RMGB3	59.5	10.5	30	3	8	10
RMGB4	59.5	10.5	30	4	8	10

Table 2. Mix proportions of the bricks evaluated.

Brick Type	GGBS	RHA	Sand	RSM	Na_2SiO_3	Water
	kg/m^3					
RMGB0	797	65	587	0	127	100
RMGB1	797	65	587	1	127	100
RMGB2	797	65	587	2	127	100
RMGB3	797	65	587	3	127	100
RMGB4	797	65	587	4	127	100

3.2. Brick Preparation

The bricks of size 230 × 110 × 75 mm were manually prepared in the laboratory, which complied with the procedure adopted by researchers in the past, as shown in Figure 1. Each batch consisted of the preparation of ten bricks. First, all the solid fractions were weighed according to the determined quantities and transferred into metal trays, as shown in Figure 1a. The solid fractions were mixed for approximately 5 min, and later, Na_2SiO_3 sol. and water in the determined quantities were added and further mixed for an additional 10 min. Finally, a homogenous mix was obtained, as shown in Figure 1b. This homogenous mix was immediately transferred into a manual brick-pressing machine, as shown in Figure 1c. After pressing, the RMGB was carefully ejected, as shown in Figure 1d, and stored in ambient conditions, as shown in Figure 1e.

3.3. Test Methods

To assess the quality and performance of the developed RMGB, various tests were conducted according to different standards. For each test, a set of 5 brick specimens were tested after curing the bricks at ambient temperature for 28 days. The sustainability analysis of the developed bricks was conducted using the life cycle assessment method. The details of the methodology are elaborated in the following sections.

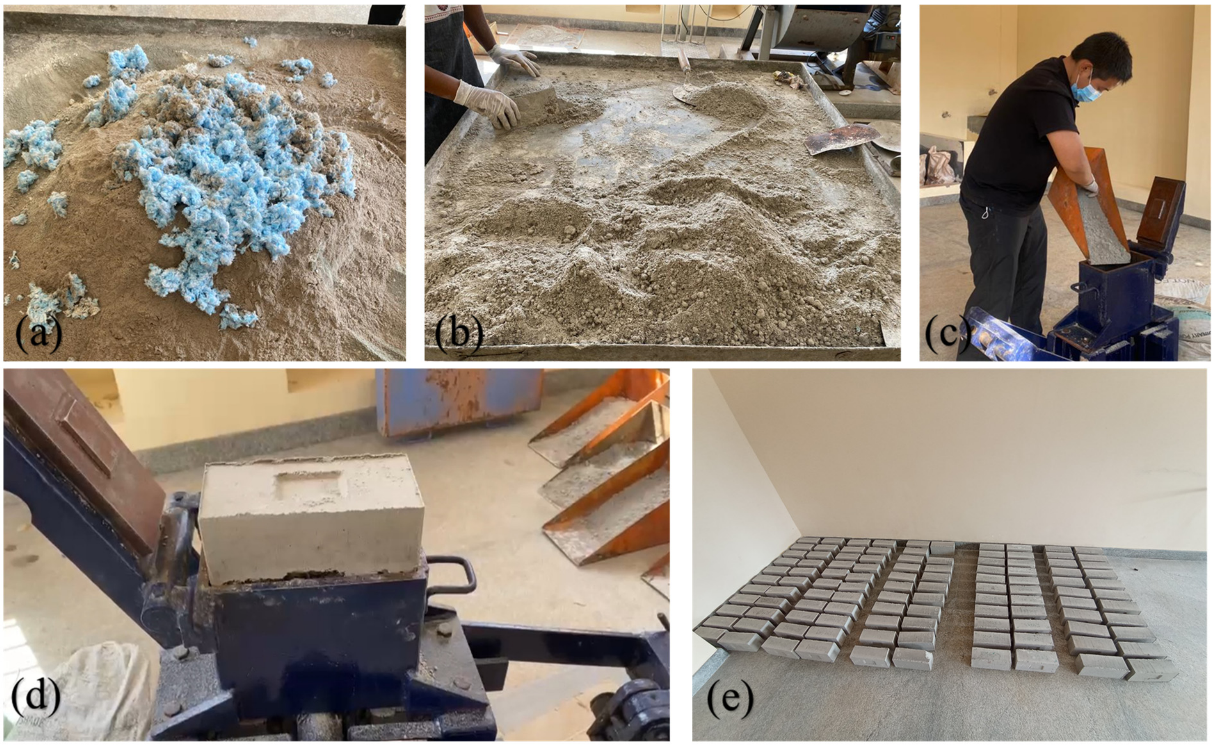

Figure 1. (**a**) Mixing of ingredients, (**b**) homogenous mix, (**c**) brick pressing, (**d**) prepared bricks, (**e**) ambient curing [32].

3.3.1. Strength and Density of Bricks

The compressive strength of RMGB was determined in accordance with IS 3495: Part 1, using a digital compression testing machine. The load was applied on the brick surface without shock at a rate of 14 N/mm^2 per minute until failure. The maximum load at failure was noted and, accordingly, the compressive strength was determined. The flexural strength of RMGB was obtained by placing the stretcher side of the brick parallel to the surface of the compression testing machine, and the load was applied at a rate of 30 kg/min as per the guidelines given in IS 4860:1968. The load at failure was noted and used to determine the flexural strength. The bulk density of RMGB was determined in accordance with ASTM C134-95. The brick specimens were dried in the oven at 110 °C for 24 h and then weighed. The length, width, and depth of the brick were measured using aVernier caliper, and the bulk density was determined according to the expression given in ASTM C134-95.

3.3.2. Durability of Bricks

The water absorption of RMGB was determined in accordance with IS 3495: Part 2. The brick specimens were dried in a standard ventilated oven at 110 °C for 24 h and cooled to a normal temperature to obtain the dry weight. The specimens were then immersed in water for 24 h at room temperature, and the saturated weight was noted. The water absorption was determined as per the expression given in IS 3495: Part 2. The efflorescence in the RMGB was determined according to IS 3495: Part 3. The process involved partly immersing the bricks in water up to a depth of 25 mm until the water was absorbed by the specimen, and then, further extra water was added. After the evaporation of the water, the bricks were examined for any perceptible salt on their surface. The qualitative assessment of efflorescence was done based on visual inspection as per IS 3495: Part 3. Where the degree of efflorescence is categorized as nil (i.e., no perceptible deposit of efflorescence), slight (i.e., 10% of the brick surface is covered with a thin deposit of salt), moderate (i.e., up to 50% of the brick surface is covered with a deposit of salt), heavy (i.e., more than 50% of the brick surface is covered with a deposit of salt), and serious (i.e., a heavy deposit of salt shown by powdering and flaking of exposed surface). The linear drying shrinkage of

RMGB was determined according to ASTM C326. The different dimensions of bricks were measured using a Vernier caliper, and the drying shrinkage in percent was calculated using the expression in ASTM C326.

3.3.3. Sustainability Assessment

The production of conventional bricks is a significant source of greenhouse gas emissions on a global scale [39]. Therefore, enhancing the performance of construction materials through the use of alternative materials is considered one of the strategies to mitigate greenhouse gas emissions and obtain low-carbon materials [30]. To assess the potential advantages of the new alternative materials, the life cycle assessment (LCA) methodology in accordance with ISO 14067 (2018) was used to evaluate the sustainability aspects. The cradle-to-gate evaluation of carbon emissions was considered in this study. This included the emissions from raw material extraction, processing, transportation, and manufacturing. Figure 2 illustrates the production process in the form of LCA system boundaries. The production process is divided into three phases, namely, the material phase, the transportation phase, and the production phase. Further, to quantify the sustainability of developed RMGB, the embodied carbon dioxide parameter (C_f) was used in the analysis process [40]. The C_f factor is described in Equation (1), and to improve the sustainability of RMGB, lower C_f values are desirable:

$$C_f = \frac{embodied\ CO_2\ (\mathrm{kgCO_2/ton})}{\mathrm{f}_c} \tag{1}$$

where
C_f = embodied carbon dioxide parameter in (kg CO_2/ton MPa),
f_c = strength of RMGB.

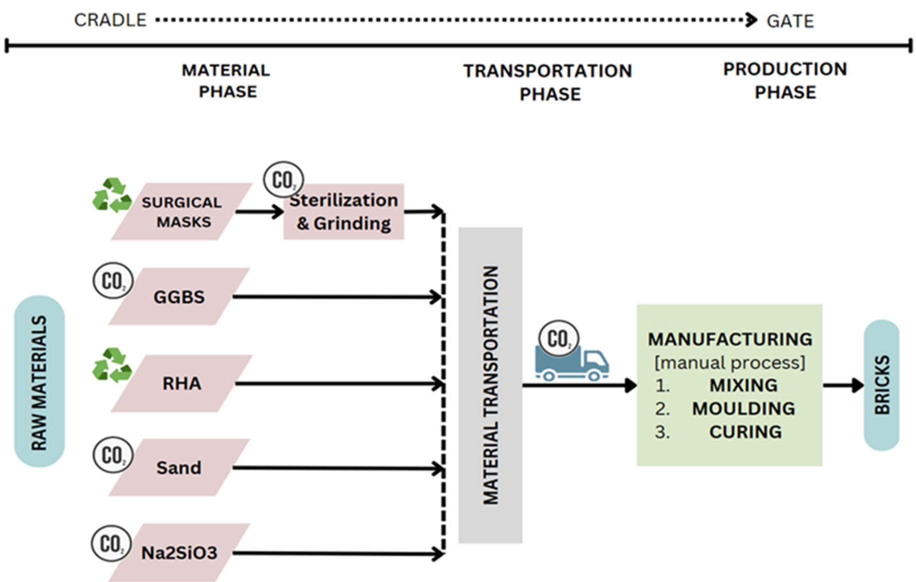

Figure 2. System boundaries adopted in LCA.

4. Results and Discussions

4.1. Strength and Density of Bricks

The results of the compressive strength are shown in Figure 3. The addition of RSM enhanced the dry and wet compressive strength of the geopolymer bricks. For instance, the increase in mean dry compressive strength after 28 days of curing was 9.17%, 10.3%, 12.9%, and 16.6% for RMGB1, RMGB2, RMGB3, and RMGB4 when compared to RMGB0, respectively. The wet compressive strength of the geopolymer bricks was tested by subjecting the samples to axial compression after soaking them in water for 24 h. The wet compressive strength improved with the addition of RSM, such that the increase in the mean wet compressive strength after 28 days of curing was 16.5%, 21.6%, 20%, and 25% for RMGB1, RMGB2, RMGB3, and RMGB4 when compared to RMGB0, respectively. Additionally, the percent reduction in wet compressive strength when compared to dry decreased with the addition of RSM. The results of the flexural strength are presented in Figure 4. As seen, the addition of RSM improved the dry and wet flexural strength of the geopolymer bricks. The increase in mean dry flexural strength after 28 days of curing was 39.13%, 31.3%, 37.4%, and 40.86% for RMGB1, RMGB2, RMGB3, and RMGB4 when compared to RMGB0, respectively. The wet flexural strength improved with the addition of RSM, and the increase in mean wet flexural strength after 28 days of curing was 56.89%, 50%, 79.3%, and 68.9% for RMGB1, RMGB2, RMGB3, and RMGB4 when compared to RMGB0, respectively. Further, the percent reduction in wet flexural strength of bricks when compared to dry decreased with the addition of RSM. It was observed that the brick specimens with a 4% addition of RSM showed the best performance with respect to strength when compared to other specimens. Such findings clearly depict the influence of RSM fibers in resisting the forces in the bricks. According to a previous study [20], the addition of polypropylene fibers restricts crack growth and improves load-carrying capacity. Besides, PP fibers have shown a positive influence on the mechanical properties of geopolymer composites [41]. Figure 5 represents the variation in the density of the different brick samples. It was observed that the addition of RSM was instrumental in reducing the self-weight of bricks by 3.92%, 4.11%, 4.84%, and 4.97% for RMGB1, RMGB2, RMGB3, and RMGB4 in comparison to RMGB0, respectively. The reduction in density is attributed to the lower specific weight of RSM. The reduction in the density of geopolymer composites with the inclusion of PP fibers has also been reported in the past [42]. Such a reduction in density, without a compromise in the strength of the bricks, makes it useful in structural and non-structural elements in bringing down their dead weight. Moreover, this will benefit tall buildings by improving the structure's performance and service life. All things considered, it is clear that RSM fibers will positively influence the strength of geopolymer bricks, and this enhancement is significant. Therefore, from the results obtained, RSM should be considered a sustainable additive in construction materials; this is because it aids in augmenting the material efficiency due to improved properties of the RMGB, and further, this will contribute towards lower carbon emission in the long span of the building's service life [43].

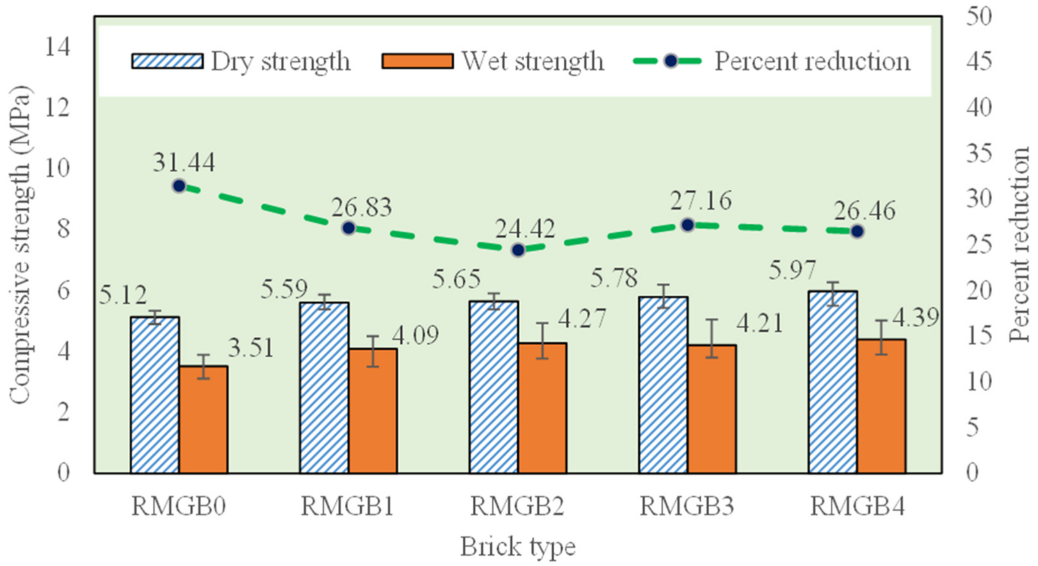

Figure 3. Compressive strength of RMGB.

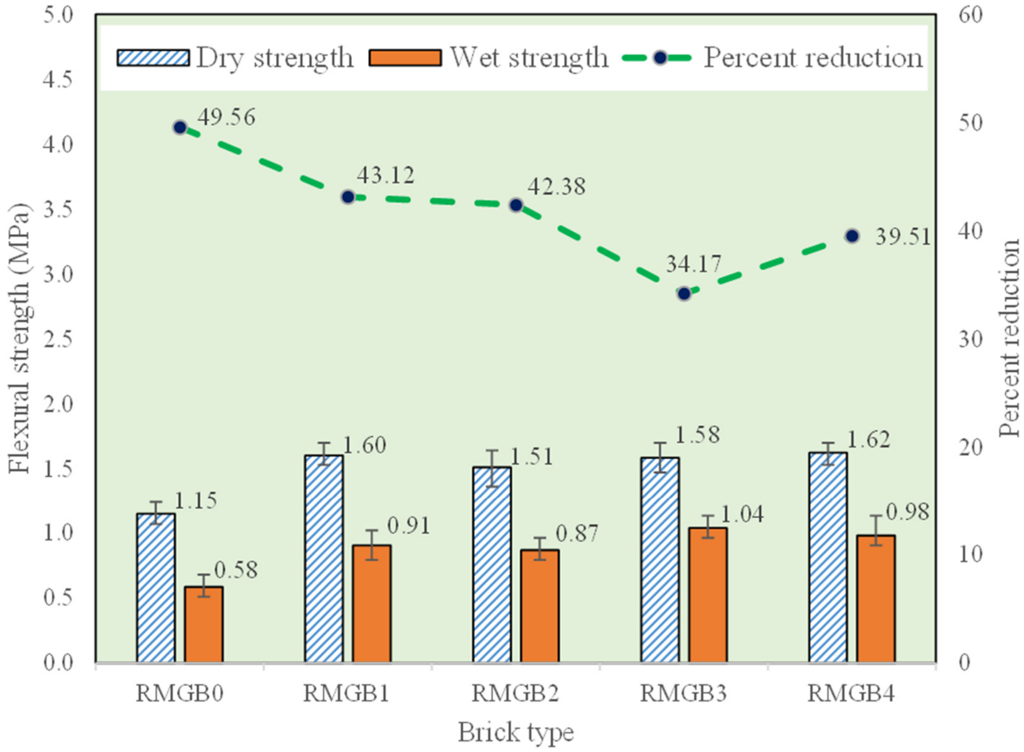

Figure 4. Flexural strength of RMGB.

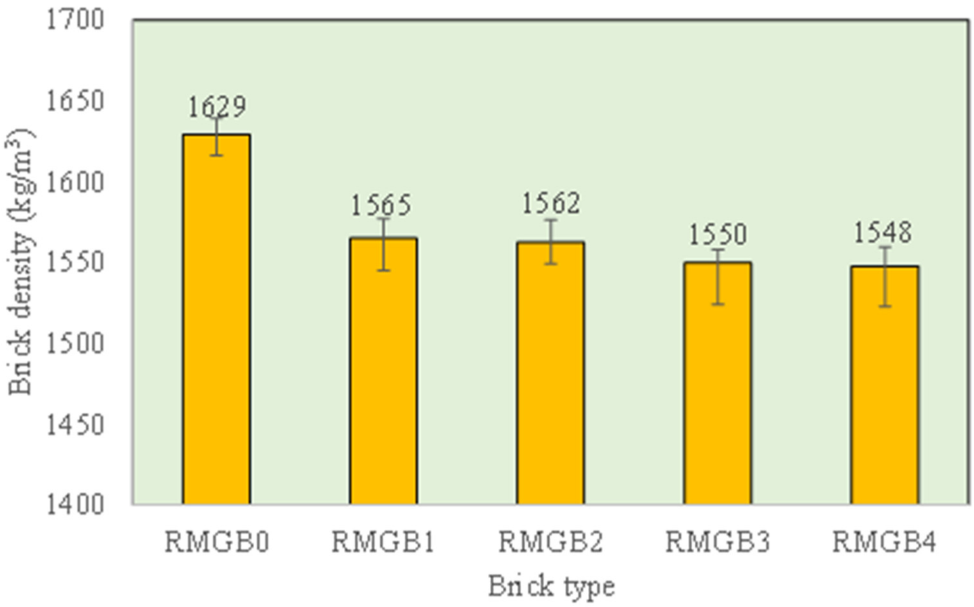

Figure 5. Density of RMGB.

4.2. Durability of Bricks

The durability of the RMGB was assessed by testing its water absorption, efflorescence, and drying linear shrinkage. The results of the water absorption test are presented in Figure 6. The addition of RSM increased the mean water absorptivity by 10.9%, 14.5%, 12.4%, and 14.4% for RMGB1, RMGB2, RMGB3, and RMGB4, when compared to RMGB0, respectively. In spite of the increase in the water absorptivity, the values were still observed to be within the limits specified by the IS 1077-1992. The increase in water absorption can be accredited to the random distribution of the shredded RSM fractions within the brick, which results in void spaces that allow water permeation. The results of the efflorescence test are shown in Figure 7. Efflorescence is due to the presence of free alkalis in the geopolymer brick. In this study, the efflorescence was observed to be constant for all the brick types, and it was not influenced by the RSM. The level of efflorescence was between slight and moderate, as per IS 3495 specifications. There are several factors that influence efflorescence in geopolymer mixes. For example, in silica-rich geopolymer systems, the leaching of free alkalis is more serious due to the low content of alumina [40]. Furthermore, alumina in the binder enhances the crosslinking in the geopolymer matrix and inhibits the movement of the alkalis, which results in lower efflorescence [44]. Besides, in ambient cured geopolymer bricks, the degree of reaction is enhanced with time, and this assists in the consumption of the alkalis till the expanse of reaction, which causes a reduction in efflorescence. Since efflorescence was determined after 28 days of curing, it can be expected that there will be some reduction in efflorescence with the aging of RMGB. The results of linear drying shrinkage are shown in Figure 8. The reduction in shrinkage was due to the addition of RSM fibers, and this can be attributed to the internal shear resistance offered by the fibers. Similar findings have also been reported when polypropylene fibers have been introduced in cement matrices [45]. On the whole, the addition of RSM into geopolymer bricks did not influence the durability properties. In contrast, the RSM fibers reduced the shrinkage in RMGB, and this will positively influence the performance of bricks in service since excessive drying shrinkage in the bricks can result in unwanted cracks, thus reducing the service life of the masonry structures.

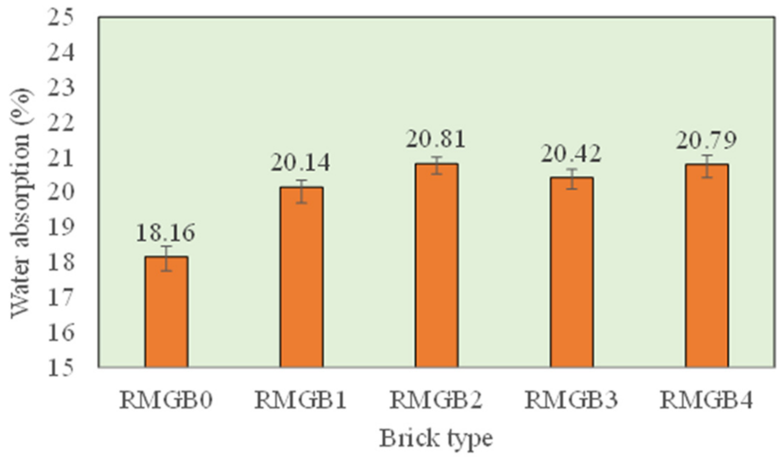

Figure 6. Water absorption of RMGB.

Figure 7. Efflorescence in RMGB.

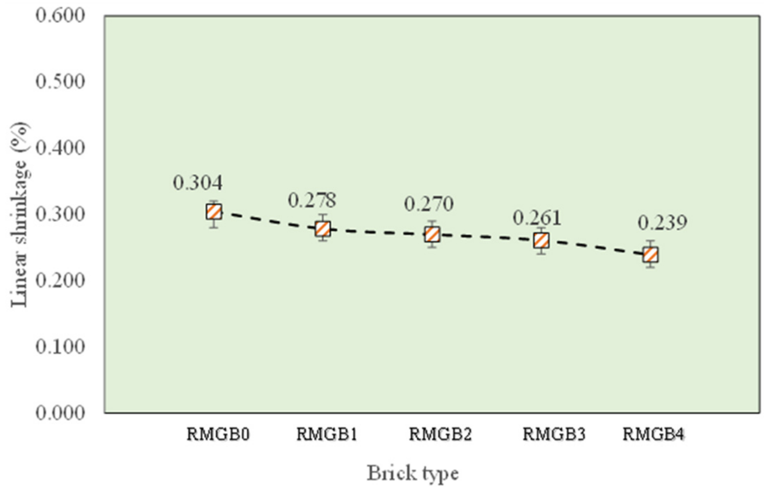

Figure 8. Linear drying shrinkage of RMGB.

4.3. Sustainability Assessment

The CO_2 emissions in the raw material phase significantly impact the product's overall carbon footprint. Among the raw materials used to produce the bricks, the RSM is a novel perspective, and CO_2 emissions associated with its processing need to be dealt with (refer to Table 3). The fresh surgical masks were ground to obtain the RSM. However, in the actual production process, the waste surgical mask would require sterilization to ensure public safety; the method of sterilization can be found in existing literature [46]. As a result, the emissions from sterilization in an 800 W microwave oven at 70 °C were taken into account for CO_2 evaluation. A duration of 60 s each for sterilization and grinding was considered, and the sterilization process consumed 0.52 kWh, and grinding consumed 0.332 kWh of power to obtain 1 kg of RSM. The emission factor for electricity consumption was considered to be 1.043 kg CO_2/kWh, which was obtained from the Agribalyse database (Version 3.0.1) using IPCC 2013 GWP100a methods in OpenLCA (version 1.11.0) [47]. The CO_2 equivalent values (refer to Table 4) for GGBS and sand were derived from published studies [48,49], and the emission value of Na_2SiO_3 from [48,50]. In the present evaluation, RHA was considered to have no CO_2 emission in the extraction phase since it was obtained from waste landfills. The material transportation emission factor of 0.0877 kgCO_2/ton·km was considered because materials were transported by freight vehicles with a capacity of ≤3.5 tons [51]. The production phase involves several manual processes, such as mixing of materials, molding of the bricks using the Mardini press, and dry curing at ambient temperature. The embodied emission of equipment used to manufacture bricks is not accounted for since the emphasis was on the raw material processes. Moreover, the brick pressing process was manual, so the emissions can be considered to be nil. The carbon footprint of the produced RMGB was evaluated by considering the inventory data adjusted to one ton of bricks, as shown in Table 4. The emissions were derived as per the inventories of 1 ton of bricks, as shown in Table 5, and the final emission values in kgCO_2/ton were obtained as 100.20, 100.76, 101.32, 101.88, and 102.44 for RMGB0, RMGB1, RMGB2, RMGB3, and RMGB4, respectively. The emission values of the brick increased from 0.56% to 2.23% with an increment in the RSM from 1% to 4%, respectively, when compared to the brick with 0% RSM. From the analysis, it is evident that there was a marginal increment in emissions with the addition of RSM in the bricks, and furthermore, the increase in emissions of RMGB was deliberated with the mechanical performance of the bricks, as shown in Figure 9. The reduction in C_f values indicated the better sustainability of RMGB. For example, the inclusion of RSM in bricks reduced the carbon emission per MPa in the range of 7.90% to 18.26% for compressive strength and 22.9% to 43.3% for flexural strength when compared to bricks without RSM, respectively. This reveals the benefits of RSM in improving material performance and, therefore, it can significantly contribute towards lowering the greenhouse gas emissions in the building sector. All in all, waste surgical masks have significant potential in the construction industry and can be considered as a sustainable additive in improving material performance, leading to better circularity rate in the construction industry. Thus, disposed surgical masks should be considered as a valuable resource for the construction industry.

Table 3. Inventory for 1 kg of RSM.

Inputs/Outputs	Inventory	Unit	Emission Factor	Unit	Embodied Carbon	Unit
Sterilization	0.52	kWh	1.04348	$kgCO_2eq/kWh$	0.543	$kgCO_2eq/kg$
Grinding	0.332		1.04348		0.346	
		Total			0.889	

Table 4. Inventory for 1 ton of brick mixes and emission factors.

	Inventory						Emission Factor	
Inputs/ Outputs	RMGB0	RMGB1	RMGB2	RMGB3	RMGB4	Units		Units
GGBS	0.505	0.5048	0.5045	0.5043	0.5041	ton	26.50	kg CO_2/ton
RHA	0.042	0.0417	0.0415	0.0413	0.0411		0.00	
Sand	0.372	0.371	0.371	0.371	0.371		26	
Na_2SiO_3	0.081	0.081	0.081	0.081	0.081		930	
RSM	0.00	0.00064	0.00128	0.00192	0.00256		889.04	
Truck	20.732	20.735	20.738	20.741	20.744	ton·km	0.088	$kgCO_2$/ton·km

Note: Transportation distances for the materials: GGBS—23 km, RHA—26 km, sand—17 km, Na_2SiO_3—21 km, RSM—27 km.

Table 5. Embodied carbon for 1 ton of brick mixes.

Inputs/ Outputs	RMGB0	RMGB1	RMGB2	RMGB3	RMGB4	Unit
GGBS	13.38	13.38	13.37	13.37	13.36	$kgCO_2$/ton
RHA	0.00	0.00	0.00	0.00	0.00	
Sand	9.67	9.67	9.66	9.66	9.65	
Na_2SiO_3	75.33	75.33	75.33	75.33	75.33	
RSM	0.00	0.57	1.14	1.71	2.28	
Truck	1.82	1.82	1.82	1.82	1.82	$kgCO_2$/ton·km
Total	100.20	100.76	101.32	101.88	102.44	$kgCO_2$/ton

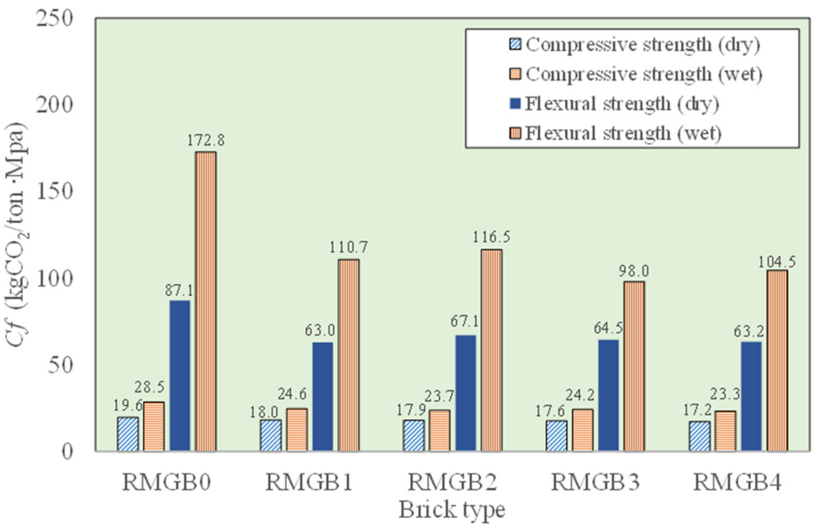

Figure 9. Embodied carbon dioxide parameter for RMGB.

5. Conclusions

The present study investigates the strength, durability, and sustainability of geopolymer bricks synthesized with GGBS, RHA, sand, Na_2SiO_3, and RSM. The bricks were ambient-cured for 28 days before testing. Based on the experimental results and analysis, the following are the findings and conclusions:

1- The incorporation of RSM enhanced the strength of geopolymer bricks. The maximum enhancement of 16.6% in compressive strength and 40.86% in flexural strength was observed for bricks with 4% RSM when compared to bricks with 0% RSM.
2- The addition of RSM has caused a maximum reduction of 4.97% in the self-weight of the bricks. The reduction in the self-weight with enhancement in the strength will improve the service life of buildings.
3- The addition of RSM increased the water absorption of bricks. The maximum increase in water absorption was 14.4% for bricks with 4% RSM when compared to bricks with 0% RSM.
4- The RSM did not significantly influence the degree of efflorescence in the bricks since all the specimens exhibited similar levels of leaching of alkalis.
5- The RSM played a role in reducing the shrinkage in the bricks, which is attributed to the internal shear resistance offered by the RSM fibers.
6- The sustainability aspect of the brick was quantified by determining the embodied carbon dioxide parameter, i.e., $kgCO_2/ton{\cdot}MPa$ (C_f). The results demonstrate that the addition of RSM has brought about a significant reduction of 12% to 40% in the C_f values when compared to bricks without RSM. Such findings are indicative of the fact that RSM can be considered a sustainable additive since it can improve the material's performance with minimal carbon emissions.
7- On the whole, RSM should be considered a valuable resource for the construction industry since it plays a catalytic role in augmenting the material performance. Such behavior can contribute to the development of low-carbon materials in the construction industry. Further, this will be useful in reducing the harmful effects of disposed surgical masks on the environment and can be helpful in the mitigation of plastic pollution.

Author Contributions: Conceptualization, N.H.; methodology, N.H.; validation, K.T. and N.H.; formal analysis, K.T., N.H. and S.P.; investigation, K.T.; resources, S.L.K., J.A., S.C. and Y.U.; data curation, K.T., N.H. and S.P.; writing—original draft preparation, N.H., K.T. and J.A.; writing—review and editing, N.H., J.A., S.L.K. and A.S.A.; visualization, N.H., K.T. and S.L.K.; supervision, N.H. and S.L.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors did not receive any funding for this research study.

Data Availability Statement: It will be provided on request.

Acknowledgments: The authors acknowledge the support provided by the Department of Civil Engineering, CHRIST (Deemed to be University).

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

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