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Benefit analysis of usage of Ceramic and Porcelain waste powder as Supplementary Cementitious Materials in interlocking paving block production

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Abstract: Concrete interlocking paving blocks are popular paving material for parking areas, walkways, gardens and rural roads. Due to its pervious nature and aesthetically pleasing appearance, popularity of using of concrete interlocking paving blocks as a paving material has increased during past few decades, both local & global contexts. However, escalation of cement prices, and unsustainable outcomes caused by excessive usage of cement has become a concern in concrete interlocking paving block production industry as well. The excessive CO₂ emission associated with cement production and considerably large embodied energy stored in cement during the production are two main factors that would lead to classify cement as an environmental unfriendly material in sustainable perspective. Hence, the introduction of partial replacement of cement by supplementary Cementitious materials in this type of product is becoming a timely need. This study was focused on partial replacement of cement by ceramic and porcelain waste powder as a supplementary cementitious material and assessing the positive impact of it on production cost and sustainability. According to the test results, it was found that cement can be replaced up to 15% (by weight) by waste ceramic & porcelain powder. Also a percentage production cost reduction of 4.1% can be observed with this approach. The Embodied Energy reduction and Embodied Carbon reduction of proposed optimum alternative mix (mix having 15% partial replacement of cement by waste ceramic and porcelain powder) are 11.8% and 18.9%, respectively compared with conventional mix.

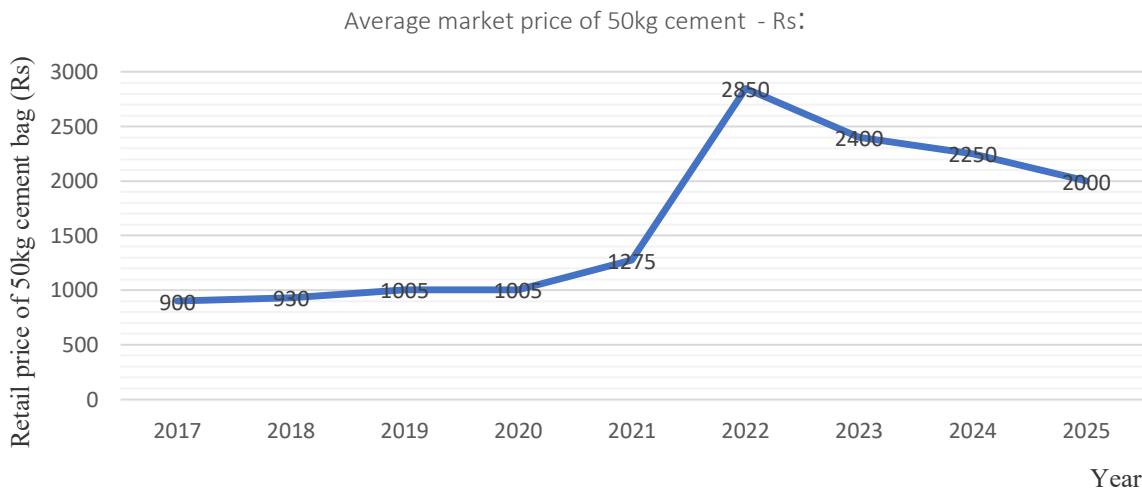
Keywords: Concrete interlocking paving blocks; Embodied Carbon; Embodied Energy; Supplementary Cementitious Materials; Sustainability.

Introduction

Cement is an essential raw material used in construction industry for various applications like concreting, wall construction, plastering, etc. Usage of precast elements for paving of roads, gardens, pathways etc. Has become a popular practice in both local and global contexts. Usually, concrete is used to produce concrete interlocking paving blocks. As concrete is a material having high compressive strength which is essential for this type of product.

However, cement, which is an essential main ingredient that affecting on price of concrete products, has significantly increased during last few years in local context. As per a study done by authors on average retail price of 50kg cement bags in Sri Lanka, more than 100% increased can be observed during last 5 years even though there is a slight drop in recent time (Central Bank of Sri Lanka). Fig. 1 shows the variation of the retail price of a 50 kg cement bag over the past few years in Sri Lanka

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Figure 1: Variation of average retail price of cement during last few years in Sri Lanka

Hence, introduction of various alternative materials at least to partially replace cement in concrete products like concrete interlocking paving blocks is becoming essential need in economic perspective. Further, various previous studies (Morgado & Hugues, 2023) have highlighted that production of cement is one of the main industries that contributes to the global warming. Hence, partial replacement of cement in concrete products is beneficial in sustainable perspectives as well. According to a recent study (Liyanage, 2019) about 3MT of ceramic & porcelain waste are generated annually in Sri Lanka.

However, most of this waste is presently used for Land filling. There are numerous researches (Morsy & Morsy, 2023) (Baskaran & K, 2013) (Sutter, 2016) in global context that highlights possibility of using ceramic & porcelain waste as a Supplementary Cementitious material (SCM) to Partially replace cement in concrete. According to (Cavalline & Armaghani, 2025) if any material is having a percentage of SiO_2 , Al_2O_3 , Fe_2O_3 more than 70%, It can be considered as a Class N SCM. According to a study of as per (Amitkumar D. Raval) chemical composition ceramic waste complies these requirements.

Considering this potential, it was decided to study the possibility of replacing cement by ceramic & porcelain waste in powder form in concrete interlocking paving block production. Further, financial benefit analysis and sustainable viability analysis of the approach were also studied.

METHODOLOGY

As per the Sri Lankan standard for concrete interlocking paving blocks (SLS 1425, 2011) there are four strength classes for these blocks. Strength class 3 was selected for this study as it is the most commonly used type if heavy vehicles are allowed to move on paving blocks. As per the standard of (SLS 1425, 2011), these blocks should exhibit compressive strength of 30 N/mm² for the compliance.

It was considered the rectangular interlocking paving blocks having standard size of 200 mm (L) × 100 mm (W) × 80 mm (T) for necessary testing during this study. It was considered Department of Environment (DOE) UK method to develop mix design for blocks. As per common practice of Sri Lanka, particle size of coarse aggregates was maintained below 12 mm even though the local standard (SLS 1425, 2011), does not specify any size limits. Accordingly, mix proportions arrived through the mix design for the control sample was as follows:

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Table 2: Mix proportions of control sample & alternative sample

Sample Number	Cement (Kg)	Ceramic Waste (%)	Ceramic waste (Kg)	Fine aggregate (Kg)	Coarse aggregate (Kg)
1 (Control sample)	320	0	0	630	1340
2	288	10	32	630	1340
3	272	15	48	630	1340
4	256	20	64	630	1340
5	240	25	80	630	1340
6	224	30	96	630	1340
7	208	35	112	630	1340

(Note: These mix proportions are for production of 1m³ of concrete with w/c ratio of 0.50)

Considering the study done by (Amitkumar D. Raval, 2013), of using ceramic waste powder for partial replacement of cement in grade 25 concrete, it was decided to vary partial replacement percentage of cement from 10% to 35% (10%, 15%, 20%, 25%, 30%, and 35%) by weight in this study. Weight of all other ingredients and the water cement ratio were maintained as same as in control sample. Those mix proportions are also pre in Table 2. The ceramic and porcelain waste used for this study was consist of discarded tile and sanitary product waste and disposed porcelain products.

(SLS 1425, 2011) specifies number of samples for mechanical testing based on the lot size of interlocking blocks. As this is a research study it is not really possible to decide number of test samples based on this guideline.

(IS 456:2000), which is the Indian standard for concrete, specifies testing of at least three (03) samples for each mechanical test if the produced concrete volume is less than or equal to 1m³. Hence, for each alternative mix, three (03) samples were used for each mechanical (Compressive and Flexural tests) tests.

These wastes were initially crushed using industrial compactor and subsequently, crushed using a metal crusher. At end of the process ceramic and porcelain waste was converted to powder form and particle size of powder form particles was maintained below 75 µm. All blocks were manually casted and were cured by immersion curing after initial setting time. A few photographs taken during production of blocks are presented in Fig. 2.

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Figure 2. Photographs taken during casting of block by authors

Figure 2.1 Raw materials



Figure 2.4 Curing cubes



Figure 2.2 Mixing Raw material



Figure 2.5 Unmolded Cube



Figure 2.3. Casted Cubes



Results & Discussion

As first test of alternative mixes developed in this study, slump tests were performed just after mixing of concrete under each mix to check workability. During mix design it was targeted a zero-slump mix. The control mix and all alternative mixes showed almost zero slumps during testing. Reported slump values are presented in Table 3.

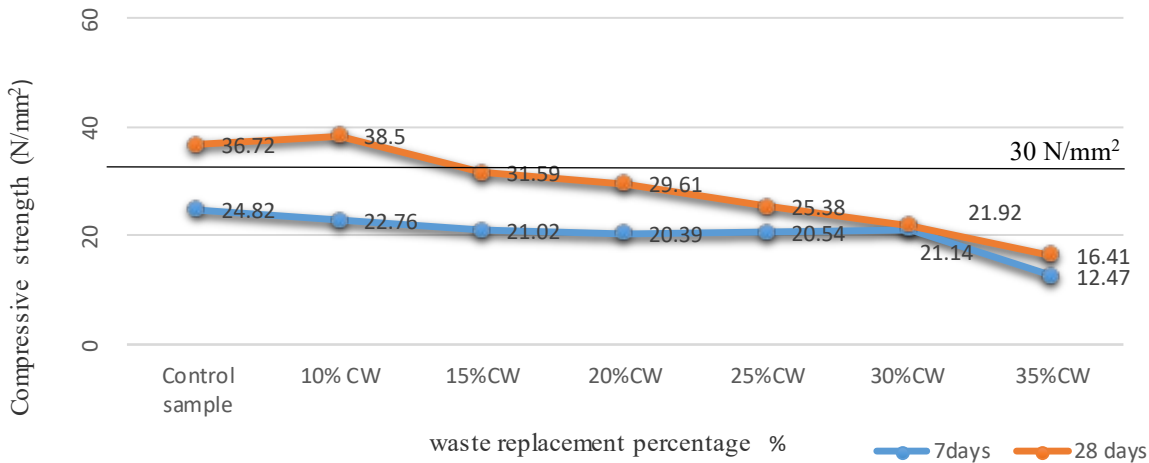
Table 3: Slump test results of alternative mixes

Cement (%)	Ceramic waste Replacement (%)	Slump (mm)
100	Control sample	Zero slump
90	10	3
85	15	2
80	20	Zero slump
75	25	Zero slump
70	30	Zero slump
65	35	2

Hence, it is evident that partially replacing cement by ceramic & porcelain waste powder has minimal effect on workability under considered partial replacement percentages. Secondly, the compressive strength of samples were

checked at 7 days and 28 days as per standard procedure of, (SLS 1425, 2011) Average compressive strength Results are presented in Fig. 3.

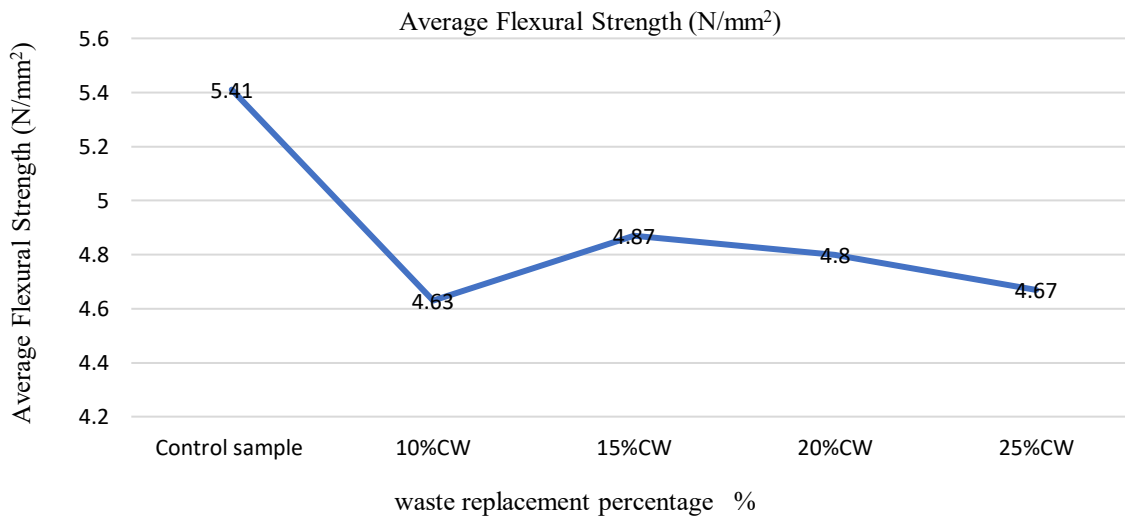
Figure 3: Variation of compressive strength of alternative mixes



As per results, it is clear that compressive strength of blocks is reducing in general when partial replacement percentage of cement is increased. This is especially evident with regard to early age strength (7day strength). This is understandable when considered about chemical process involved in concrete hardening. However, samples having partial replacement percentage of 10% and 15% have achieved the target average compressive strength of 30 N/mm² at 28 days.

Even though local standard does not direct to test flexural & tensile splitting tests of blocks, certain international codes such as Indian code (IS 15658 : 2006) specify such tests too for concrete interlocking paving blocks. Accordingly, flexural tests were performed for control samples and samples having ceramic & porcelain waste powder up to 25%. The tensile splitting tests were performed for control samples and samples having ceramic & porcelain waste powder up to 15%. Both of these tests were performed as per Indian standard. Results of above tests are presented in Fig. 4 and Fig. 5 respectively.

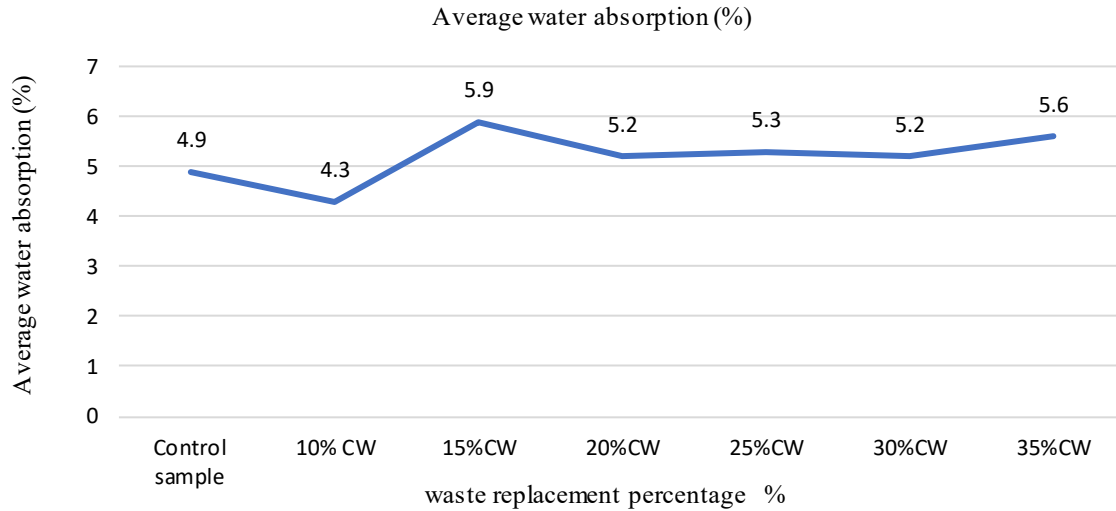
Figure 4: Variation of average flexural strength of alternative samples



It is clear that both flexural strength and tensile splitting strength of interlocking paving blocks are reducing with the introduction of SCM. However, reported flexural & spilt tensile test of all samples are at acceptable level for interlocking blocks as per (IS 15658 : 2006)

Finally, water absorption of sample of all considered mixes were checked. Average water absorptions of considered samples are presented in Fig. 6. Any significant variation was not observed between samples of different mixes considered in the study and all samples have shown results below specified water absorption percentage of 6%.

Figure 6: Variation of average water absorption



Considering all of above results, it was identified that best possible percentage of replacing cement by ceramic & porcelain waste in powder form is 15% by weight of cement. The financial benefit analysis & sustainable viability analysis of this mix were performed with respect to the control mix.

A cost analysis for production of a block under control mix and for a block under alternative mix 3 (the sample where 15% cement was replaced by ceramic & porcelain waste) were prepared considering present market prices of material and labour. The summary of this calculation is presented in Table 4.

Table 4: Cost analysis of control sample & sample 3

Material	Control sample			15% CW sample		
	Qty	Rate	Cost (LKR)	Qty	Rate	Cost (LKR)
Cement	539kg (≈10.8 bags)	Rs. 1,950 / 50kg bag	21060.00	456kg (≈9.1 bags)	Rs. 1,950 / 50kg bag	17745.00
Ceramic Waste				82kg		-
River Sand	0.4623 m ³	Rs. 29,000 / cube	4737.35	0.4623 m ³	Rs. 29,000 / cube	4737.35
Aggregate	0.983 m ³	Rs. 14,000 / cube	4862.90	0.983 m ³	Rs. 14,000 / cube	4862.90
Water	269L approx.	Rs. 0.30 / L	80.70	269L approx.	Rs. 0.30 / L	80.7
Mold Oil	1 L	Rs. 300 / L	300.00	1 L	Rs. 300 / L	300.0
Transport cost (within 10km)	1	Rs. 1000.00	1000.00	1	1500.00	1000.0
Labour + Other Costs			16250.00			17575.00
Total cost for 1000 Nos			48290.95			46300.95
Cost per block			48.29			46.30

As per the analysis of Table 4, it is clear that it can achieve cost saving of about 4.1% from the proposed alternative approach per block. It may be possible to increase this saving further under a commercial production approach.

To analyze the sustainable viability of proposal alternative mix, calculation of Embodied Energy (EE) and Embodied Carbon (EC) of proposed alternate block with 15% ceramic and porcelain waste and conventional block were calculated as per the approach proposed by Hammond & Jones (Hammond & Jones, 2008) . During this calculation, effects of production, transportation and preparation of each raw material used for mixes were considered. Summary of results of these EE and EC estimations were presented in Table 5.

Table 5: EE and EC Calculation Summary

Material	EE (MJ)per block		(kg/ CO ₂) per block	
	Control mix	% CW +85% OPC	Control mix	% CW +85% OPC
OPC	2.436	2.0669	0.3935	0.3338
CW		0.0369		0.0019
Sand	0.1203	0.1203	0.0071	0.0071
Aggregate	0.2604	0.2604	0.0152	0.0152
Total EE	2.8167	2.4845	0.4158	0.3580
Reduction from control mix (%)	11.79		13.90	

According to the results of the analysis, it is evident that adoption of proposed alternative mix would reduce Embodied Energy by 11.8% and Embodied Carbon content by 13.9% from control mix during. Production of block of concrete interlocking paving blocks. This would be a great achievement in sustainable perspective as the reduction of EE & EC would directly make a positive impact on controlling global warming and other environmental concern in present world.

Conclusion

This study was focused on analyzing the possibility of partially replacing cement by ceramic and porcelain waste (in powder form) in production of block of strength class 3 and its benefit analysis in economic and sustainable perspectives. According to the experimental study performed in this regard it was found that replacing cement up to 15% (by weight) from ceramic & porcelain waste (in powder form) is possible, without affecting to required mechanical and physical characteristics of paving blocks. As per the cost analysis performed under this approach with 15% partial replacement of cement, it was able to achieve a cost reduction of 4.1% from the cost of conventional blocks. Further, in sustainability perspective this approach would lead to reduction of both Embodied Energy and Embodied Carbon emission by 11.8% and 13.9% respectively. Hence, the proposed alternative mix would be a great alternative solution for concrete interlocking paving block production in structural, financial and sustainable perspectives.

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