DESIGNING AND DEVELOPING A PROTOTYPE OF SMART AND HYBRID PAVING SYSTEM

Nipun Rochana Kumarage

(218070M)

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

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Declaration

I declare that this is my own work, and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning, and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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The above candidate has carried out research for the Master thesis under my supervision.

Name of Supervisor : Prof. (Mrs.) C. Jayasinghe

Signature of Supervisor : *UOM Verified Signature* Date : 18/12/2022

Name of Supervisor : Dr K.P.H. Perera

Signature of Supervisor : *UOM Verified Signature* Date : 18/12/2022

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Abstract

Landfilling has now become a prime concern all around the world, not only because it squanders usable land, it causes major environmental issues such as contamination of soil, water, and air, as well as an impact on human health. Glass is one of these waste products which is often dumped when mixed with impurities. A similar landfill was found in a Sri Lankan glass factory dumping its waste for over 20 years. Moreover, one of the major drawbacks of Permeable Interlocking Concrete Paving (PICP) is its unsatisfying appearance. Although many researchers created better aesthetic appearances for PICP, none were cost-effective. Hence, a study was implemented to solve these two issues by developing sustainable paving blocks with smart top-layer customizations utilizing this glass waste. Initially, finite element modelling was used to determine the optimal paving block dimensions, and 200x100x80 mm^3 was discovered to be the ideal paving block dimension for cobble-type paving blocks. Following that, tests were performed on glass waste to determine its suitability for use as fine aggregate. In all tests, glass waste exhibited favourable results. As a result, a mix design was developed using this glass waste, and it was discovered that it could replace 100% of the fine aggregate while maintaining structural strength. Three alternatives were proposed to meet the customers' aesthetic satisfaction and were tested in accordance with the SLS 1425 standard, in which all three alternatives resulted satisfactorily. Finally, a Life Cycle Costing Assessment (LCCA) was performed to determine the economic feasibility of the proposed products. LCCA indicated that when only mortar is considered, the proposed mix has a 37% cost reduction, and after smart top layer customizations, two alternatives had 6% and 5% cost reductions, while the final alternative had a 17% cost increment compared to existing paving blocks.

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List of Abbreviations

Abbreviation	Description
AADTT	Average Annual Daily Truck Traffic
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BS/ BS EN	British Standards
FEM	Finite Element Modelling
ICE	Inventory of Carbon and Energy
ICPI	Interlocking Concrete Pavement Institute
IRC	Indian Roads Congress
IS	Indian Standards
LCCA	Life Cycle Costing Assessment
LKR	Sri Lankan Rupee
Mn	Millions
NPV	Net Present Value
PAP	Porous Asphalt Paving
PCP	Permeable Concrete Paving
PGP	Plastic Grid Paving
PICP	Permeable Interlocking Concrete Paving
SLS	Sri Lankan Standards
SSD	Saturated Surface Dry

1: INTRODUCTION

1.1 Background

Permeable Interlocking Concrete Paving (PICP) is widely used as a low-maintenance, eco-friendly, and cost-effective paving alternative [1]. PICP is a system in which concrete paving blocks are designed and laid with sufficient spacing between them to allow stormwater to infiltrate the base layer [2]. Therefore, the joints and spaces between the pavers are kept void without using sand or any other binding material, and the structural strength is provided by the mortar block and its interlocking behaviour. Paving blocks are commonly made with mortar, and multicolour pigments are frequently used to improve their aesthetic [3], [4]. However, these colour differences were insufficient to meet customers' aesthetic expectations. As a result, many researchers attempted to change its appearance by customizing the paving block with clay and creating stone pavers [5], [6]. Despite their success, these alternatives were not economically viable due to higher prices.

Moreover, landfilling has become a major issue in recent years, not only because it squanders usable land and also because it causes major environmental issues such as contamination of soil, water, and air, as well as an impact on human health. One of these waste products is glass waste. Throughout the years, numerous research attempts have been made to reuse and recycle glass waste [7]–[10]. However, only 100% pure glass waste is recycled, and when mixed with impurities, it is frequently dumped, as the world's largest countries, such as Russia, China, and the United States, dump 80%, 75%, and 66% of their glass waste into landfills, respectively [10]. A similar sanitary land fill was discovered in a glass factory in Sri Lanka, where the rejection at the washing drum (where recycled glass is washed) was found to be dumped at the site. This waste contained finer glass particles, coarse plastics, metals, and numerous impurities. According to the information provided by the factory officials, this glass factory generates around 6-7 tons of waste per day and has been dumping this waste for the past 20 years. This is a significant amount of waste and raises concerns about the impact on the environment and public health. Now the factory aims to address this issue and implement a more sustainable waste management practice.

1.2 Research Problem

The current paving blocks used by the customer are no longer satisfactory in terms of color and shape. In an effort to improve their appearance, researchers have attempted to modify the pavers using natural stones, but these attempts have proven to be unsuccessful and not cost-effective. As a result, a new method of customization is needed in order to maintain economic feasibility. Additionally, the disposal of glass waste in landfills has negative effects on the environment and human health, reducing usable land area and causing environmental issues. In order to address this issue, it is necessary to find a way to use this waste in a more sustainable manner.

1.3 Research Aim

The research aim was to produce an economically viable, aesthetically appealing, sustainable concrete paving block for the market utilizing waste products from glass industry.

1.4 Research Objectives

This research's objective was to produce a sustainable paving block manufactured using waste materials generated from the glass industry. In order to meet the main objective, the study focused on the following sub-objectives:

- To determine the optimum dimensions for cobble-type proposed paving blocks
- To determine an optimum mix proportion
- Feasibility analysis of the proposed paving block with standardized testing
- Life cycle costing assessment on proposed blocks

1.5 Research Methodology

The proposed methodology was divided into four work packages (WPs). These WPs are described in Figure 1:

WP 1 - Literature review on concrete interlocking
Data on existing paving materials, their advantages, structural properties, and standard testing proceedings were identified.
WP 2 – Identify optimum paving block dimensions using FEM
Finite element modelling was used to determine the optimum paving block dimensions.
WP 3 – Experimental procedure
Tests on glass waste aggregate, determination of optimum mix design using glass waste as fine aggregate and proposed alternatives were tested to be accepted in vehicular and pedestrian pavements
WP 4 – Life cycle costing assessment (LCCA)
Life cycle costing assessment was conducted to find the cost save in the long run

Figure 1: Proposed Methodology

1.6 Major findings

This research explored the possibility of utilising dumped glass waste to make a paving block that is relatively low in cost, superior in appearance, and as a method of sustainable construction. The main finding was that the proposed paving blocks met the SLS 1425 strength requirements for pedestrian and vehicular pavements.

1.7 Thesis Outline

The thesis outline is explained under Table 1.

Table 1: Thesis Outline

Chapter 1	Introduction • Background • Research problem • Research aim • Objectives of the research • Research Methodology • Outline of the thesis
Chapter 2	Literature Review • Introduction • Importance of permeable pavement systems • Different permeable pavement systems • Characteristics of permeable pavement systems • Selection of the best pavement system for development • Standards for testing
Chapter 3	Determining optimum paving block dimensions using FEM • Finite element modelling was conducted to determine the optimum dimensions for cobble type paving blocks
Chapter 4	Experimental Procedure • Tests on aggregates • Determination of optimum mix design • Testing of Proposed paving blocks
Chapter 5	Life Cycle Costing Assessment • Initial cost • Maintenance and rehabilitation cost • Residual value • Life cycle costing assessment
Chapter 6	Discussion and selection of the best alternative
Chapter 7	Conclusion

2: LITERATURE REVIEW

2.1 Introduction

Landscaping has gained immersed attention of building developers and homeowners recently. Landscaping was defined as the design and arrangement of natural and manmade elements through scientific knowledge and resource conservation [11]. It is now considered a significant part of the building plan and affects the total property value [12]. Whereas an Athens study confirmed the fact by stating that landscaping can improve the resell value of residential houses by 3-5% [13]. Landscaping can be categorized into several elements, such as designing, paving, planting, furnishing, and protection [14]. Therefore, land paving is one of the key elements of landscaping. An appropriate paving technique selection will depend on the location, costs, safety aspects, and the homeowners' aesthetic preferences [15]. Moreover, when external paving is considered, maintaining a good drainage technique is the key to mitigating stormwater runoff and facilitating water table replenishment through rainwater infiltration [16].

2.2 Importance of permeable paving systems

Front gardens and lawns have great importance in the context of climate change. Although they are designed to create pleasant townscapes, they also help to reduce flooding risks by soaking up the stormwater and absorbing carbon dioxide from the atmosphere [17]. Increased car ownership, pressure on roadside parking, and change of fashion in pavement design resulted in new paving systems [17]. In addition, a BBC article stated that people in the UK tend to move on to paved gardens as it is easier to maintain when compared with grass lawns [18]. However, many studies stated that increased hard surfacing on land had major drawbacks [19], [20]. Initially, paving systems prevented rainwater infiltration, leading to increased flood risk by increasing the surface runoff [21], [22]. This risk is expected to increase with time since rainfall is predicted to become more frequent and intense in the future [23], as a study in the United Kingdom predicted that a current 1 in 100-year rainfall might occur as frequently as 1 in 25 years by the 2080s [24].

The other main concern of pavement systems is the development of the heat island effect due to hard surfacing generated by pavement systems [25]. A study in 2008 stated that the average urban surface spread in four metropolitan areas in the USA is as follows: 29-41% vegetation, 19-25% roofs, and 29-39% in paved surfaces [26]. The above values show that over 60% of urban surfaces are covered with manmade hardscapes. Furthermore, this percentage can be expected only to increase with time. Therefore, this development of the heat island effect leads to many environmental issues for the urban population [27]. Such as critical impacts on human comfort, health and wellbeing, and the local atmosphere [28]–[31].

Therefore, developing a paving system should ensure that it allows stormwater penetration to the ground surface and reduces the impact on the urban heat island effect. The following section describes several permeable paving systems currently used in the industry to prevent the aforementioned adverse impacts.

2.3 Different paving systems

Several paving systems were identified which can be used to mitigate the aforementioned adverse impacts and satisfy the requirements of a paving system. It was found that porous asphalt paving, permeable concrete paving, permeable interlocking concrete paving, and plastic grid paving were the leading permeable paving systems. A detailed description of each paving system and its advantages and disadvantages are discussed in subsections 2.3.1 to 2.3.4.

2.3.1 Porous Asphalt Paving

Porous Asphalt Paving (PAP) can be defined as asphalt pavement developed with materials screened to reduce the percentage of fines [32]. Which eventually allows for better rainwater infiltration, as shown in Figure 2. The thickness of a wearing surface of PAP varies from 75 mm to 180 mm, depending on the traffic load the pavement is expected to bear [33]. The void percentages in most PAPs were around 15% [34]. In 1970 Franklin institute of Philadelphia improved this method to reduce drainage structures [35]. In addition, a geotextile can be applied under the aggregate to filter pollutants and fines [35]. Some advantages of PAP are as follows: reduction of stormwater systems, reduction in street flow during inclement weather, and reduction of night glare and splash visibility during inclement weather increased [36], [37]. Furthermore, a Taiwan study stated that PAP is more cost-effective when compared with open-graded asphalt, and cost can be further reduced by using sustainable materials such as steel slag, which is technically viable and environmentally friendly [38].

Figure 2: Porous Asphalt Pavement

However, although PAP illustrated promising performances in stormwater management, it has many concerns regarding economic aspects as it requires higher installation and maintenance costs compared with other pavement systems [39], [40]. It also has limitations when meeting freezing and thawing cycles [32]. A Swedish study in 2000 confirmed this fact by stating that if the moisture content of the soil is higher, it has increased the thawing effect rapidly in PAP, and it is more resilient to freezing when compared with conventional pavement [41]. A Switzerland study also stated that, for winter maintenance, PAP needs de-icing salts and thawing products as same as conventional asphalt pavements. However, due to the higher void content of the asphalt layer, there is a tendency that these de-icing salts can penetrate to the bottom through the voids, resulting in ice staying longer on the surface. [42]. Finally, although PAP can be considered for public street paving, it is not feasible to use it for household gardens and roads due to its required installation resources.

2.3.2 Permeable concrete Paving

Permeable Concrete Paving (PCP) is another similar pavement to PAP. PCP is created by mixing Portland cement with more course aggregate, increasing the void percentage and allowing water to drain easily as shown in Figure 3. Therefore, PCP can be defined as a concrete pavement that provides a network for stormwater infiltration into the subbase and base layers [43]–[45]. An ASTM is yet to be designed to PCP with the porous concrete's complexity. However, previous studies have used ASTM C39 to test compressive strength in PCP [46]. A typical PCP was found to inhibit a permeability from 20 to 500 m/day, compressive strength of 5.5 to 20 MPa, and air voids of about 15% to 30% [47], [48].

Figure 3: Permeable Concrete Pavement

In urban environments, PCP can be very beneficial as it enables the dissipation of stormwater runoff and improves the water quality concerning metals, nitrogen, phosphorus, and suspended solids [49]–[51]. In addition to stormwater runoff reduction, an Indian study stated that the PCP could reduce the heat island effect and the generated traffic noise [52]. Also, it was found that cement consumption is relatively low in PCP compared with conventional concrete pavements [46]. Moreover, a life cycle assessment in Greece stated that permeable concrete emits only 2% of conventional concrete's CO_2 produced, producing 19.5 kg CO_2 / m^3 than 903 kg CO_2 / m^3 [53].

Although PCP can bring the benefits mentioned above, its effectiveness and durability are major drawbacks in the long run. A winter study in the USA identified some of the factors: premature failure, deterioration of pavement characteristics when exposed to chemical and physical attacks, and clogging of the PCP from sand applied on the pavement [54]. It was also found that clogging of PCP can occur due to the transportation of sand by traffic and stormwater runoff from the adjacent lands [47], [55].

2.3.3 Permeable Interlocking Concrete Paving

The Permeable Interlocking Concrete Paving (PICP) system has been widely used for the past 25 years as one of the famous permeable paving systems [56]. PICP is being used in the industry as an eco-friendly and cost-effective paving alternative that is durable, has low maintenance, and is highly versatile [1]. Specifically, these blocks can prevent rainwater gathering and resultant flooding and provide a solid surface that provides better runoff for chemicals, oils, and other liquids [1]. Furthermore, PICPs can be easily used for multiple landscaping applications such as stormwater reusing and vegetation [1]. PICP is the system where concrete paving blocks are designed and laid with sufficient spacing between blocks so that stormwater can infiltrate the base layer [2]. The joints and spaces between pavers are kept void without filling them with sand or any binding material, as shown in Figure 4, and the structural strength is obtained by its interlocking behaviour. Therefore, the void percentage of the paving system is 8 to 20% of the paving area [57] which allows for better stormwater infiltration. Figure 5 illustrates the sub-structure of a PICP in which the joints between pavers allow water to infiltrate the bedding layer. This bedding layer is usually a 2-5mm aggregate layer laid on a geotextile [58]. This geotextile is used to improve the inflow water quality [59].

Figure 4: Permeable interlocking concrete pavement

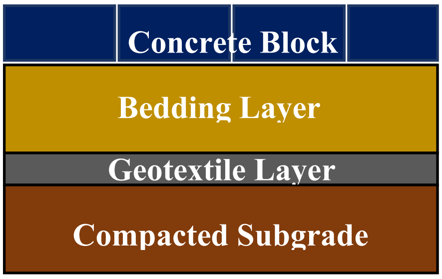

Figure 5: Substructure of PICP Pavement

PICP has been a main focus area for research for the last few decades because of its ability to construct using vast materials. Researchers have made many attempts to reduce the construction cost by replacing aggregate with: mud, fly ash [60], [61], ceramic tiles [62], and even waste materials [63]. A Chinese study stated that in creating paving blocks recycled coarse concrete aggregate can be used up to 60%, and recycled concrete fine aggregate can be used up to 20% [64].

Researchers also attempted to customize the blocks' appearance to meet customer satisfaction by changing their shape [65] and introducing vast pigments [66] which are currently adopted worldwide. Several attempts were also made to create the paving blocks using different materials, such as granite and natural rocks. However, these became impractical due to higher costs [67]. Hence, although many attempts were made, there is still room for innovative designs to meet the aesthetic satisfaction of customers.

Moreover, PICP was found to have a better impact on the thermal environment than asphalt pavements, where a difference of 10°C could be seen during a scorching measurement period [68]. Also, it stated the reflectivity, absorptivity, and emissivity of permeable interlocking concrete paving to be 0.22, 0.78, and 0.9, respectively, which were found comparatively better than asphalt pavements with approximate values of 0.13, 0.87, and 0.923 [68].

Embodied energy is another primary concern regarding construction materials, as researchers and people are trying their best to reduce carbon emissions worldwide [69], [70]. For example, according to the Inventory of Carbon and Energy (ICE) of Bath University, paving blocks have a higher embodied energy than regular concrete as it specified the values of 1.03 MJ/kg for heavy-duty pavers and 0.95 MJ/kg for domestic pavers [71]. Furthermore, by using a waste material, we can further reduce the embodied energy of the proposed block because waste materials contain negative embodied energies, as the energy required to incinerate the waste is saved [72].

2.3.4 Plastic Grid Paving System

Plastic Grid Paving (PGP) is a system where interconnected plastic grids are laid on top of a prepared surface and later filled with gravel or topsoil planted with grass. The functionality of PGP is similar to that of PICP, where the voids in the pavement allow to disperse of runoff water into the bottom surface. However void percentage in PGP is higher than PICP, as shown in Figure 6, to have a better infiltration of stormwater runoff. For PGP, the void percentage varies from 90 to 98% compared with 8 to 20% in PICP [2]. These grids are often created by lightweight injection moulded plastic, and these can be created with 100% post-consumer plastic (High-Density Poly Ethylene) with added 3% carbon black for UV protection [73]. These grids should be able to carry a load of 402 kg/cm^2 (5700psi) when filled with sand over a depth of road base [73].

Figure 6: Plastic Grid Pavement filled with grass and gravel

2.4 Characteristics of permeable paving systems

This section addresses previous research findings on the characteristics of permeable pavement systems. Three characteristics were addressed in subsections 2.4.1 to 2.4.3: surface water infiltration, pavement clogging, and the maintenance requirements of each pavement. Finally, subsection 2.4.4 summarises the aforementioned permeable pavement systems' void percentage, infiltration, and compressive strengths.

2.4.1 Infiltration of Surface Water

Compared with traditional pavements, pervious pavements systems had significantly reduced stormwater runoff and peak flow rates in urban catchments. A USA study measured the removal rates of PC and PICP compared with an impervious asphalt surface. The permeable surfaces showed a mean runoff reduction of 98% compared to 35% on impervious surfaces [74]. Regarding PGP, a study conducted in the USA stated that PGP filled with topsoil and grass had shown around 93% runoff reduction compared to a conventional asphalt surface [33]. Also, a study conducted in North Carolina found a rational runoff coefficient of 0.2 - 0.5 on a pavement created by PGP [75]. Jayasuriya and Kadurupokune conducted a more detailed study in Melbourne, where they found: that peak discharges were reduced by 40 – 55% in PICP and by 45 – 60% in PGP, runoff volumes were reduced by 43 – 55% in PICP and by 52 – 62% in PGP and for the runoff to occur a traditional asphalt pavement needed only 3 mm rainfall where it had required a rainfall of 13 mm for PICP and 18 mm for PGP [76]. In Belgium, another fascinating study was carried out where they measured the effect of laying grass in PGP. They concluded that greened PGP performances were beneath open-jointed PGP, and the recovery time had increased to two days, whereas the open-jointed PGP dried in a few hours [77].

Several studies have been conducted to find the runoff coefficient for PICP, and they came up with several conclusions. Two studies in 1995 and 1997 stated that 60% of the runoff volumes and peak flow rates had been reduced by the PICP when compared with traditional asphalt pavements [78], [79]. Later, a USA study in 2006 stated that the runoff coefficient reduction could be as high as 72% in PICP pavements compared to asphalt pavements [80]. Additionally, an Australian study stated that the imperviousness of streets could be reduced by 42% by installing PICP [81].

2.4.2 Clogging of pavement

Past research indicates that clogging and failure of permeable pavement can occur due to many reasons, such as poor design, poor construction, poor maintenance, low permeability of the soil, and lack of sediment erosion control during construction [56], [79], [82]. A German study in 2006 found that the infiltration rate is affected by the pavement's age, mainly due to the filling of joints and pores of the permeable pavement with mineral and organic fines. It also stated that the infiltration rate would decrease and become steady after 10 years to 20 – 25% of the initial infiltration [83]. A 17-week model for permeable paving systems was conducted in Australia to analyze the effects of up to 17 years of operation. It found that the removal of almost 100% of the Total Suspended Solids of the stormwater can be expected from permeable pavements. These TSS would accumulate at the bottom of the pavement, leading to clogging and ponding. It also stated that PICP is more likely to pond after 5 years of operation due to its geotextile layer at the bottom, and PAP is likely to pond after 8.5 years of operation [84]. However, a Spanish study found that in fully clogged PICP, 81% infiltration could be achieved when rainfall intensity is at 55 mm/h, and the maximum infiltration rate was found to be 64 mm/h at a rainfall intensity of 125 mm/h [85]. An Australian study also stated that in a PICP system, infiltration could be fully functional, although the appearance seemed clogged, and 92% of the sediments lie in the paving layer and bedding layer of the pavement [56]. A study was also conducted for 20 PCP car parks to find the depth of sedimentation, with the use of a computerized tomography (CT) scanner, and they concluded by stating that a reduction of porosity of PCP was found on the top 25 mm of the PCP, which can be due to clogging [86].

2.4.3 Maintenance of Pavement

Permeable pavements allow infiltration of stormwater through joints and voids. However, these joints and voids get clogged with sediment and fines after some time. Hence, preventive and restorative measurements are required to uphold the hydrological benefits of permeable pavements [87]. A European study stated that PAP and PCP were susceptible to clogging within the first 3 years of usage and the top layer needs to be replaced and reinstated after each period for proper drainage [58]. Various researchers have opted out that maintenance for PICP should be carried out by removing pollutants from the pavers and replacing the bedding layer from time to time to maintain proper stormwater infiltration [2], [88], [89]. However, a Canadian study stated that infiltrations would increase by removing the top 10-20 mm of joint filler for low daily traffic areas, and removal depth should be increased to 20-25mm for areas with high traffic [90]. Studies also state that proper maintenance can improve the infiltration of PICP by up to 65% [91], [92].

For PICP, vacuuming and yearly sweeping improved the pavement's hydrological characteristics [93]. The same was found with PCP. However, pressure washing was highly effective with PCP [94]. Even though pressure washing was effective, Fassman stated that dislodging sediments should not be recommended as those can be washed to a reticulate system [82]. Some USA authorities encourage routine sweeping up to three or more times a year. However, Australia and Europe discourage frequent maintenance as they consider it unnecessary [95]. Moreover, an eight-year-old and a 6-year-old study stated that hydrological performances were satisfactory for PICP when no maintenance was carried out despite significant clogging [56], [96].

2.4.4 Summary of the characteristics of the permeable pavement systems

This subsection contains a summary description of the main properties of the aforementioned paving systems, with Table 2 addressing the void content, permeability, and compressive strength.

Table 2: Summary of the characteristics of permeable pavement systems

Characteristic	PAP	PCP	PICP	PGP
Void Content	15-20% [97]	15-25% [98]	8-20% [2]	90-98% [2]
Permeability (ASTM method)	1-5 mm/s [99]	10-20 mm/s [100]	10-20 mm/s [101]	
Compressive Strength	1.75- 2.25 MPa [102]	2.8-28 MPa [98]	15-50 MPa [103]	40 MPa [73]

2.5 Selection of the best paving system for development

The selection of a paving technique depends on location, costs, safety, and aesthetic preferences [15]. However, in this study, the main focus was to develop a paving system, meanwhile utilizing the glass waste created by the glass industry. Subsections 2.5.1 and 2.5.2 summarizes the advantages and disadvantages of the existing permeable paving systems. Finally, subsection 2.5.3 concludes with selecting the best paving system to be developed for home gardens.

2.5.1 Advantages of the considered permeable paving systems

This subsection focuses on the advantages of each permeable paving system. The following Table 3 indicates a summary of the advantages of considered permeable paving systems.

Table 3: Advantages of the considered permeable paving systems

PAP	PCP	PICP	PGP
Satisfactory permeability [35]	Satisfactory permeability [50]	Satisfactory permeability [57]	Satisfactory permeability [2]
Reduction of night glare [36], [37]	Reduction of heat island effect and generated traffic noise [52]	Easy application with labour-intensive construction [104]	Easy application with labour-intensive construction [105]
	Reduction of cement consumption [46]	Ability to change the composition of the block and alter its appearance since its permeability will depend on the joints [2]	Ability to be constructed using 100% post-consumer plastic [73]
	Emission of 2% of the total CO_2 emission in conventional concrete [53]	Ability to introduce waste material in the creation of a sustainable block [63]	

According to the above table, satisfactory permeability was discovered to be an advantage for all four permeable pavement methods. It was also discovered that PAP has the added benefit of reducing night glare. Compared to traditional concrete, PCP had benefits in terms of cement consumption and CO_2 emissions. According to the literature, PCP also reduced the generated traffic noise. Ease of installation and labour-intensive construction was found to be added benefits for both PICP and PGP. Since the permeability of PICP was determined by the joints rather than the block composition, PICP was able to change its appearance by incorporating a variety of materials, including waste materials. Finally, the PGP was able to be formed entirely of post-consumer plastics, making it a sustainable paving system.

2.5.2 Disadvantages of the considered paving systems

This subsection was used to discuss the disadvantages of each permeable paving system. The following includes a summary of the considered permeable paving systems.

Table 4: Disadvantages of the considered permeable paving systems

PAP	PCP	PICP	PGP
Limitations in meeting aesthetic satisfaction of customers	Limitations in meeting aesthetic satisfaction of customers	Limitations in meeting aesthetic satisfaction of customers	Limitations in meeting aesthetic satisfaction of customers
Requirement of heavy machinery and equipment [106]	Higher comparative initial cost and machinery requirement [107]		Inability to incorporate any other waste materials except plastic
Pressure washing is required once every 3 years due to clogging [94]	Since its permeability relies on the mixture hard to alter the appearance		
	Pressure washing is required once every 3 years due to clogging [94]		

Among the disadvantages of the considered permeable paving methods, it was discovered that all pavements trailed in the component of achieving consumer aesthetic satisfaction. The high initial cost and machinery requirements of PAP and PCP were discovered to be disadvantages of these two paving methods. The inability to employ waste materials other than glass was discovered to be a restriction for plastic grid pavers.

2.5.3 Selection of the best pavement system for development

Compared to impermeable pavement systems, all four permeable paving systems had satisfactory permeability. However, according to the literature, plastic grids demonstrated the highest permeability with the highest amount of voids. Because of their ease of application, PICP and PGP were found to be more suitable for home gardens, while PAP and PCP were found to be more suitable for public car parks and urban streets. In addition, pressure washing was required once in 3 years to maintain a satisfactory permeability for PAP and PCP. However, according to the literature, PICP maintained a reduced yet acceptable permeability without extra maintenance.

Among the alternatives, PICP provided a more significant potential for invention with superior aesthetic appearances because its permeability was determined by the joints rather than the material composition, and it could be built with a diverse range of materials.

Hence, PICP was selected as the best paving system for development for this research project. Therefore, the project aim was to develop a prototype of a smart and hybrid interlocking paving block . The literature findings were presented at the 13th International Conference On Sustainable Built Environment 2022 (ICSBE 2022). (The published paper is attached in Annex 1.)

2.6 Standards for testing

Several international standards have been developed around the globe for designing interlocking concrete paving blocks. The main structural parameter is the block's compressive strength which is determined based on its application. Table 5 specifies the different structural strength requirements based on international standards.

Table 5: International standards of structural strength recommendation on paving blocks

Standard	Strength/ Traffic Class	Specified Average Compressive Strength (MPa)	Minimum Recommended Compressive Strength (MPa)	Minimum Thickness (mm)
ASTM C936 [108]	All types	55 (Sample of 3)	50	60 or (length/4), whichever is higher
BS 6717-1 [109]	All types	49 (Sample of 16)	40	60, 65, 80 or 100
SLS 1425 Part II [110]	Class 1	50 (Sample of 8)	40	80 or 100
	Class 2	40 (Sample of 8)	32	80 or 100
	Class 3	30 (Sample of 8)	25	80 or 100
	Class 4	15 (Sample of 8)	12	60 or 80
IS:15658:2021 [111]	Very heavy traffic	-	55	100
	Heavy traffic	-	50	100
	Medium traffic	-	40	80
	Light traffic	-	35	60
	Non traffic	-	30	50

Moreover, the SLS 1425 standard was chosen as the framework for evaluating the suitability of the prototypes for the Sri Lankan market. This standard provides a comprehensive set of guidelines for determining the quality and performance of building materials, ensuring that the prototypes meet the necessary requirements for use in this market. According to the specification, the final prototypes must pass four tests to determine their suitability for automotive and pedestrian pavements, which are as follows:

- Compressive strength test
- Slip and skid resistance test
- Water absorption test
- Abrasion resistance test

These tests and procedures are later discussed in detail in the Experimental Procedure (Chapter 4).

2.7 Selection of innovative material for the paving blocks

Several attempts were made to incorporate a variety of materials into the paving block. Aircrete, granite, and glass waste landfills were among the materials tried out during the study. Which is covered in detail under subsections 2.7.1 to 2.7.3.

2.7.1 Creating paving blocks with aircrete

Aircrete is a building material made from a mixture of cement, water, and small air-filled bubbles. It is lightweight, strong, and has excellent insulation properties, making it a popular choice for construction projects [112]. The air bubbles in the material are created by adding an aerating agent to the cement mixture, which causes it to foam and expand. This process also reduces the weight of the material, making it easier to work with and transport.

One of the main advantages of creating a paving block with aircrete is its lightweight nature. Because they are made with air bubbles, they are significantly lighter than traditional concrete blocks and can be created with densities even less than 450 kg/m^3 [112], which makes them easier to handle and transport. This can make them a cost-effective option for paving projects, as they require less installation labour and equipment. In addition to being lightweight and easy to work with, it has a high thermal resistance. It is also resistant to fire, rot, and pests, which makes it a durable material for building homes and other structures [113].

To better understand the product, a field visit was made to a mini aircrete manufacturing plant that produces aircrete wall panels. It was seen that aircrete was created by mixing cement, water, and a special aerating agent, and this aerating agent (foam) was created in a specialized machine called a foam generator, as shown in Figure 7 and Figure 8. The generated foam is then mixed with other ingredients in an aircrete mixer, as shown in Figure 9 and Figure 10. Finally, the created foamy mixture is then poured into moulds or forms to create blocks or panels.

Figure 7: Foam generator

Figure 8: Generated foam

Figure 9: Aircrete mixing equipment

Figure 10: Picture of the inside of the aircrete mixing equipment

Despite the advantages, such as being lightweight, easy to install, and affordable, the potential downside is its compromised compressive strength

(< 3 N/mm^2), which is mainly due to its lower density and increased void content [113]. According to SLS 1425 standard, Class 1 paving blocks require a minimum compressive strength of 50 N/mm^2, and even Class 4 pedestrian paving blocks require a minimum compressive strength of 15 N/mm^2 which is way higher than 3 N/mm^2, therefore creating a paving block out of aircrete was not an option.

2.7.2 Creating a paving block with granite

The literature revealed that many researchers attempted to make paving blocks out of granite, granite powder, and other granular materials [114], [115]. Paving blocks made of granite can be a popular choice for outdoor surfaces because of their durability and natural beauty. Granite is a type of igneous rock that is formed when molten rock cools and solidifies. It is made up of minerals such as quartz, feldspar, and mica, which give it its characteristic grainy texture and hard, dense structure [116].

Granite is highly resistant to damage from water, weather, and heavy loads, making it an ideal material for paving surfaces [114]. It is also easy to maintain and withstand regular use's wear and tear. Because of its durability and resistance to damage, paving blocks made of granite can be very much suitable for high-traffic areas such as driveways, sidewalks, and patios.

Granite paving blocks can also be made available in a wide range of colours, sizes, and styles to suit different design preferences [117]. They can be cut into various shapes and sizes to create intricate patterns and designs. They can also be polished to a smooth, shiny finish for a more elegant look.

Despite its high durability characteristics, there are several reasons why it is not feasible to use paving blocks made of granite for paving projects. First, granite is a relatively expensive material compared to other options, such as concrete or asphalt [118]. This would make the paving blocks made of granite much more expensive to produce, making them less affordable for many customers. Granite is also a very hard and dense material, making it difficult to work with and shape into paving blocks. This would make the production of granite paving blocks more time-consuming and labour-intensive, further increasing the cost.

In conclusion, while granite may be a beautiful and luxurious material, it is not a practical or cost-effective option for paving projects due to its high cost and weight, which makes it unfeasible for use in paving blocks.

2.7.3 Creating paving blocks with glass waste

Using glass waste as a fine aggregate in concrete blocks can be a sustainable and cost-effective solution for reducing the amount of traditional sand used in the mixture. Several studies have demonstrated the feasibility and benefits of using glass waste in concrete.

For example, a review paper published in the International Journal of Civil Engineering and Technology stated that replacing sand with crushed glass in concrete can improve the strength and durability of the material [119]. Another Lebanon study stated that using glass waste as a fine aggregate can reduce the cost of concrete [120].

Additionally, using glass waste in concrete can help reduce the demand for natural sand, which is a finite resource. As the demand for sand continues to increase [121], finding alternative sources like glass waste can help conserve natural resources and protect the environment.

A sanitary glass waste landfill was discovered at a glass factory in Horana, where they had been dumping waste on the site for the past 20 years, accumulating over half an acre, as shown in Figure 11 and Figure 12.

Figure 11: Sanitary glass waste landfills at Horana glass factory

Figure 12: Sanitary glass waste landfills at Horana glass factory

The landfill material is a composition of finer glass particles with many impurities, as shown in Figure 13. This waste product is the recycling plant's washing drum rejection, where the washing drum collects used glass goods (Figure 14), washers, and crushers inside the washing drum (Figure 15) and screens the coarser particles for recycling while rejecting the finer particles with impurities as shown in Figure 15.

Figure 13: Landfill glass waste material

Figure 14: Used glass products fed to the washing drum

Figure 15: Washing drum of the recycling plant

According to factory officials, approximately one tipper load of waste is produced and discarded on-site per each working day, weighing around 6 - 7 tonnes. As a result, this glass waste landfill product was chosen for this study to replace fine aggregate in concrete paving blocks.

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3: DETERMINING OPTIMUM PAVING BLOCK DIMENSIONS USING FEM

There are around 40 paving block shapes that have been patented. However, few are ideal for traffic pavements [122]. The road construction industry's most commonly used paving block shapes are Cobble, Uni, Key Stone, Clover, and Honey. The cobble type was selected for this research because of its wide use and easy application. Furthermore, cobble-type paving blocks have been developed with various dimensions [122]. Therefore, finite element modelling was conducted to find the ideal paving block dimensions for cobble-type. Authorities such as ASTM have developed many guidelines defining restrictions on physical properties for blocks to retain permeable properties [108], [123]. This chapter is focused on finite element modelling and analysing the deflections of interlocking concrete blocks for several paving block sizes and then selecting the optimum paving block dimensions for the cobble-type.

3.1 Finite element modelling

Finite Element Modelling (FEM) is a popular method for performing numerical analyses in many applications. It is frequently used in engineering designs because it reduces costs when compared to physical modelling. Depending on the user's selection, FEM analysis can be performed in either 2D or 3D. FEM analysis was carried out for this study using ABAQUS/CAE software, which can effortlessly generate, edit, monitor, and visualize complex finite element models.[124]. The details of the developed model are described in the following section.

3.1.1 Properties of the model and subgrade layers

The model was developed on a square plane with an area of 1 m^3. Figure 16 depicts layers of subgrade, base, sand, and concrete blocks. A steel loading plate with an area of 69,750 mm^2 (225 mm x 310 mm) with a contact area equal to a single wheel-tire was used at the centre of the model [125].

3.1.2 FEM model development

The ABAQUS model was created with the listed material properties given in Table 6 [126], [127]. The paving block layer was organised using a stretcher bond.

Table 6: Material properties used in the FEM model

	Subgrade	Base	Sand	Concrete
Density (kg/m^3)	1600	1800	1680	2400
Youngs Modulus E (GPa)	0.12	0.24	0.01	23.2
Poisson ratio	0.40	0.30	0.26	0.20

[128]

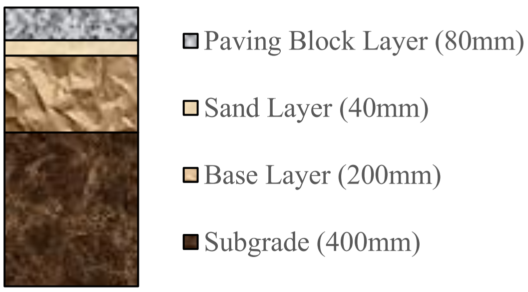

Figure 16: Section view of the FEM model [128]

Mampearachi and Gunathilake's boundary conditions were used as a guide to define the boundary conditions [129]. Horizontal movements at the model's corners were restrained while allowing vertical deflections, and the bottom of the subgrade was defined as fixed, as shown in Figure 17. In addition, all vertical contact surfaces were given a tie constraint to maintain a collective vertical settlement among the model's layers. Figure 18 depicts the boundary conditions of the ABAQUS model.

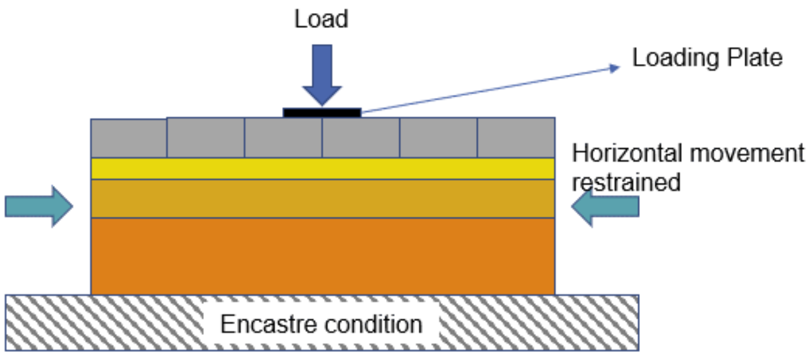

Figure 17: Boundary and loading conditions [128]

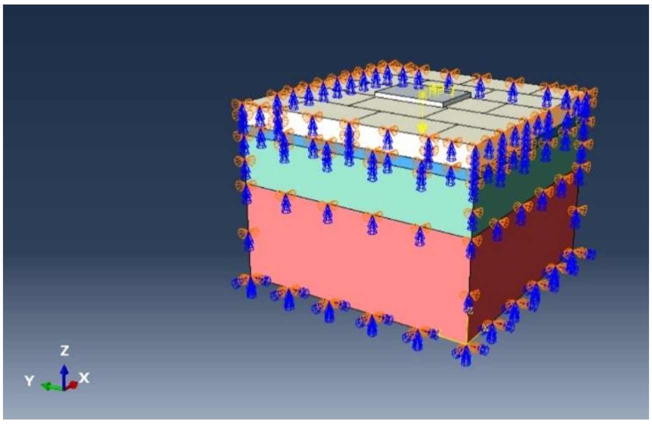

Figure 18: Boundary conditions of the ABAQUS model [128]

3.1.3 Loading conditions

The model was loaded with the help of a loading plate. The plan area of the loading plate was 69,750 mm^2 (225 mm x 310 mm), roughly equal to the contact area of a single tire [125]. A point load was applied to the centre of the plate, as shown in Figure 17.

3.1.4 Validation of the model

A similar ANSYS FEM model was developed for cobble-type paving blocks with results from a physical model [127]. As a result, the results of this physical model were used to validate the developed ABAQUS model. The deformations were compared for point loads of 10 kN, 40 kN, and 60 kN, as shown in following Figure 19.

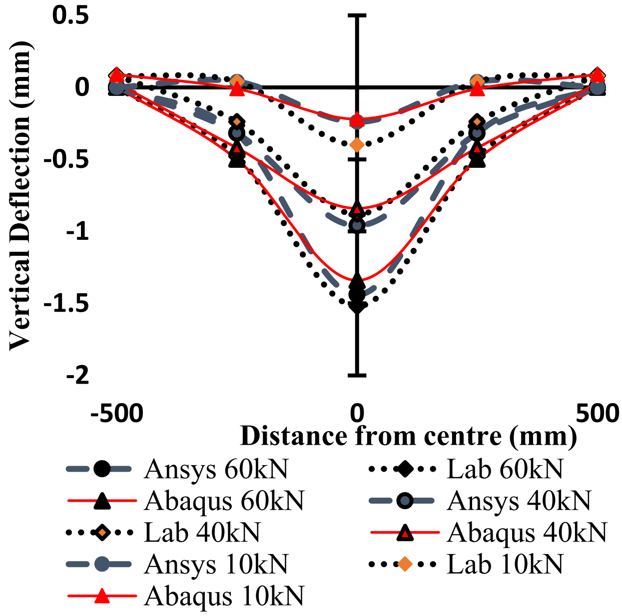

Figure 19: Verification of the ABAQUS model [128]

From the results of Figure 19, it was visible that the results of the ABAQUS model were approximately equal to the results of the physical model and the Ansys model obtained from the literature. Hence, the ABAQUS model was validated.

3.1.5 Development of the alternative paving block dimensions

The American Society for Testing and Materials (ASTM) created a specification (ASTM C936) to alter dimensions for solid concrete paving blocks [108]. When defining new paving block dimensions, the standard recommends pursuing the following guidelines:

- The exposed face area should be less than 0.065 m^2
- The overall length divided by thickness should be less than 4
- The minimum thickness should be 60 mm

Alternative 1 was selected using the dimensions provided in the SLS 1425 standard [103], and alternatives 2 and 3 were defined using the aforementioned guidelines. These two alternatives were developed to have an increased plan area, and the dimensions of the alternatives are shown in Table 7. These dimensions were rounded to the nearest 5 mm, considering practicality.

Table 7: Alternative paving block sizes

Alternative	Length (mm)	Width (mm)	Thickness (mm)
1	200	100	80
2	300	200	75
3	250	250	65

[128]

3.1.6 The meshing of the model

A mesh sensitivity analysis was performed to determine the best mesh size for each FEM model. The global element size of each part/layer was altered to change the mesh size changing the total number of elements. For example, alternative 1's total number of elements ranged from 117 to 56708 when the global element size was changed from 0.2 mm to 0.01 mm. The mesh ratios between the layers had to be kept constant for the mesh sensitivity analysis. Hence a uniform mesh was maintained throughout the model, as shown in Figure 20, without altering mesh sizes from layer to layer.

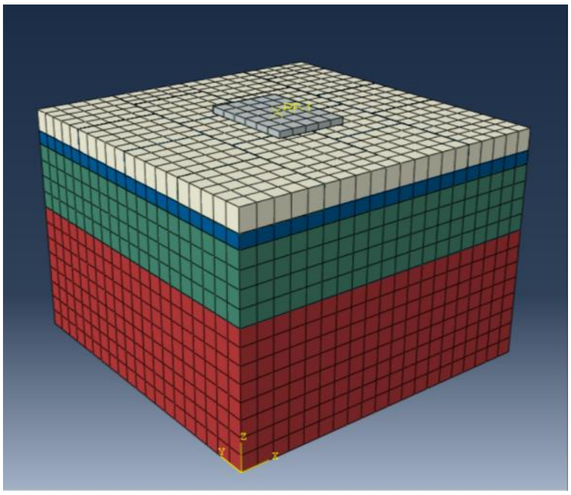

Figure 20: Meshing of the model [128]

3.1.7 Surface tolerance standard

The ASTM standard makes no mention of surface tolerance. However, institutions, such as the Interlocking Concrete Pavement Institute (ICPI) and The Indian Roads Congress (IRC), requested contractors to maintain the surface tolerance/flatness less than 10 mm for a 3 m interval [130], [131], and this value was used as the model's threshold.

3.1.8 FEM Analysis

Elasticity and Poisson's ratio were included as the linear properties in the model, and the results were obtained through a static, linear perturbation analysis.

3.2 Finite element modelling results and discussion

For the three different block dimensions, three finite element models were created. Then, individual mesh sensitivity analyses were performed for each alternative to determine the ideal mesh size for each alternative. Figure 21 depicts the mesh sensitivity analysis conducted for alternative 1, where deflections merged at the global element size of 0.05 m, resulting in approximately 5000 total elements. Alternatives 2 and 3 deflections merged at 2000 and 1000 total elements, respectively.

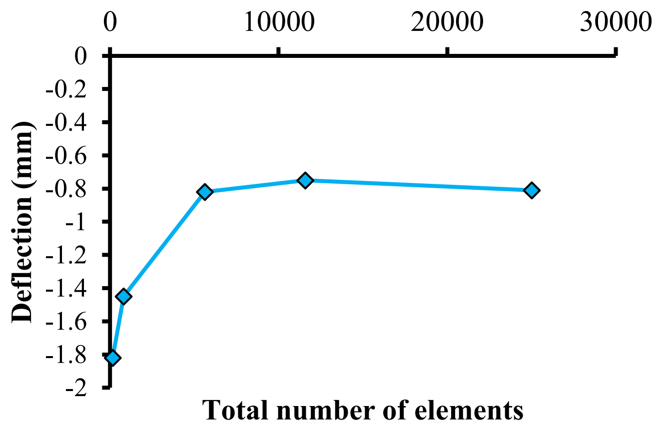

Figure 21: Mesh sensitivity analysis for alternative 1 [128]

The vertical deflections were measured using the converged mesh size. For example, since alternative 1 converged at a global size of 0.05 m with 5000 total elements, this mesh size was used to measure the vertical deflection of alternative 1. Figure 22 depicts the alternative 1 vertical deflection, which was similar to the deflection shape found in the literature [129]. The centre of the loading plate had the maximum deflection, which was the same for all three alternatives. Figure 23 shows a cross-section through the pavement's centre that was used to determine the maximum deflection at the centre. A vertical scale deformation factor of 60 was used for clear visibility.

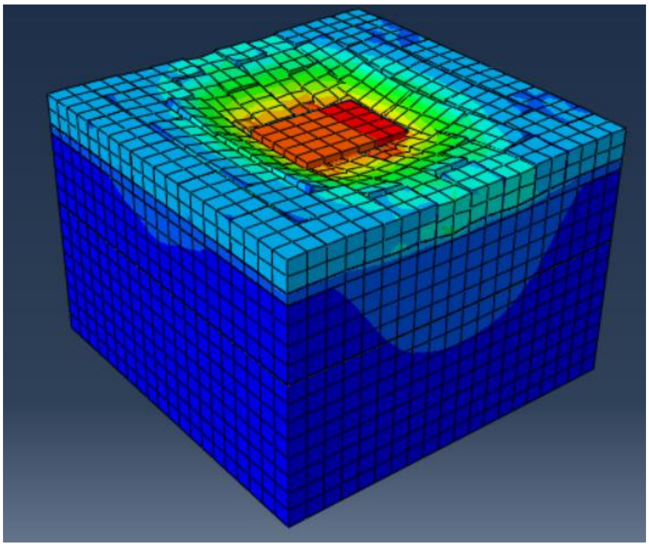

Figure 22: Vertical deflection of ABAQUS FEM for alternative 1 [128]

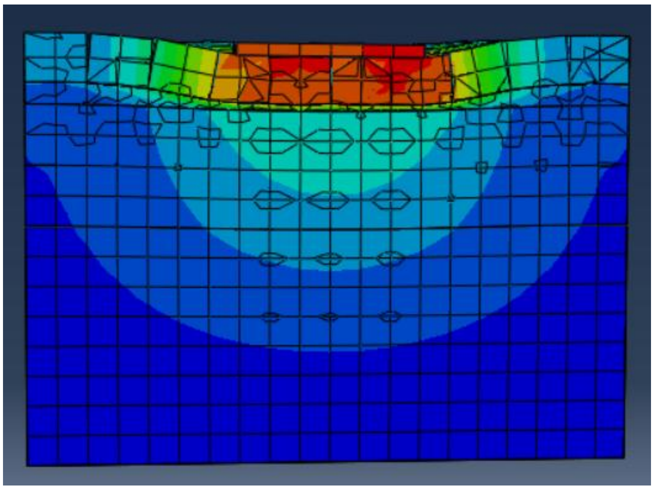

Figure 23: Vertical deflection at the centre cross-section of alternative 1 [128]

Similar efforts were made for all three alternatives, and the maximum values of vertical deflections were obtained and summarised as in Figure 24.

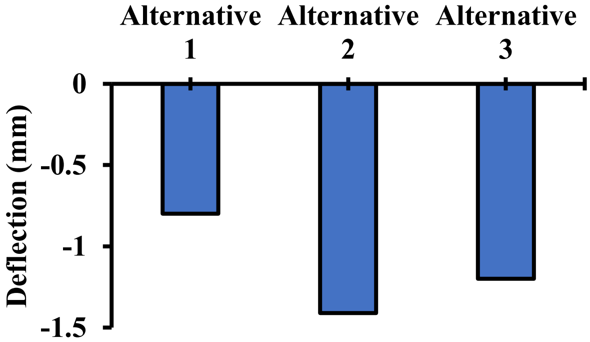

Figure 24: Maximum vertical deflection [128]

Alternative 1, which had the SLS-recommended paving block size, had the lowest vertical deflection of 0.8 mm. Alternatives 2 and 3 had vertical deflections of 1.4 mm and 1.2 mm, respectively, as per Figure 24. However, according to ICPI and IRC, all vertical deflections were acceptable, and there was no clear evidence to reject paving blocks with larger plan areas. The plan areas of the three alternatives were, respectively, 0.02 m^2, 0.06 m^2, and 0.0625 m^2. Alternatives 2 and 3 have a plan area increase of 200% and 212.5%, respectively, compared to alternative 1, where the deformations increased by 75% and 50%, respectively. In addition, when the plan area of a block is minimum, it implies that more blocks will be used to create the pavement, and more joints will be available, resulting in higher joint concentration and higher permeability.

Furthermore, paving blocks with extensive plan areas will have higher weights. Having blocks with higher weights may necessitate higher labour requirements during installation and can be a disadvantage in handling and installing the paving blocks.

Hence, the paving block with dimensions of alternative 1, which was recommended by SLS 1425, had lesser deformations, it will also be easy to install, and it maintained a higher joint concentration, leading to a higher permeability in the pavement. Hence, alternative 1 paving block dimensions were selected as the most appropriate block dimensions for this research study. This finite element analysis resultwere published at the 8th International Multidisciplinary Engineering Research Conference 2022 (MERCon 2022) [128]. (The published paper is attached in Annex 2)

4: EXPERIMENTAL PROCEDURE

The experimental procedure was divided into three sections. The first is to determine the aggregate properties, the second is to determine the optimum mix design, and the final is testing of proposed paving block alternatives, as detailed in sections 4.1 to 4.3, respectively.

4.1 Tests on aggregates

The following tests were conducted to identify the properties and determine the acceptability of glass waste aggregate as a replacement for fine aggregate to create the mix designs. The tests performed on aggregate were: sieve analysis, silt content test, SSD Specific gravity test, and water absorption test. These tests were also carried out on m-sand, which was used as the fine aggregate in the reference mix. Subsections 4.1.1 to 0 discuss the procedure and results of each test.

4.1.1 Sieve Analysis of aggregate

The gradation requirements were checked using sieve analysis of glass waste aggregate and m-sand. Initially, a sieve analysis of the entire glass waste aggregate was performed, where glass waste aggregate started to remain from 37.5 mm. However, because this study aimed to replace fine aggregate with glass waste aggregate, only particles passing through the 4.75 mm sieve were chosen, and a sieve analysis was performed using the sieve shaker, as shown in Figure 26, in accordance with BS 882. [109].

Figure 25 shows the results of the sieve analyses for glass waste aggregate and m-sand. Furthermore, according to the BS 882 standard, the glass waste aggregate showed a perfect gradation for fine aggregate, as in Figure 25.

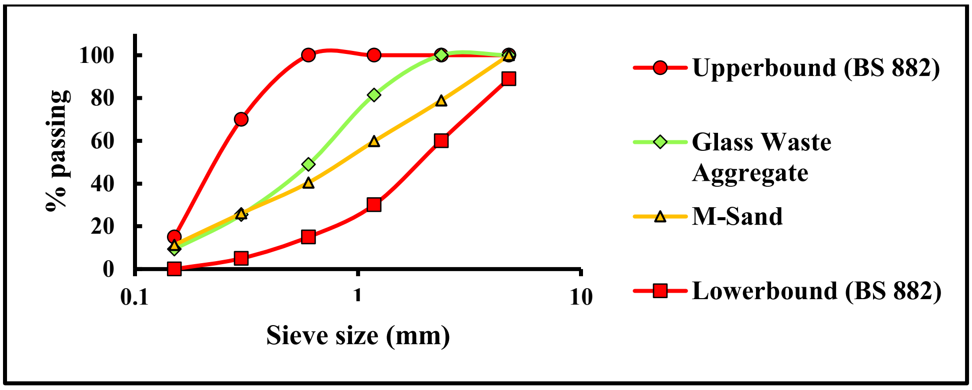

Figure 25: Sieve analysis of Fine aggregate

Figure 26: Sieve shaker used for the sieve analysis

4.1.2 Silt Content of aggregate

Since the glass waste aggregate contained a high concentration of impurities, the silt content of the aggregate was determined using the sedimentation method as specified in IS 2386-2. [111]. Figure 27 shows a photograph of the graduated cylinder after sedimentation. The volumes were measured, and the silt content was calculated as described in Equation 1. The silt content measurement and calculation results are shown in Table 8.

Equation 1: Methodology for calculating silt content of fine aggregate

The total volume of aggregate = V1

The volume of silt = V2

Silt content = (V2/V1) x 100%

Table 8: Calculation of silt content of fine aggregate

	Glass Waste Aggregate	**M-Sand**
Volume of aggregate	*88*	*74*
Volume of silt	*4*	*4*
Silt content of aggregate	*4.55%*	*5.4%*
Maximum Silt Content	***8%***	***8%***
Acceptability	*Acceptable*	*Acceptable*

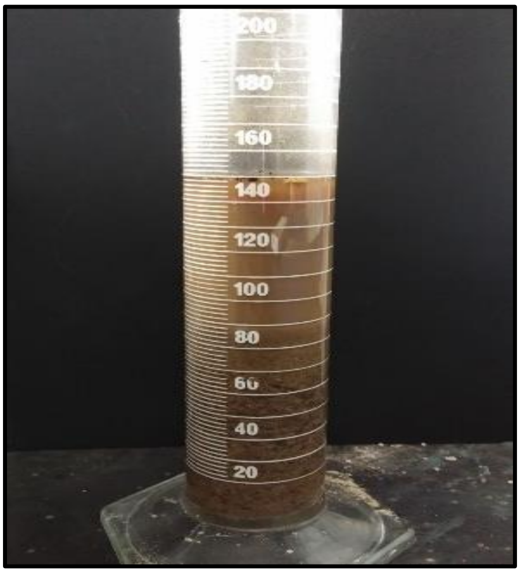

Figure 27: Photo of the graduated cylinder after sedimentation to calculate silt content

4.1.3 SSD Specific gravity of aggregate

The saturated surface dry (SSD) specific gravity of the glass waste aggregate was calculated using the AASHTO T-84 standard [132]. The SSD-specific gravity was calculated using measurements obtained with a scale and pycnometer, as shown in Figure 28, and the procedure is explained in Equation 2.

Equation 2: Methodology for calculating SSD specific gravity of fine aggregate

Weight of bottle filled with water without entrapped air = W1

Weight of aggregate = W2

Weight of bottle filled with water and aggregate without entrapped air = W3

*Specific gravity = (W2/(W1-(W3-W2))*Table 9 denotes the results and calculations for the SSD-specific gravity of glass waste aggregate and m-sand fine aggregate.

Table 9: Calculation of SSD-specific gravity of fine aggregate

	Glass Waste Aggregate	**M-Sand**
Weight of bottle filled with water without entrapped air (g)	*132.06*	*132.06*
Weight of aggregate (g)	*11*	*14*
Weight of bottle filled with water and aggregate (g)	*138.69*	*140.95*
Specific gravity	*2.52*	*2.74*

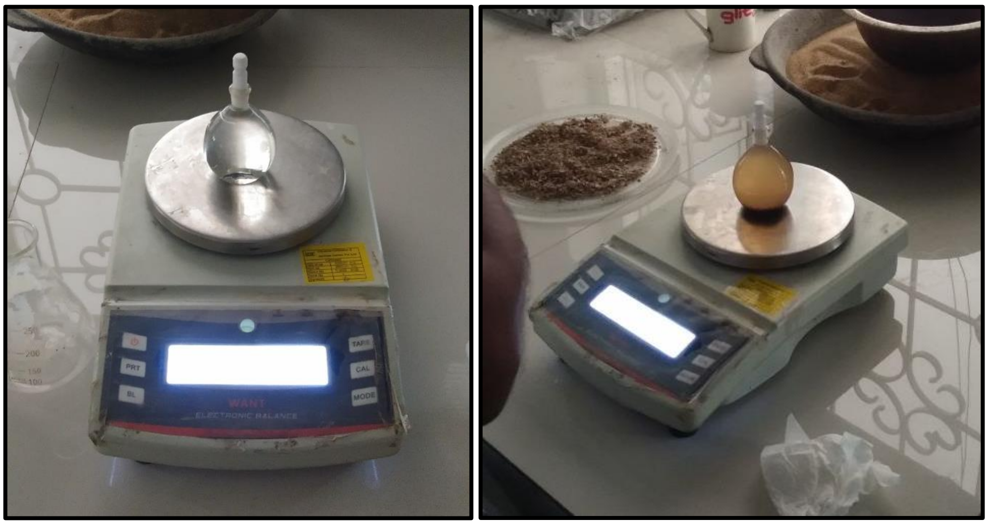

Figure 28: Pycnometer measurements obtained during the SSD specific gravity calculation

4.1.4 Water absorption of aggregate

The AASHTO T-84 standard was used to measure aggregate water absorption [132]. The water absorption was calculated after obtaining the weight difference in SSD aggregate and dry aggregate, as shown in Figure 29 and using the method described in Equation 3.

Equation 3: Methodology for calculating water absorption of fine aggregate

Weight of SSD aggregate = W1

Weight of dry aggregate = W2

Water absorption = (W1-W2/W2) x 100%

Table 10 shows measurements and results used in calculating the water absorption of glass waste aggregate and m-sand.

Table 10: Calculation of water absorption of fine aggregate

	Glass Waste Aggregate	M-Sand
Weight of SSD aggregate (g)	*142.2*	*148.3*
Weight of dry aggregate (g)	*140.56*	*148.68*
Weight of absorbed water (g)	*1.34*	*1.18*
Water absorption (%)	*0.95*	*0.8*

Figure 29: Measuring the weight of dry aggregate for water absorption calculation of aggregates

4.2 Optimum mix design

All mix designs were created in accordance with BS 5328 standard [109]. The procedure for determining the optimal mortar mix is summarised in Figure 30, and it is detailed later in subsections 4.2.1 to 4.2.7.

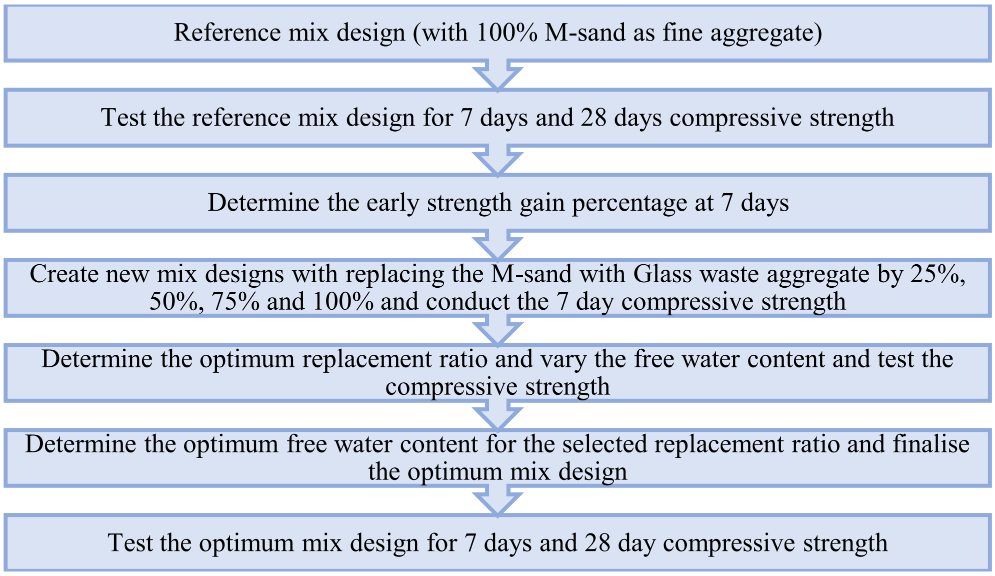

Figure 30: Methodology for determining the optimum mix

4.2.1 Design of the reference mix

Initially, a reference mix with a fine aggregate content of 40% of the total aggregate was created. For the reference mix, M-sand was used as the fine aggregate, and a 10 mm chip was used as the coarse aggregate. Since high concrete strength is desired, a water-reducing admixture called "Hypercrete HES" was used. The reference mix was designed in accordance with BS 5328, with the following mix proportions for 1 m^3 of concrete:

- Cement 540 kg
- Water 180 kg
- M sand 710.7 kg
- 10 mm chip aggregate 1072.4 kg
- Hypercrete HES water reducing admixture 7.2 kg

4.2.2 Testing of the reference mix for 7-day and 28-day compressive strength

This reference mix's compressive strength was tested after 7 and 28 days. Figure 31 depicts a box and whisker plot of the reference mix's compressive strength results after 7 and 28 days.

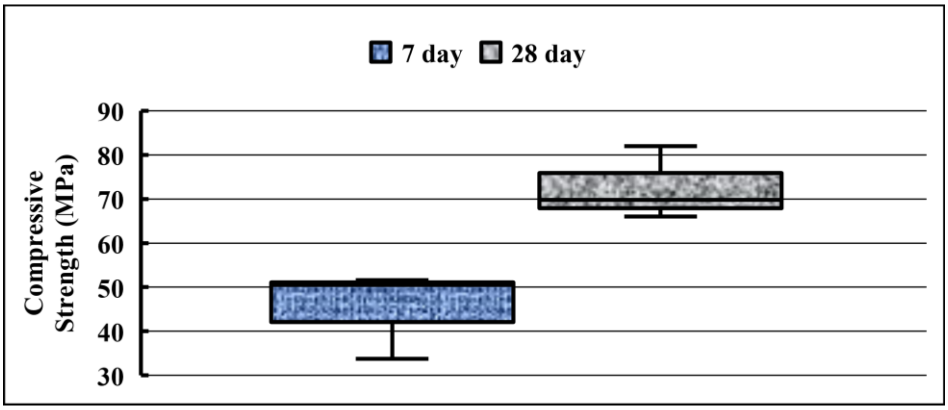

Figure 31: 7-day and 28-day compressive strengths of reference mix design

4.2.3 Relationship between 7-day and 28-day compressive strength gain

The above testing results were used to establish a relationship between the compressive strength gain at 7-days and 28-days because 7-day strength could be increased by introducing water-reducing admixtures from the conventional values [133]. Therefore, with the results obtained from Figure 31, the compressive strength gain at 7 days was calculated according to Equation 4.

Average 7-day compressive strength for reference mix = 45.25 MPa

Average 28-day compressive strength for reference mix = 64.8 MPa

Equation 4: Calculation of 7-day compressive strength gain

$$Compressive\ strength\ gain = \frac{7\ day\ compressive\ strength}{28\ day\ compressive\ strength}\ x\ 100\% = \frac{45.25\ MPa}{64.8\ MPa}\ x\ 100\% = 69.8\%$$

4.2.4 Replacement of fine aggregate with glass waste aggregate

Following that, the cement content, fine aggregate content, and water content of the mix design were held constant and m-sand was then replaced with glass waste aggregate, and paving blocks were cast and tested for 7-day compressive strength. Figure 32 shows box whisker plots for compressive strengths obtained after 7 days of replacing m-sand with glass waste aggregate by 25%, 50%, 75% and 100%.

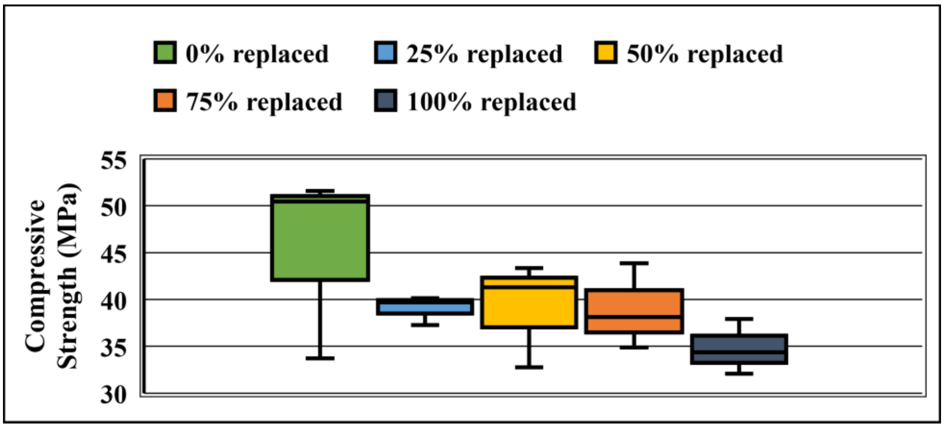

Figure 32: 7-day compressive strength of paving blocks after replacing fine aggregate with glass waste aggregate

According to Figure 32, replacing m-sand with glass waste aggregate resulted in an apparent reduction in compressive strength.

4.2.5 Determination of optimum fine aggregate replacement ratio with glass waste

The obtained relationship of 7-day and 28-day compressive strengths under Equation 4 predicted 28-day compressive strengths for each replacement ratio as shown in Table 11.

Table 11: Prediction of 28-day compressive strength with replacement of fine aggregate with glass waste

	Average 7-day compressive strength	Predicted 28-day compressive strength
0% replaced	*45.25*	*64.80*
25% replaced	*39.04*	*55.91*
50% replaced	*39.14*	*56.05*
75% replaced	*38.95*	*55.78*
100% replaced	*34.79*	*49.82*

The minimum compressive strength requirement for paving blocks is 50 MPa, according to the SLS 1425 standard. According to Table 11 results, the predicted 28-day compressive strengths for 0% to 75% replacement corresponded to values greater than 50 MPa. However, 100% replacement resulted in a slightly lower compressive strength of 49.82 MPa or nearly 50 MPa. Because the free water content of the mix influences the compressive strength of the final concrete [134], this reduction was ignored, and the 100% replacement ratio was chosen as the best replacement ratio.

4.2.6 Determining the optimum free water content for the selected replacement ratio and the optimum mix design

The free water content of the mixture primarily influences packing density, which in turn influences the compressive strength of the block [134]. As a result, mix designs for three free water contents were developed for the selected 100% replacement ratio: 180 kg/m^3, 200 kg/m^3, and 220 kg/m^3. Figure 33 depicts the results of the 7-day concrete strength of these three mixes.

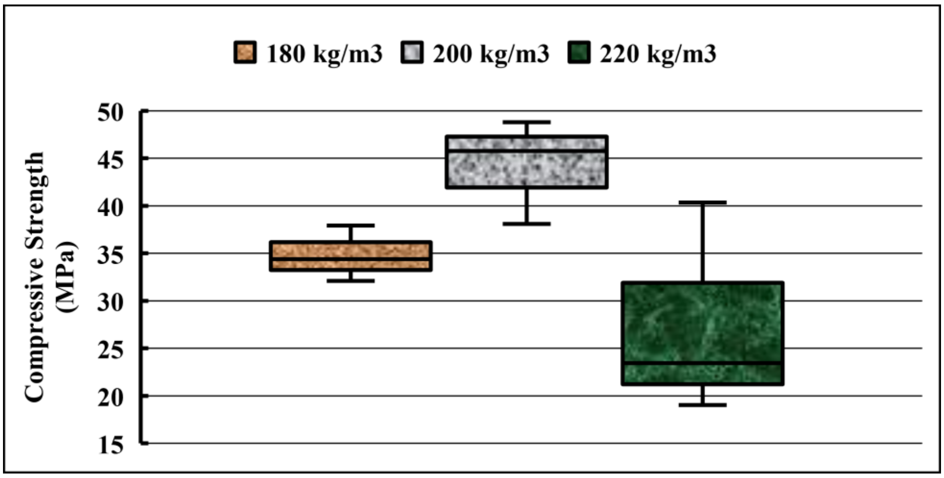

Figure 33: Variation of compressive strength with free water content

Figure 33 identifies a compressive strength peak at a free water content of 200 kg/m3 and a water-cement ratio of 0.37. As a result, the following mix design was chosen for use in the paving blocks. The ingredients used in a 1 m^3 concrete mix included:

- Cement 540 kg
- Water 200 kg
- Glass waste aggregate 651.6 kg
- 10 mm chip aggregate 984.7 kg
- Hypercrete HES water-reducing admixture 7.2 kg

4.2.7 Testing of the optimum mix design for 7-day and 28-day compressive strength

Ten paving blocks were cast with the above-mentioned optimum mix design, and the achieved compressive strengths at 7 and 28 days are shown in Figure 34's box-whisker plot.

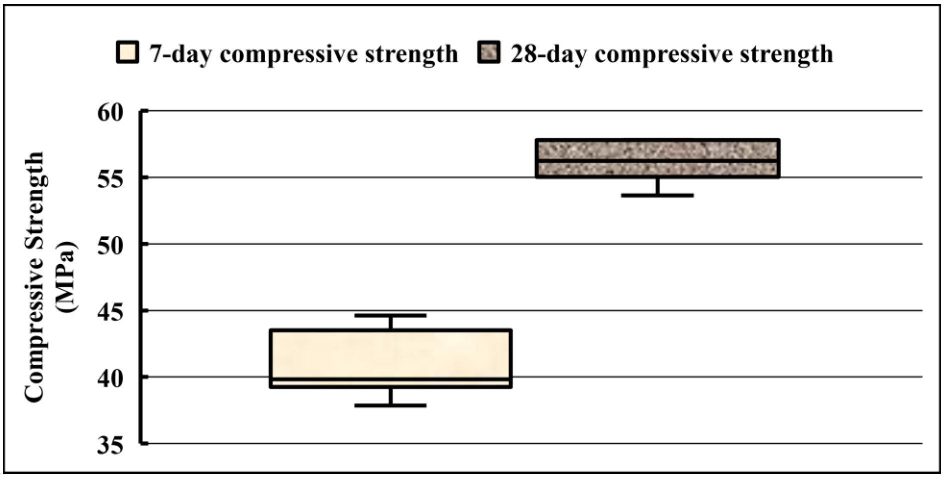

Figure 34: 7-day and 28-day compressive strengths of the final optimum mix design

4.3 Testing of the proposed paving block

Based on the final obtained optimum mortar mix, and because one of the other concerns of existing paving blocks was the limitation of aesthetic appearance, as seen in Figure 46, three top-layer alternatives were proposed to meet the requirement. The first alternative is a polished top surface with larger glass particles at the top to give a customised look (Figure 35). The second alternative is a polished top surface with several quartz particles introduced at the top (Figure 36), and the final alternative was to have a terracotta top for the block (Figure 37).

Figure 35:Proposed Alternative 1

Figure 36: Proposed Alternative 2

Figure 37: Proposed Alternative 3

Following the development of the paving block alternatives, the proposed blocks were tested in accordance with the SLS 1425 standard to ensure that they could be used in both pedestrian and vehicular pavements. Compression, slip and skid resistance, water absorption, and abrasion resistance were all tested. Sections 4.3.1 to 4.3.4 discuss the procedure and results of these tests.

Furthermore, commercially available paving blocks (Figure 46) were also purchased and tested in conjunction with the proposed alternative blocks in order to compare the results.

4.3.1 Compressive strength test on paving alternatives

According to Table 5, several compressive strength standards are used worldwide. However, this study uses SLS 1425 standard [103]. All blocks were tested using a compression testing machine that met BS EN 12390-4 standards (Figure 39), with a knot-free 4 mm plywood packing at the time of testing, as shown in Figure 38. All compressive strengths of blocks were calculated, and values were corrected using SLS 1425 Part II thickness and chamfer correction factors. Figure 40 depicts the compressive strength test results for the three alternatives and the market-available paving block.

Figure 38: 4mm plywood packing provided at the time of testing

Figure 39: Machine used for compression test on blocks

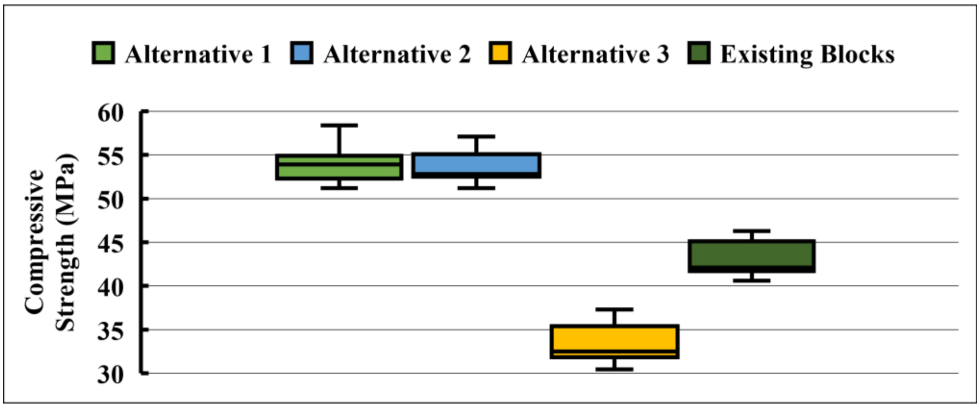

Figure 40: Compressive strength test results of alternatives

Figure 40 reveals that alternatives 1 and 2 have higher compressive strengths when compared to alternative 3 and the market's existing blocks. Furthermore, alternatives 1 and 2 met the SLS 1425 class 1 compressive strength requirements. Moreover, the lower compressive strength values in alternative 3 could be attributed to the addition of the terracotta layer, which has a low compressive strength. As a result, according to the standard, alternative 3 can only be classified as a paving block of class 3. Furthermore, the market paving blocks had compressive strengths in the range of 40 - 50 MPa, which falls under class 2.

4.3.2 Slip and skid resistance test on paving alternatives

Slip and Skid resistance was measured using an ASTM E303 Pendulum Friction Tester, as shown in Figure 41, and the results were compared to SLS 1425 standards. The standard required samples to have unique dimensions of 135 x 80 x 20 mm3, as shown in Figure 41. The rubber slider on the pendulum arm was dragged across the wetted specimen along a 126 mm contact length. The value at which the pointer rests on the test scale was used to determine the skid resistance value. It was recommended that the skid resistance value be greater than 55. The mean skid resistance test results for the three alternatives and the existing block are shown in Table 12.

Table 12: Test results of slip and skid resistance test for proposed alternative paving blocks

Item	Mean Skid Resistance Value
Alternative 1	*75*
Alternative 2	*75*
Alternative 3	*71*
Existing block	*75*

Table 12 shows that all three proposed block alternatives and the existing market block had slip and skid resistance values greater than 70, which is far greater than the standard of 55.

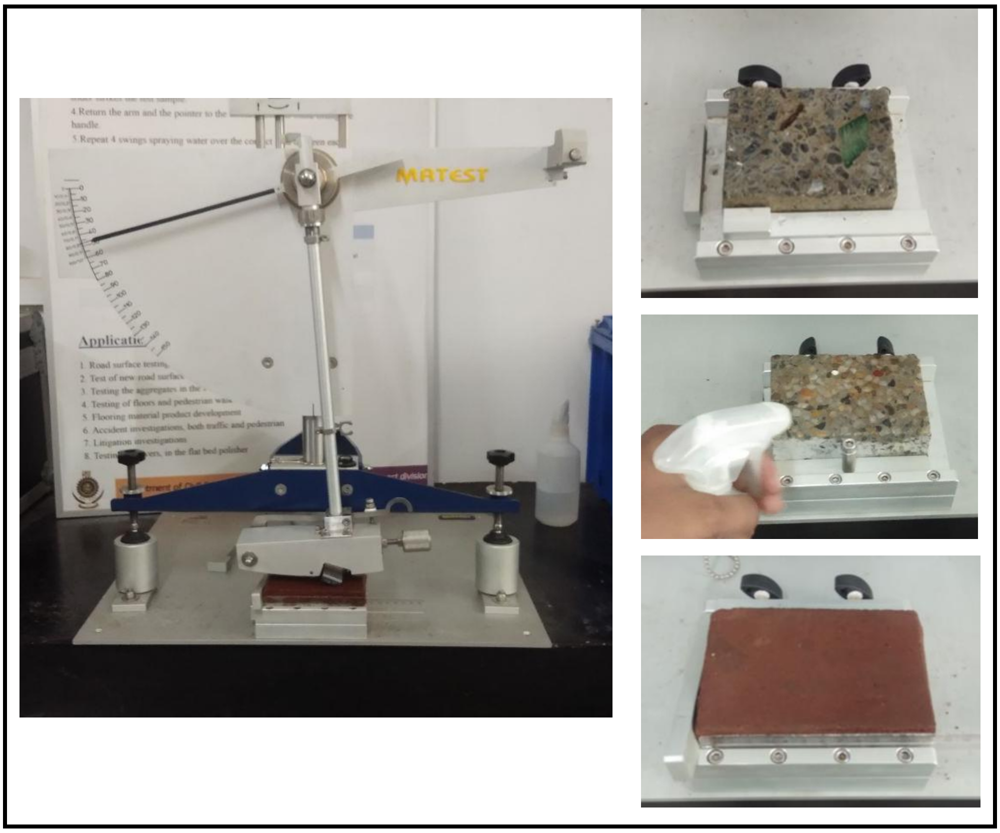

Figure 41: Pendulum Friction Tester with the test specimen used for slip and skid resistance test

4.3.3 Total water absorption test on paving alternatives

Paving block durability was evaluated by measuring total water absorption in accordance with the SLS 1425 Part II standard. First, the blocks were submerged in water for at least 3 days until they reached a constant weight (a mass difference of less than 0.1% over a 24-hour period), and then the specimen was dried inside an oven, as shown in Figure 43, and heated at a temperature of (105 ∓ 5 ℃) for at least 3 days until the mass difference for a 24h period became less than 0.1%. The given water absorption threshold is a maximum of 6%. Table 13 shows the mean results of the paving block alternatives, and Figure 42 shows the individual results of the water absorption test. Therefore, it was visible that all of the proposed paving blocks met the SLS 1425 durability requirements.

Table 13: Test results of water absorption test for proposed alternative paving blocks

Item	Mean Water Absorption (%)
Alternative 1	*1.18*
Alternative 2	*1.4*
Alternative 3	*2.37*
Existing block	*3*

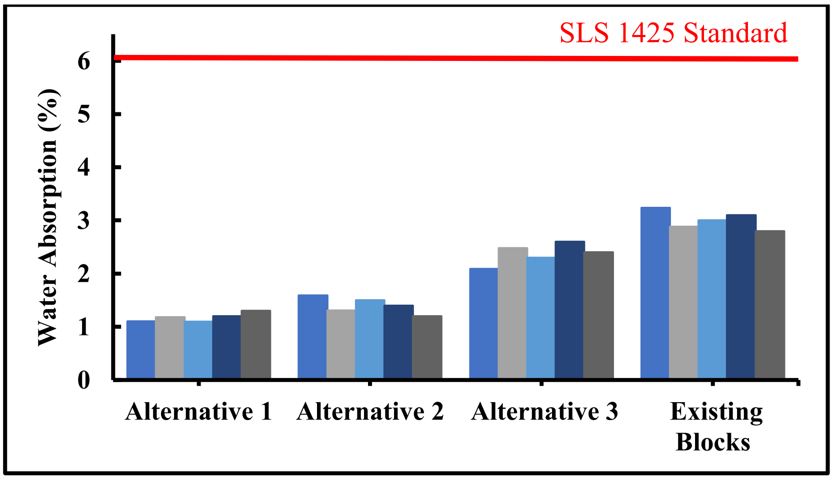

Figure 42: Water absorption test results of paving alternatives

4.3.4 Abrasion Resistance test on paving alternatives

The SLS 1425 recommended abrasion resistance measuring wearing machine with a wide abrasion wheel was unavailable in the country. As a result, an abrasion resistance test based on the ASTM C418 standard was performed. First, the paving blocks were sandblasted for 60 seconds at a distance of 75 ± 25 mm from the nozzle with the apparatus shown in Figure 44 and an air pressure of 410 kPa. The paver's lost volume was determined, and the abrasion coefficient was calculated with a standard threshold of 15 cm^3/cm^2. Figure 45 shows the mean abrasion coefficients for various alternatives. Equation 5 also denotes the method for calculating the abrasion coefficient.

Equation 5: Methodology for calculating the abrasion coefficient

Volume loss due to abrasion (cm^3) = V

Area of surface abraded (cm^2) = A

Abrasion coefficient = V/A

Figure 43: Oven used to conduct the water absorption of the paving alternatives

Figure 44 : Sandblasting apparatus

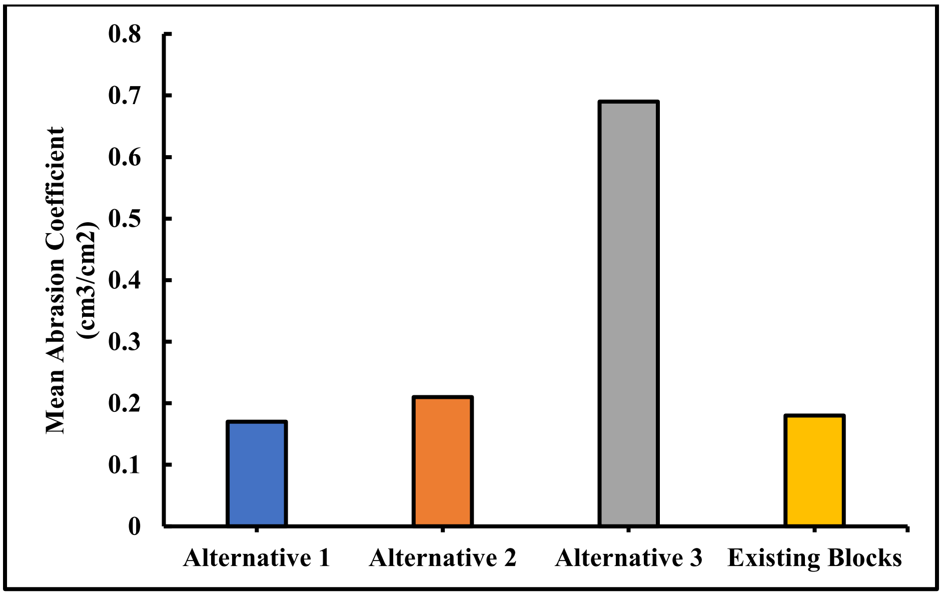

Figure 45: Abrasion test results of the alternatives

Figure 45 shows that alternatives 1, 2, and the existing blocks had roughly equal abrasion coefficients of around 0.2 cm^3/cm^2. However, the abrasion coefficient of alternative 3 was around 0.7 cm^3/cm^2. This increase in value was primarily due to the terracotta top layer, which abraded easily.

5: LIFE CYCLE COSTING ASSESSMENT (LCCA)

The proposed alternatives were subjected to a life cycle costing assessment (LCCA) to understand the associated costs thoroughly. According to Applied Research Associates in Virginia, pavement life cycle costs are the sum of the initial, maintenance, and rehabilitation costs minus residual value [135]. Furthermore, the literature suggests that the life cycle costing for interlocking concrete block pavement be carried out for 30 years [135]. As a result, each proposed alternative was subjected to a life cycle costing analysis for 30 years. Furthermore, an industrial paving block mix from the literature was selected [136], and a cost comparison was performed. The proposed alternatives' initial costs, maintenance costs, and residual values are described in subsections 5.1 to 5.3, and the life cycle costing assessment for 30 years is calculated in subsection 5.4.

5.1 Initial cost

The initial cost of the pavement includes all costs associated with its construction. Therefore, to calculate the total pavement cost, the mortar cost was first calculated using Table 14. Following that, the total initial unit cost of the proposed alternatives was calculated using Table 15. Finally, Table 16 calculated the initial costs for a one-kilometre stretch of proposed pavements.

Table 14: Unit cost calculation between proposed mix and industrial mix

Item	**Unit rate (LKR)**	**Proposed mix**		**Industry Mix**	
		Amount	**Cost**	**Amount**	**Cost**
Material Cost					
Cement (kg)	48.00	540.00	25920.00	1020.00	48960.00
Sand (kg)	8.29			1310.00	10858.09
Glass waste (kg)		651.60			
Coarse aggregate (kg)	5.26	984.70	5177.84	340.00	1787.82
Water (kg)	0.10	200.00	20.00	300.00	30.00
Admixture (kg)	750.00	7.20	5400.00		
Transportation cost					
Cement (kg)	0.5	540	270	1020	510.00
Sand (kg)	1.09			1310.00	1428.70
Glass waste (kg)	3.53	651.60	2302.47		
Coarse aggregate (kg)	1.05	984.70	1035.57	340.00	357.56
Total Cost per m^3		40125.9		63932.2	
No. of blocks per m^3		562.5		562.5	
Mortar cost per block (LKR)		**71.3**		**113.7**	
Mortar Cost reduction per block		**37%**		-	

The study found that using glass waste as a fine aggregate in the production of paving blocks can significantly reduce the cost of mortar. As shown in Table 14, using glass waste as a fine aggregate resulted in a cost savings of 37% compared to traditional aggregate materials. This significant cost savings demonstrate the potential economic benefits of incorporating glass waste into production. Furthermore, this waste material can reduce the negative environmental and health impacts associated with disposing of glass in landfills. Next, Table 15 calculates the final unit costs of the proposed alternatives after customization.

Table 15: Final unit cost per block for each proposed alternatives

Item	Unit rate (LKR)	Alternative 1		Alternative 2		Alternative 3		Existing block	
		Amount	Cost	Amount	Cost	Amount	Cost	Amount	Cost
Mortar cost per block (LKR)			71.3		71.3		53.50		113.7
Finishing Cost									
Quartz (m^3)	5.5			0.1	0.6				
Terracotta layer (Nos)	100					1	100		
Pigments (kg)	1000							0.01	10
Polishing machinery cost (Nos)	750	0.01	7.50	0.01	7.50				
Labour charge casting (Day)	3500	0.005	17.5	0.005	17.5	0.005	17.5	0.005	17.5
Labour charge polishing (Day)	3500	0.01	35	0.01	35				
Total unit cost per alternative (LKR)			**131.3**		**131.9**		**171.0**		**141.2**
Cost reduction			**7%**		**7%**		**-21%**		

According to Table 15 results, alternatives 1 and 2 were able to maintain its final costs below the costs of existing blocks, even after customization, to meet customer aesthetic satisfaction. Finally, the initial cost of a one-kilometre stretch of a 3.5-meter-wide single-lane road was calculated. Sand and base layer thicknesses of 25 mm and 150 mm were adopted from the literature [135]. The total initial cost for the proposed alternatives was then calculated using Table 16.

Table 16: Total Initial cost for proposed alternatives

Item	Quantity (1km)	Alternative 1		Alternative 2		Alternative 3		Existing block	
		Unit Rate LKR	Cost LKR (Mn)	Unit Rate LKR	Cost LKR (Mn)	Unit Rate LKR	Cost LKR (Mn)	Unit Rate LKR	Cost LKR (Mn)
Pavers	175000	171	29.871	171	29.996	222	38.903	184	32.123
Sand (m3)	87.5	22615	1.979	22615	1.979	22615	1.979	22615	1.979
Base (m3)	525	10601	5.565	10601	5.565	10601	5.565	10601	5.565
Total Initial Cost (LKR) (Mn)		**37.415**		**37.540**		**46.447**		**39.667**	
Cost Reduction		**6%**		**5%**		**-17%**			

According to the Table 16 results, Alternatives 1 and 2 had roughly equal initial pavement costs of 37.5 LKR Mn, while Alternative 3 had the highest initial cost at 46.5 LKR Mn and existing block pavement initial cost of 39.5 LKR Mn for a 1 km stretch.

5.2 Maintenance and rehabilitation cost

Maintenance and rehabilitation costs are factored into life cycle assessments to determine expected pavement performance and costs over the life of the pavement. For example, Table 17 depicts the maintenance and rehabilitation costs of interlocking pavement for a road with an average annual daily truck traffic (AADTT) of less than 250 (AADTT < 250) [135].

Table 17: Maintenance and rehabilitation plan of Interlocking concrete block pavements

Expected Year	Activity Description	Quantity replacement
10	*Replace Cracked Pavers*	*2%*
20	*Replace Worn/Rutted Pavers (wheel path)*	*5%*
30	*Replace Cracked Pavers*	*2%*
40	*Replace Worn/Rutted Pavers (wheel path)*	*5%*

[135]

As a result, the maintenance and rehabilitation costs for a design life of 30 years can be calculated, as shown in Table 18. Finally, these costs' Net Present Value (NPV) was also calculated for use in life cycle costing with a discount rate of 10%.

Table 18: Maintenance and rehabilitation costs for proposed alternatives up to 30 years

Item	**Quantity**	**Alternative 1**		**Alternative 2**		**Alternative 3**		**Existing block**	
		Unit Rate (LKR)	**Cost LKR (Mn)**	**Unit Rate (LKR)**	**Cost LKR (Mn)**	**Unit Rate (LKR)**	**Cost LKR (Mn)**	**Unit Rate (LKR)**	**Cost LKR (Mn)**
Replace cracked pavers (10 y)	3500	171	0.597	171	0.600	222	0.778	184	0.642
Replace rutted pavers (20 y)	8750	171	1.494	171	1.500	222	1.945	184	1.606
Replace cracked pavers (30 y)	3500	171	0.597	171	0.600	222	0.778	184	0.642
Total Maintenance and Rehabilitation Cost (LKR) (Mn)		**2.688**		**2.700**		**3.501**		**2.891**	
Total Maintenance and Rehabilitation NPV (LKR) (Mn)		**0.487**		**0.489**		**0.634**		**0.523**	

5.3 Residual Value

To ensure a fair comparison of alternatives, the LCCA must include the residual value of any unused rehabilitation activity at the end of the analysis period. The residual value is often calculated concerning the proposed life prediction method in life cycle assessment. Since the design life of these blocks are 30 years, the residual value of the initial blocks could be regarded as zero. However, the residual value was calculated for the rehabilitation work that hasn't fulfilled its design life. The residual value was calculated according to Equation 6.

Equation 6: Residual Value

$$Residual\ Value = Rehabilitation\ cost\ x\ \frac{(Design\ life - Activity\ age)}{Design\ life}$$

Afterwards, the residual values were discounted for the net present value with a discount rate of 10%, and the calculation of discounted residual values for proposed alternatives is shown in Table 19.

Table 19: Calculation of discounted residual values for proposed alternatives

Item	Alternative 1		Alternative 2		Alternative 3		Existing block	
	Residual Value (Mn)	NPV (Mn)	Residual Value (Mn)	NPV (Mn)	Residual Value (Mn)	NPV (Mn)	Residual Value (Mn)	NPV (Mn)
Replaced cracked pavers (10 y)	0.014	0.002	0.014	0.002	0.018	0.003	0.015	0.002
Replaced rutted pavers (20 y)	0.070	0.027	0.070	0.027	0.091	0.035	0.075	0.029
Replaced cracked pavers (30 y)	0.042	0.042	0.042	0.042	0.054	0.054	0.045	0.045
Total Residual NPV (LKR) (Mn)	**0.07**		**0.07**		**0.09**		**0.08**	

5.4 Life Cycle Costing Assessment (LCCA)

The life cycle costs for proposed alternatives were calculated using the formulae given in Equation 7 using the above-obtained initial costs, maintenance and rehabilitation costs, and residual values, and the results are shown in Table 20.

Equation 7: Life cycle costing

$$Life\ Cycle\ Costing = Initial\ Cost + M\ \&\ R\ Cost - Residual\ Value$$

Table 20: Life Cycle Costing of proposed alternatives

	Alternative 1	**Alternative 2**	**Alternative 3**	**Existing Blocks**
Total Initial Cost (LKR) (Mn)	37.415	37.540	46.447	39.667
Total Maintenance and Rehabilitation NPV (LKR) (Mn)	0.487	0.489	0.634	0.523
Total Residual NPV (LKR) (Mn)	0.07	0.07	0.09	0.08
Life Cycle Costing (LKR) (Mn)	**37.831**	**37.958**	**46.988**	**40.114**
Cost Reduction	**6%**	**5%**	**-17%**	**-**

Table 20 presents the results of a cost-benefit analysis comparing the life cycle costs of the proposed alternatives for paving blocks with existing blocks. The analysis shows that proposed alternatives 1 and 2 have comparable life cycle costs for a design life of 30 years. Furthermore, these alternatives reduce approximately 2 LKR Mn in life cycle costs for a 3.5 m wide, 1 km road compared to existing blocks. However, proposed alternative 3 has a higher life cycle cost, with a 17% increase over the pavement with existing blocks. Therefore, while alternatives 1 and 2 are cost-effective and sustainable solutions, alternative 3 is not as financially viable as the first two alternatives.

6: DISCUSSION AND SELECTION OF THE BEST ALTERNATIVE

According to the results of the tests on the glass waste, the waste product had a perfect gradation to be used as a fine aggregate, its silt content was less than the threshold, and its water absorption was less than the maximum. As a result, it was discovered to be a potential waste product capable of replacing fine aggregate in any concrete mortar mixture.

Following the detailed procedure described in subsection 4.2, it was determined that this glass waste product could be used as a one-to-one replacement for fine aggregate, and the optimum mix design was calculated. Following the selection of the best mix, three top-layer alternatives with a better appearance than existing paving blocks (Figure 46) were proposed.

Figure 46: Existing cobble-type paving blocks

Three alternatives were proposed to accommodate the aesthetic preferences of the customers. The SLS 1425 standard was used to evaluate the acceptability of paving for pedestrian and vehicular pavements for these three alternatives. The tests included compression, slip and skid resistance, abrasion resistance, and water absorption. Regarding compressive strength test results, alternatives 1 and 2 had the highest compressive strength, with an average compressive strength of around 55 MPa. Furthermore, the compressive strength of existing blocks averaged 43 MPa. However, alternative 3 had the lowest compressive strength due to the terracotta layer. As a result, according to the SLS 1425 standard, alternatives 1 and 2 satisfied class 1 compressive strength requirements, while alternative 3 only met class 3 compressive strength requirements.

Although the slip and skid resistance requirement was only 55, all three proposed alternatives resulted in values greater than 70. These values were nearly identical to the existing blocks' slip and skid resistance values, which yielded an average of 75. The threshold for water absorption was given as 6%. However, all three proposed alternatives resulted in lower water absorption values. The water absorption values of all three proposed alternatives were lower than those of the existing blocks, implying greater durability in the long run. In addition, alternatives 1 and 2 demonstrated the greatest durability in this test, with an average water absorption of 1%. The abrasion test revealed that alternative 1,2 had abrasion coefficients that were similar to the existing blocks, with a mean of around 0.2 cm^3/cm^2. Alternative 3 had a higher mean abrasion coefficient due to the easily abraded terracotta top layer.

According to the results of the life cycle costing assessment, it was possible to reduce the cost of mortar by 37% by replacing fine aggregate with glass waste, which is a significant benefit. Furthermore, despite the fact that these blocks were customised to have better aesthetic appearances, due to the savings in mortar cost, it was possible to finish some of these new customizations under the block's existing production cost. Compared to the final costs of existing blocks, alternatives 1 and 2 showed a 7% cost reduction for the final product, while alternative 3 showed a 17% cost increase. Alternative 3's cost mainly increased due to the terracotta tile. A summary of the above-conducted tests is indicated in the following Table 21. Where a colour code indicated in Figure 47 was used to compare with the existing paving blocks easily.

Table 21: Selection of the best alternative

	Alternative 1	Alternative 2	Alternative 3	Existing Blocks
Appearance				
Average Compressive strength (Mpa)	**54.16**	**53.74**	**33.49**	**43.16**
Average Slip and Skid Resistance	**75**	**75**	**71**	**75**
Average Water Absorption (%)	**1.18**	**1.4**	**2.37**	**3**
Mean abrasion coefficient (cm^3/cm^2)	**0.17**	**0.21**	**0.69**	**0.18**
Life cycle cost reduction (%)	**6**	**5**	**-17**	

Positive Improvement	**Similar Result**	**Negative Improvement**

Figure 47: Colour code used in Table 21

Finally, proposed alternatives 1 and 2 indicated potential paving blocks that could be manufactured at a lower cost than existing market blocks while maintaining a superior aesthetic appearance. These two alternatives outperformed the existing blocks in compressive strength, water absorption, cost, and aesthetic appearance while maintaining satisfactory slip, skid, and abrasion resistance, where alternative 1 indicated slight superiority when compared with alternative 2. Therefore, alternatives 1 and 2 can be recommended for production.

Despite being inferior to the existing blocks in some assessments and in terms of cost, Alternative 3 passed all SLS 1425 tests. Therefore it can be concluded as all three alternatives can be recommended for production. However, when it comes to compression strength, aesthetic appearance, durability, and cost, alternatives 1 and 2 outperform alternative 3 and the existing paving blocks.

Overall, all three proposed alternatives met the requirements of SLS 1425 standard and can be recommended for production. However, if the options were to be ranked, alternative 1 would be the best. Alternative 2 is the second option, followed by alternative 3.

7: CONCLUSION

A glass waste material that had been dumped for a long time was used to create a sustainable paving block with alternative top layers. First, the best paving block dimensions for cobble-type paving blocks were determined using finite element modelling, which concluded with 200 x 100 x 80 mm^3 being the best dimensions for cobble-type paving. The glass waste was then tested to determine its properties and characteristics in order to meet all of the requirements of fine aggregate. Using the methodology described in Section 4.2, the optimal mix of glass waste was determined. Glass waste was discovered to replace 100% of the fine aggregate while still meeting the minimum compressive strength requirement. Then, three alternatives with three top layers were developed to meet the customers' aesthetic satisfaction.

Alternatives 1 and 2 outperformed existing blocks in compressive strength and water absorption when tested in accordance with the SLS 1425 standard. Meanwhile, alternative 3 was inferior to existing blocks in terms of compressive strength and abrasion resistance. However, all three alternatives passed the SLS 1425 testing requirements and could be classified as suitable for use in pedestrian and vehicular pavements. All three alternatives and the existing blocks were subjected to a life cycle cost analysis. It was found that a 37% cost reduction was probable when the fine aggregate was replaced with glass waste. Moreover, Alternatives 1 and 2 were discovered to be the most cost-effective of the options as they indicated around a 5% cost reduction after customization compared to existing blocks. Therefore, alternatives 1 and 2 were chosen as the more appealing alternatives.

In summary, this study introduced a potential fine aggregate waste product that had not been dumped for many years and used it to create a sustainable smart paving block that met all necessary standards and outperformed the market's existing blocks.

Reference List

[1] A. Tirpak, R. J. Winston, M. Feliciano, and J. D. Dorsey, ‘Stormwater quality performance of permeable interlocking concrete pavement receiving run-on from an asphalt traffic lane in a cold climate’, *Environ Sci Pollut Res Int*, vol. 27, no. 17, pp. 21716–21732, Jun. 2020, doi: 10.1007/S11356-020-08707-2.

[2] J. Mullaney and T. Lucke, ‘Practical Review of Pervious Pavement Designs’, *Clean (Weinh)*, vol. 42, no. 2, pp. 111–124, Feb. 2014, doi: 10.1002/CLEN.201300118.

[3] A. Mahmoodi, Z. Jiryaei, A. Dadras, M. Khorasani, and X. Shi, ‘A hybrid yellow nanopigment as an environmentally sound alternative to lead chromate pigment for pavement markings’, *J Clean Prod*, vol. 319, p. 128733, Oct. 2021, doi: 10.1016/J.JCLEPRO.2021.128733.

[4] H. S. Lee, J. Y. Lee, and M. Y. Yu, ‘Influence of iron oxide pigments on the properties of concrete interlocking blocks’, *Cem Concr Res*, vol. 33, no. 11, pp. 1889–1896, Nov. 2003, doi: 10.1016/S0008-8846(03)00209-6.

[5] D. A. Randolph, K. Rajendra, and D. W. Starr, ‘Decorative Concrete Block Pavements’, *J Transp Eng*, vol. 114, no. 4, pp. 409–419, Jul. 1988, doi: 10.1061/(ASCE)0733-947X(1988)114:4(409).

[6] Mr. M. Vimalanathan, ‘Interlocking Pavers Using Waste Kadapa Stone’, *Int J Res Appl Sci Eng Technol*, vol. 6, no. 3, pp. 1197–1200, Mar. 2018, doi: 10.22214/IJRASET.2018.3188.

[7] E. Bernardo, L. Esposito, E. Rambaldi, A. Tucci, and S. Hreglich, ‘Recycle of Waste Glass into “Glass–Ceramic Stoneware”’, *Journal of the American Ceramic Society*, vol. 91, no. 7, pp. 2156–2162, Jul. 2008, doi: 10.1111/J.1551-2916.2008.02460.X.

[8] I. Demir, 'Reuse of waste glass in building brick production', *https://doi.org/10.1177/0734242X08096528*, vol. 27, no. 6, pp. 572–577, May 2009, doi: 10.1177/0734242X08096528.

[9] M. N. N. Khan, A. K. Saha, and P. K. Sarker, 'Reuse of waste glass as a supplementary binder and aggregate for sustainable cement-based construction materials: A review', *Journal of Building Engineering*, vol. 28, p. 101052, Mar. 2020, doi: 10.1016/J.JOBE.2019.101052.

[10] J. H. Butler and P. D. Hooper, 'Glass Waste', *Waste: A Handbook for Management*, pp. 307–322, Jan. 2019, doi: 10.1016/B978-0-12-815060-3.00015-3.

[11] Eckbo. Garrett, *Urban landscape design*. McGraw-Hill, 1964.

[12] S. A. Olayinka, O. S. Adekunle, and H. A. Musa, 'Exploring the Effect of Landscaping on Property Value in Meeting the Contemporary Sub-Sahara Environment', *Env. Design & Construction Mgt. (JECM-4)*, vol. 18, no. 4, Oct. 2020.

[13] L. M. Anderson and H. K. Cordell, 'Residential Property Values Improved by Landscaping with Trees', *Southern Journal of Applied Forestry*, vol. 9, no. 3, pp. 162–166, Aug. 1985, doi: 10.1093/SJAF/9.3.162.

[14] M. R. Pawsey, 'Providing Campus Environmental Coherence by Landscaping.', *Planning for Higher Education*, vol. 11, no. 1, pp. 25–29, 1982.

[15] S. Bretz, H. Akbari, and A. Rosenfeld, 'Practical issues for using solar-reflective materials to mitigate urban heat islands', *Atmos Environ*, vol. 32, no. 1, pp. 95–101, Jan. 1998, doi: 10.1016/S1352-2310(97)00182-9.

[16] C. Kusumastuti, H. P. Chandra, K. Wibisono, and A. C. Hartono, ‘Eco Drainage System for Surface Runoff Reduction in Indonesia’, *Civil Engineering Dimension*, vol. 21, no. 1, pp. 29–35, 2019, doi: 10.9744/CED.21.1.29-35.

[17] D. A. Alexander, ‘The environmental importance of front gardens’, *http://dx.doi.org/10.1680/muen.2006.159.4.239*, vol. 159, no. 4, pp. 239–244, May 2015, doi: 10.1680/MUEN.2006.159.4.239.

[18] H. Low and T. Heyden, ‘The decline of the British front garden - BBC News’, *BBC News Magazine*, May 15, 2015. Accessed: Sep. 21, 2021. [Online]. Available: https://www.bbc.com/news/magazine-32780242

[19] J. Harvey, A. Saboori, M. Dauvergne, W. Steyn, A. Jullien, and H. Li, ‘COMPARISON OF NEW PAVEMENT CONSTRUCTION GHG AND ENERGY IMPACTS IN DIFFERENT REGIONS’, 2014.

[20] D. A. Kelly, ‘Impact of paved front gardens on current and future urban flooding’, *J Flood Risk Manag*, vol. 11, pp. S434–S443, Jan. 2018, doi: 10.1111/JFR3.12231.

[21] J. G. Lee and J. P. Heaney, ‘Estimation of Urban Imperviousness and its Impacts on Storm Water Systems’, *J Water Resour Plan Manag*, vol. 129, no. 5, pp. 419–426, Sep. 2003, doi: 10.1061/(ASCE)0733-9496(2003)129:5(419).

[22] P. Willems, K. Arnbjerg-Nielsen, J. Olsson, and V. T. V. Nguyen, ‘Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings’, *Atmos Res*, vol. 103, pp. 106–118, Jan. 2012, doi: 10.1016/J.ATMOSRES.2011.04.003.

[23] J. M. Murphy, D. M. H. Sexton, G. J. Jenkins, and B. B. B. Booth, ‘UK Climate Projections Science Report: Climate Change Projections’, 2009. Accessed: Sep. 21, 2021. [Online]. Available:

https://www.researchgate.net/publication/313212734_UK_Climate_Projections_Science_Report_Climate_Change_Projections

[24] M. Sanderson, 'Changes in the frequency of extreme rainfall events for selected towns and cities', 2010.

[25] A. Mohajerani, J. Bakaric, and T. Jeffrey-Bailey, 'The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete', *J Environ Manage*, vol. 197, pp. 522–538, Jul. 2017, doi: 10.1016/J.JENVMAN.2017.03.095.

[26] H. Akbari and L. S. Rose, 'Urban Surfaces and Heat Island Mitigation Potentials', *J Hum Environ Syst*, vol. 11, no. 2, pp. 85–101, Dec. 2008, doi: 10.1618/JHES.11.85.

[27] J. Yang, Z. H. Wang, and K. E. Kaloush, 'Environmental impacts of reflective materials: Is high albedo a "silver bullet" for mitigating urban heat island?', *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 830–843, Jul. 2015, doi: 10.1016/J.RSER.2015.03.092.

[28] S. Grimmond, 'Urbanization and global environmental change: local effects of urban warming', *Geographical Journal*, vol. 173, no. 1, pp. 83–88, Mar. 2007, doi: 10.1111/J.1475-4959.2007.232_3.X.

[29] T. Ichinose, F. Matsumoto, and K. Kataoka, 'Counteracting Urban Heat Islands in Japan', *Urban Energy Transition*, pp. 365–380, Jan. 2008, doi: 10.1016/B978-0-08-045341-5.00015-3.

[30] A. Synnefa, T. Karlessi, N. Gaitani, M. Santamouris, D. N. Assimakopoulos, and C. Papakatsikas, 'Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate', *Build Environ*, vol. 46, no. 1, pp. 38–44, Jan. 2011, doi: 10.1016/J.BUILDENV.2010.06.014.

[31] J. Yang *et al.*, ‘Characteristics of indoor air quality at urban elementary schools in Seoul, Korea: Assessment of effect of surrounding environments’, *Atmos Pollut Res*, vol. 6, no. 6, pp. 1113–1122, Nov. 2015, doi: 10.1016/j.apr.2015.06.009.

[32] S. W. Goh and Z. You, ‘Mechanical Properties of Porous Asphalt Pavement Materials with Warm Mix Asphalt and RAP’, 2012, doi: 10.1061/(ASCE)TE.

[33] EA. Dreelin, L. Fowler, and C. R. . Carroll, ‘A test of porous pavement effectiveness on clay soils during natural storm events’, *Water Res*, vol. 40, no. 4, pp. 799–805, 2006, doi: 10.1016/J.WATRES.2005.12.002.

[34] C. Sangiorgi *et al.*, ‘A complete laboratory assessment of crumb rubber porous asphalt’, *Constr Build Mater*, vol. 132, pp. 500–507, Feb. 2017, doi: 10.1016/J.CONBUILDMAT.2016.12.016.

[35] T. Cahill, M. Adams, and C. Marm, ‘POROUS ASPHALT : THE RIGHT CHOICE FOR POROUS PAVEMENTS’, *HMAT: Hot Mix Asphalt Technology*, vol. 8, no. 5, Sep. 2003.

[36] M. Hossain and L. A. Scofield, ‘Porous pavement for control of highway run-off’, no. FHWA/AZ91-352, Jul. 1991.

[37] K. Younger, R. G. Hicks, and J. Gower, ‘EVALUATION OF POROUS PAVEMENTS USED IN OREGON. FINAL REPORT. VOLUME II - APPENDICES’, Dec. 1994.

[38] J. S. Chen, C. H. Yang, and C. te Lee, ‘Field evaluation of porous asphalt course for life-cycle cost analysis’, *Constr Build Mater*, vol. 221, pp. 20–26, Oct. 2019, doi: 10.1016/J.CONBUILDMAT.2019.06.072.

[39] J. C. Nicholls and I. G. Carswell, 'THE DESIGN OF POROUS ASPHALT MIXTURES TO PERFORMANCE-RELATED CRITERIA', *TRL REPORT 497*, 2001.

[40] Y. Yildirim, T. Dossey, K. W. Fults, and M. Trevino, 'Winter Maintenance Issues Associated with New Generation Open-Graded Friction Courses', Aug. 2006.

[41] M. Backstrom, 'Ground temperature in porous pavement during freezing and thawing', *J Transp Eng*, vol. 126, no. 5, pp. 375–381, Sep. 2000, doi: 10.1061/(ASCE)0733-947X(2000)126:5(375).

[42] T. Iserning, H. Koster, and I. Scazzrca, 'Experiences with Porous Asphalt in Switzerland', *Transp Res Rec*, vol. Transporta, no. 1265, 1990.

[43] M. Wanielista, M. Chopra, J. Spence, and C. Ballock, 'Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit', 2007.

[44] M.-G. Lee, M. Tia, S.-H. Chuang, Y. Huang, and C.-L. Chiang, 'Pollution and Purification Study of the Pervious Concrete Pavement Material', *Journal of Materials in Civil Engineering*, vol. 26, no. 8, p. 04014035, Aug. 2013, doi: 10.1061/(ASCE)MT.1943-5533.0000916.

[45] E. Gomez-Ullate, E. Castillo-Lopez, D. Castro-Fresno, and J. R. Bayon, 'Analysis and Contrast of Different Pervious Pavements for Management of Storm-Water in a Parking Area in Northern Spain', *Water Resources Management 2010 25:6*, vol. 25, no. 6, pp. 1525–1535, Dec. 2010, doi: 10.1007/S11269-010-9758-X.

[46] N. Xie, M. Akin, and X. Shi, 'Permeable concrete pavements: A review of environmental benefits and durability', *J Clean Prod*, vol. 210, pp. 1605–1621, Feb. 2019, doi: 10.1016/J.JCLEPRO.2018.11.134.

[47] P. T. Weiss, M. Kayhanian, J. S. Gulliver, and L. Khazanovich, 'Permeable pavement in northern North American urban areas: research review and knowledge gaps', *https://doi.org/10.1080/10298436.2017.1279482*, vol. 20, no. 2, pp. 143–162, Feb. 2017, doi: 10.1080/10298436.2017.1279482.

[48] V. Schaefer, K. Wang, M. Suleiman, and J. Kevern, 'MIX DESIGN DEVELOPMENT FOR PERVIOUS CONCRETE IN COLD WEATHER CLIMATES', Feb. 2006. Accessed: Sep. 22, 2021. [Online]. Available: https://www.perviouspavement.org/downloads/Iowa.pdf

[49] G. M. Kim, J. G. Jang, H. R. Khalid, and H. K. Lee, 'Water purification characteristics of pervious concrete fabricated with CSA cement and bottom ash aggregates', *Constr Build Mater*, vol. 136, pp. 1–8, Apr. 2017, doi: 10.1016/J.CONBUILDMAT.2017.01.020.

[50] R. R. Holmes, M. L. Hart, and J. T. Kevern, 'Enhancing the Ability of Pervious Concrete to Remove Heavy Metals from Stormwater', *J Sustain Water Built Environ*, vol. 3, no. 2, p. 04017004, Feb. 2017, doi: 10.1061/JSWBAY.0000823.

[51] G. N. McCain and M. Suozzo, 'A Laboratory Study on the Effects of Winter Surface Applications on the Hydraulic 1 Conductivity of Porous Concrete Pavements 2 3', *undefined*, 2010.

[52] A. K. Chandrappa and K. P. Biligiri, 'Pervious concrete as a sustainable pavement material-Research findings and future prospects: A state-of-the-art review', *Constr Build Mater*, vol. 111, pp. 262–274, May 2016, doi: 10.1016/J.CONBUILDMAT.2016.02.054.

[53] E. K. Anastasiou, A. Liapis, and M. Papachristoforou, 'Life Cycle Assessment of Concrete Products for Special Applications Containing

EAF Slag', *Procedia Environ Sci*, vol. 38, pp. 469–476, Jan. 2017, doi: 10.1016/J.PROENV.2017.03.138.

[54] G. N. McCain Jr and M. M. Dewoolkar, 'Effects of Winter Surface Applications on Hydraulic Conductivity of Porous Concrete Pavements', 2010.

[55] A. Kia, H. Wong, and C. Cheeseman, 'Clogging in permeable concrete: A review', *J Environ Manage*, vol. 193, pp. 221–233, May 2017, doi: 10.1016/J.JENVMAN.2017.02.018.

[56] T. Lucke and S. Beecham, 'Field investigation of clogging in a permeable pavement system', *http://dx.doi.org/10.1080/09613218.2011.602182*, vol. 39, no. 6, pp. 603–615, 2011, doi: 10.1080/09613218.2011.602182.

[57] W. F. Hunt and K. A. Collins, 'Permeable Pavement: Research Update and Design Implications', *NORTH CAROLINA COOPERATIVE EXTENSION SERVICE*, 2008, Accessed: Sep. 23, 2021. [Online]. Available: https://nacto.org/docs/usdg/urban_waterways_permeable_pavement_hunt.pdf

[58] M. Scholz and P. Grabowiecki, 'Review of permeable pavement systems', *Build Environ*, vol. 42, no. 11, pp. 3830–3836, Nov. 2007, doi: 10.1016/J.BUILDENV.2006.11.016.

[59] T. Puehmeier and A. P. Newman, 'Oil Retaining and Treating Geotextile for Pavement Applications', 2008.

[60] C. Udawattha, H. Galabada, and R. Halwatura, 'Mud concrete paving block for pedestrian pavements', *Case Studies in Construction Materials*, vol. 7, pp. 249–262, Dec. 2017, doi: 10.1016/J.CSCM.2017.08.005.

[61] A. Kumar and S. Kumar, 'Development of paving blocks from synergistic use of red mud and fly ash using geopolymerization', *Constr Build Mater*, vol. 38, pp. 865–871, Jan. 2013, doi: 10.1016/J.CONBUILDMAT.2012.09.013.

[62] C. S. G. Penteado, E. Viviani De Carvalho, and R. C. C. Lintz, 'Reusing ceramic tile polishing waste in paving block manufacturing', *J Clean Prod*, vol. 112, pp. 514–520, Jan. 2016, doi: 10.1016/J.JCLEPRO.2015.06.142.

[63] E. Ganjian, G. Jalull, and H. Sadeghi-Pouya, 'Using waste materials and by-products to produce concrete paving blocks', *Constr Build Mater*, vol. 77, pp. 270–275, Feb. 2015, doi: 10.1016/J.CONBUILDMAT.2014.12.048.

[64] X. Wang, C. S. Chin, and J. Xia, 'Material Characterization for Sustainable Concrete Paving Blocks', *Applied Sciences 2019, Vol. 9, Page 1197*, vol. 9, no. 6, p. 1197, Mar. 2019, doi: 10.3390/APP9061197.

[65] M. Rachmat and T. N. Salsabilla, 'Analysis of hexagonal paving block as a better paving shape', *IOP Conf Ser Mater Sci Eng*, vol. 527, no. 1, p. 012068, May 2019, doi: 10.1088/1757-899X/527/1/012068.

[66] H. S. Lee, J. Y. Lee, and M. Y. Yu, 'Influence of iron oxide pigments on the properties of concrete interlocking blocks', *Cem Concr Res*, vol. 33, no. 11, pp. 1889–1896, Nov. 2003, doi: 10.1016/S0008-8846(03)00209-6.

[67] E. Boonen and S. Smets, 'High-quality materials for road paving of natural stone: results of the PREMANAT research project', *OCW mededelingen = Bulletin CRR*, no. 120, Sep. 2019.

[68] S. A. Tan and T. F. Fwa, ‘Influence of pavement materials on the thermal environment of outdoor spaces’, *Build Environ*, vol. 27, no. 3, pp. 289–295, Jul. 1992, doi: 10.1016/0360-1323(92)90030-S.

[69] I. Karlsson, J. Rootzén, and F. Johnsson, ‘Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project’, *Renewable and Sustainable Energy Reviews*, vol. 120, p. 109651, Mar. 2020, doi: 10.1016/J.RSER.2019.109651.

[70] F. Shi, T. Huang, H. Tanikawa, J. Han, S. Hashimoto, and Y. Moriguchi, ‘Toward a Low Carbon–Dematerialization Society’, *J Ind Ecol*, vol. 16, no. 4, pp. 493–505, Aug. 2012, doi: 10.1111/J.1530-9290.2012.00523.X.

[71] Hammond Geoffrey and Jones Craig, *The Inventory of Carbon and Energy (ICE)*. BSRIA, 2011. Accessed: Sep. 07, 2022. [Online]. Available: https://ghgprotocol.org/Third-Party-Databases/Bath-ICE

[72] U. G. Y. Abeysundara and S. Babel, ‘A quest for sustainable materials for building elements in Sri Lanka: Foundations’, *Environ Prog Sustain Energy*, vol. 29, no. 3, pp. 370–381, Oct. 2010, doi: 10.1002/EP.10420.

[73] GrassPave, ‘GrassPave | Grass Paver | Permeable Grass Surface | ACF Env.’, 2021. https://acfenvironmental.com/products/stormwater-management/permeable-porous-paving/grasspave2-grass-paver/ (accessed Sep. 30, 2021).

[74] K. A. Collins, W. F. Hunt, and J. M. Hathaway, ‘Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina’, *J Hydrol Eng*, vol. 13, no. 12, pp. 1146–1157, Dec. 2008, doi: 10.1061/(ASCE)1084-0699(2008)13:12(1146).

[75] B. Hunt, S. Stevens, and D. Mayes, 'Permeable Pavement Use and Research at Two Sites in Eastern North Carolina', *Global Solutions for Urban Drainage*, pp. 1–10, 2002, doi: 10.1061/40644(2002)39.

[76] N. Jayasuriya and N. Kadurupokune, 'Comparative performance of permeable and porous Pavements', 2010.

[77] F. Straet, E. Beckers, and A. Degre, 'Hydraulic behaviour of greened porous pavements: a physical study TERRA-multiscale soil systems View project GISER Gestion Intégrée sol érosion Ruissellement View project', 2008.

[78] C. J. Pratt, J. D. G. Mantle, and P. A. Schofield, 'UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality', *Water Science and Technology*, vol. 32, no. 1, pp. 63–69, Jan. 1995, doi: 10.1016/0273-1223(95)00539-Y.

[79] C. J. Pratt, 'Design Guidelines for Porous/Permeable pavements', in *Sustaining Urban water resources in the 21st century*, 1997.

[80] J. K. Gilbert and J. C. Clausen, 'Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut', *Water Res*, vol. 40, no. 4, pp. 826–832, Feb. 2006, doi: 10.1016/J.WATRES.2005.12.006.

[81] K. Rankin and J. E. Ball, 'A Review of the Performance of Permeable Pavers', 2004.

[82] E. A. Fassman and S. Blackbourne, 'Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils', *J Hydrol Eng*, vol. 15, no. 6, pp. 475–485, Mar. 2010, doi: 10.1061/(ASCE)HE.1943-5584.0000238.

[83] S. Borgwardt, 'LONG-TERM IN-SITU INFILTRATION PERFORMANCE OF PERMEABLE CONCRETE BLOCK PAVEMENT', 2006.

[84] C. F. Yong, A. Deletic, T. D. Fletcher, and M. Grace, 'The clogging behaviour and treatment efficiency of a range of porous pavements', in *11 th International Conference on Urban Drainage, Edinburgh, Scotland, UK*, 2008. Accessed: Sep. 27, 2021. [Online]. Available: https://www.academia.edu/49829885/The_clogging_behaviour_and_treatment_efficiency_of_a_range_of_porous_pavements

[85] N. González-Angullo, D. Castro, J. Rodríguez-Hernández, and J. W. Davies, 'Runoff infiltration to permeable paving in clogged conditions', *Urban Water J*, vol. 5, no. 2, pp. 117–124, Jun. 2008, doi: 10.1080/15730620701723538.

[86] M. Kayhanian, D. Anderson, J. T. Harvey, D. Jones, and B. Muhunthan, 'Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots', *J Environ Manage*, vol. 95, no. 1, pp. 114–123, Mar. 2012, doi: 10.1016/J.JENVMAN.2011.09.021.

[87] K. Sehgal, J. Drake, T. van Seters, and W. K. vander Linden, 'Improving Restorative Maintenance Practices for Mature Permeable Interlocking Concrete Pavements', *Water 2018, Vol. 10, Page 1588*, vol. 10, no. 11, p. 1588, Nov. 2018, doi: 10.3390/W10111588.

[88] C. Pratt, 'Permeable pavements for stormwater quality enhancement', *cedb.asce.org*, 1990.

[89] V. Colandini, M. Legret, Y. Brosseaud, and J.-D. Baladès, 'Metallic pollution in clogging materials of urban porous pavements', *Elsevier*, 1995, Accessed: Sep. 30, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/027312239500538X

[90] C. Gerrits and W. James, ‘Restoration of Infiltration Capacity of Permeable Pavers’, *Global Solutions for Urban Drainage*, pp. 1–16, 2002, doi: 10.1061/40644(2002)77.

[91] E. Z. Bean, W. F. Hunt, D. A. Bidelspach, and R. J. Burak, ‘STUDY ON THE SURFACE INFILTRATION RATE OF PERMEABLE PAVEMENTS’, 2004.

[92] C. Dierkes, L. Kuhlmann, J. Kandasamy, and G. Angelis, ‘Pollution Retention Capability and Maintenance of Permeable Pavements’, 2007.

[93] D. Pezzaniti, S. Beecham, and J. Kandasamy, ‘Influence of clogging on the effective life of permeable pavements’, *Proceedings of the Institution of Civil Engineers: Water Management*, vol. 162, no. 3, pp. 211–220, 2009, doi: 10.1680/WAMA.2009.00034.

[94] M. B. Chopra, E. Stuart, and M. P. Wanielista, ‘Pervious Pavement Systems in Florida—Research Results’, *Low Impact Development 2010: Redefining Water in the City - Proceedings of the 2010 International Low Impact Development Conference*, pp. 193–206, 2010, doi: 10.1061/41099(367)18.

[95] B. Shackel, ‘THE DESIGN, CONSTRUCTION AND EVALUATION OF PERMEABLE PAVEMENTS IN AUSTRALIA’, 2010.

[96] T. Hess and C. Ibe, *Evaluation of the performance of permeable pavement at Lamb Drove FINAL - PDF Free Download*. Departmentof Environmental Science and Technology, Cranfield University, 2011.

[97] T. N. Mansour and B. J. Putman, ‘Influence of Aggregate Gradation on the Performance Properties of Porous Asphalt Mixtures’, *Journal of Materials in Civil Engineering*, vol. 25, no. 2, pp. 281–288, Feb. 2013, doi: 10.1061/(ASCE)MT.1943-5533.0000602.

[98] T. Joshi and U. Dave, ‘Evaluation of strength, permeability and void ratio of Pervious concrete with changing W/C ratio and aggregate size’, *IJCIET_07_04_023 International Journal of Civil Engineering and Technology*, vol. 7, no. 4, pp. 276–284, 2016, Accessed: Jul. 10, 2022. [Online]. Available: http://www.iaeme.com/IJCIET/index.asp276http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4http://www.iaeme.com/IJCIET/index.asp277http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4

[99] J. B. Król, R. Khan, and A. C. Collop, ‘The study of the effect of internal structure on permeability of porous asphalt’, *https://doi.org/10.1080/14680629.2017.1283355*, vol. 19, no. 4, pp. 935–951, May 2017, doi: 10.1080/14680629.2017.1283355.

[100] B. Huang, H. Wu, X. Shu, and E. G. Burdette, ‘Laboratory evaluation of permeability and strength of polymer-modified pervious concrete’, *Constr Build Mater*, vol. 24, no. 5, pp. 818–823, May 2010, doi: 10.1016/J.CONBUILDMAT.2009.10.025.

[101] H. Li, M. Kayhanian, and J. T. Harvey, ‘Comparative field permeability measurement of permeable pavements using ASTM C1701 and NCAT permeameter methods’, *J Environ Manage*, vol. 118, pp. 144–152, Mar. 2013, doi: 10.1016/J.JENVMAN.2013.01.016.

[102] X. Ma, Q. Li, Y. C. Cui, and A. Q. Ni, ‘Performance of porous asphalt mixture with various additives’, *https://doi.org/10.1080/10298436.2016.1175560*, vol. 19, no. 4, pp. 355–361, Apr. 2016, doi: 10.1080/10298436.2016.1175560.

[103] SLS, ‘Sri Lanka Standards 1425’, 2011. Accessed: Apr. 08, 2022. [Online]. Available: http://slsi.lk/index.php?lang=en

[104] N. A. A. Bari, N. A. Abdullah, R. Yusuff, N. Ismail, and A. Jaapar, ‘Environmental Awareness and Benefits of Industrialized Building Systems (IBS)’, *Procedia Soc Behav Sci*, vol. 50, pp. 392–404, Jan. 2012, doi: 10.1016/J.SBSPRO.2012.08.044.

[105] South African Coal Ash Association., ‘Road wearing surfaces utilising ash products and a plastic geogrid’, 1994.

[106] J. Mahoney and S. Zinke, ‘Asphalt pavement analyzer equipment acquisition’, Connecticut Advanced Pavement Laboratory, May 2008. doi: 10.21949/1503647.

[107] A. K. Chandrappa and K. P. Biligiri, ‘Pervious concrete as a sustainable pavement material – Research findings and future prospects: A state-of-the-art review’, *Constr Build Mater*, vol. 111, pp. 262–274, May 2016, doi: 10.1016/J.CONBUILDMAT.2016.02.054.

[108] ASTM International, *ASTM Standards*. 2021. Accessed: Jan. 09, 2022. [Online]. Available: https://www.astm.org/about/overview.html

[109] BS, ‘British Standards - European Standards’, 2022. https://www.en-standard.eu/bs-standards/ (accessed Sep. 05, 2022).

[110] Sri Lanka Standards Institution, ‘Sri Lanka Standards Institute’, 2022. https://www.slsi.lk/index.php?lang=en (accessed Jul. 20, 2022).

[111] IS, ‘Bureau of Indian Standards’, 2022. https://www.crsbis.in/BIS/publicdashAction.do (accessed Sep. 05, 2022).

[112] A. Ahmed, ‘Sustainable Construction Using Autoclaved Aerated Concrete (Aircrete) Blocks’, Oct. 2017, Accessed: Dec. 13, 2022. [Online]. Available: https://crimsonpublishers.com/rdms/pdf/RDMS.000518.pdf

[113] A. Ahmed and J. Kamau, 'Advantages and Implications of Low Density Aircrete Products for the Construction Industry', 2017, Accessed: Dec. 13, 2022. [Online]. Available: http://www.ijset.net/index_issue.php?iid=50

[114] E. A. Gerns, B. Wonneberger, and M. J. Scheffler, 'Design and Selection of Exterior Granite Pavers', *ASTM Special Technical Publication*, no. 1394, pp. 109–120, 2001, doi: 10.1520/STP13543S.

[115] G. Anusha *et al.*, 'Experimental Study on Properties of Concrete Paver Blocks by Partially Replacing Cement with Granite Powder', in *Materials Science and Engineering*, 2021. Accessed: Dec. 13, 2022. [Online]. Available: https://iopscience.iop.org/article/10.1088/1757-899X/1145/1/012074/meta

[116] A. Hussin and C. Poole, 'The Intragranular Textures of Aggregates and its Correlation to the Physical Properties (Tekstur dalaman Butiran dalam Agregat dan Perkaitannya dengan Sifat Fizikal)', *Sains Malays*, vol. 39, no. 1, pp. 39–43, 2010.

[117] B. Prieto, P. Sanmartín, B. Silva, and F. Martínez-Verdú, 'Measuring the color of granite rocks: A proposed procedure', *Color Res Appl*, vol. 35, no. 5, pp. 368–375, Oct. 2010, doi: 10.1002/COL.20579.

[118] M. L. Birkholz, 'Granite on the Ground: Former Nazi Party Rally Grounds, Nuremberg/Germany. A brief introduction', in *Bauhaus-Institut für Geschichte und Theorie der Architektur und Planung Symposium*, 2015. Accessed: Dec. 13, 2022. [Online]. Available: http://reichsparteitagsgelaende.de/stationen/grosse_strasse.htm.

[119] G. Lalitha, C. Sasidhar, and C. Ramachandrudu, 'A REVIEW PAPER ON STRENGTH AND DURABILITY STUDIES ON CONCRETE FINE AGGREGATE REPLACED WITH RECYCLED CRUSHED GLASS', *International Journal of Civil Engineering and Technology*

(IJCIET), vol. 8, no. 2, pp. 199–202, 2017, Accessed: Dec. 14, 2022. [Online]. Available: http://www.iaeme.com/IJCIET/index.asp199http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=2http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=2

[120] Y. Lin, T. Shao, A. Jahami, J. Khatib, and R. Raydan, ‘Production of Low-Cost, High-Strength Concrete with Waste Glass as Fine Aggregates Replacement’, *Buildings 2022, Vol. 12, Page 2168*, vol. 12, no. 12, p. 2168, Dec. 2022, doi: 10.3390/BUILDINGS12122168.

[121] M. Dan Gavriletea, ‘Environmental Impacts of Sand Exploitation. Analysis of Sand Market’, *Sustainability 2017, Vol. 9, Page 1118*, vol. 9, no. 7, p. 1118, Jun. 2017, doi: 10.3390/SU9071118.

[122] W. Mampearachchi, *Handbook on Concrete Block Paving*. Springer Singapore, 2019. doi: 10.1007/978-981-13-8417-2/COVER.

[123] EUPAVE, ‘European Concrete Paving Association (EUPAVE)’, 2022. https://www.eupave.eu/ (accessed Mar. 07, 2022).

[124] Dassault Systèmes®, ‘Abaqus CAE - SIMULA™ by Dassault Systèmes®’, 2022. https://www.3ds.com/products-services/simulia/products/abaqus/abaquscae/ (accessed Feb. 11, 2022).

[125] B. C. Panda and A. K. Ghosh, ‘Structural Behavior of Concrete Block Paving. I: Sand in Bed and Joints’, *J Transp Eng*, vol. 128, no. 2, pp. 123–129, Mar. 2002, doi: 10.1061/(ASCE)0733-947X(2002)128:2(123).

[126] M. Hafezolghorani, F. Hejazi, R. Vaghei, M. S. bin Jaafar, and K. Karimzade, ‘Simplified damage plasticity model for concrete’, *Structural Engineering International*, vol. 27, no. 1, pp. 68–78, Feb. 2017, doi: 10.2749/101686616X1081.

[127] W. Mampearachchi, P. Gunarathna, W. K. Mampearachchi, and W. P. H. Gunarathna, 'Finite-Element Model Approach to Determine Support Conditions and Effective Layout for Concrete Block Paving Design and Development of a Portable Wireless Axle Load Measuring System View project Finite-Element Model Approach to Determine Support Conditions and Effective Layout for Concrete Block Paving', 2010, doi: 10.1061/(ASCE)MT.1943-5533.0000118.

[128] N. R. Kumarage, C. Jayasinghe, K. P. H. Perera, K. K. G. K. D. Kariyawasam, and S. Herath, 'Assessment of the optimum dimensions for cobble-type paving blocks using finite element modeling', in *2022 Moratuwa Engineering Research Conference (MERCon)*, Jul. 2022, pp. 1–5. doi: 10.1109/MERCON55799.2022.9906237.

[129] D. Gunatilake and W. K. Mampearachchi, 'Finite element modelling approach to determine optimum dimensions for interlocking concrete blocks used for road paving', *https://doi.org/10.1080/14680629.2017.1385512*, vol. 20, no. 2, pp. 280–296, Feb. 2017, doi: 10.1080/14680629.2017.1385512.

[130] IRC, *GUIDELINES FOR THE USE OF INTERLOCKING CONCRETE BLOCK PAVEMENT - THE INDIAN ROADS CONGRESS*. 2004. Accessed: Apr. 09, 2022. [Online]. Available: https://law.resource.org/pub/in/bis/irc/irc.gov.in.sp.063.2004.pdf

[131] ICPI, 'Construction Tolerances and Recommendations for Interlocking Concrete Pavements - Interlocking Concrete Pavement Institute', 2022. Accessed: Apr. 09, 2022. [Online]. Available: https://icpi.org/government-tech-specs

[132] AASHTO, 'American Association of State Highway and Transportation Officials (AASHTO Resource)', 2022. http://www.aashtoresource.org/about-us (accessed Sep. 09, 2022).

[133] A. Jumadurdiyev, M. H. Ozkul, A. R. Saglam, and N. Parlak, 'The utilization of beet molasses as a retarding and water-reducing admixture for concrete', *Cem Concr Res*, vol. 35, no. 5, pp. 874–882, May 2005, doi: 10.1016/J.CEMCONRES.2004.04.036.

[134] X. Zhang, Y. wen Chiu, H. Hao, and J. Cui, 'Free water effect on the dynamic compressive properties of mortar', *Cem Concr Compos*, vol. 118, p. 103933, Apr. 2021, doi: 10.1016/J.CEMCONCOMP.2021.103933.

[135] Applied Research Associates Inc., 'Interlocking Concrete Pavement Life-Cycle Cost Comparison Tools', Virginia, Oct. 2020. Accessed: Oct. 14, 2022. [Online]. Available: https://icpi.org/s/Municipal-Street-Sidewalk-Utility-Cuts-User-Delay-LCCA-Reports.pdf#page=38

[136] H. A. C. K. Hettiarachchi and W. K. Mampearachchi, 'Validity of aggregate packing models in mixture design of interlocking concrete block pavers (ICBP)', *https://doi.org/10.1080/14680629.2017.1393001*, vol. 20, no. 2, pp. 462–474, Feb. 2017, doi: 10.1080/14680629.2017.1393001.

Annex 1

OVERVIEW OF PERMEABLE PAVING SYSTEMS AND SELECTION OF THE IDEAL PAVING SYSTEM FOR HOME GARDENS

N.R. Kumarage[1*], C. Jayasinghe [1], K.P.H. Perera [2]
[1]University of Moratuwa, Sri Lanka
[2]Southern Alberta Institute of Technology, Canada
E-mail: kumaragenipun@gmail.com, TP: +94765288282

Abstract: With the rapid technological development, many people moved towards living an online life with much of their work related to the internet. This eventually resulted in more work reducing humans' free time. This behaviour leads people to move toward items that require less maintenance, which is less work. Therefore, the traditional lawns with grass covers are now being faded away. It was replaced with hard-paved surfaces. However, these paving systems resulted in the trapping of stormwater, increasing the risk of flooding. Therefore, it led to the development of permeable paving systems. This paper focuses on an overview of four leading permeable paving systems, including Porous Asphalt Pavements (PAP), Permeable Concrete Pavements (PCP), Permeable Interlocking Concrete Pavements (PICP), and Plastic Grid Pavements (PGP). The advantages and disadvantages of each paving system are discussed along with a comparison of characteristics between the paving systems. Finally, concluding as permeable interlocking concrete paving as the most suitable pavement system to be used in home gardens.

Keywords: Permeable pavements; Interlocking blocks; Porous pavements; Plastic grid pavers; Permeable concrete

1 Introduction

Landscaping has gained immersed attention of building developers and homeowners recently. Landscaping was defined as the design and arrangement of natural and manmade elements through scientific knowledge and resource conservation (Garrett, 1964). It is now considered a significant part of the building plan and affects the total property value (Olayinka et al., 2020). Whereas an Athens study confirmed the fact by stating that landscaping can improve the resell value of residential houses by 3-5% (Anderson and Cordell, 1985). Landscaping can be categorized into several elements, such as designing, paving, planting, furnishing, and protection (Pawsey, 1982). Therefore, land paving is one of the key elements of landscaping. An appropriate paving technique selection will depend on the location, costs, safety aspects and the homeowners' aesthetic preferences (Bretz et al., 1998). Moreover, when external paving is considered, developing a good drainage technique is the key in mitigating stormwater runoff and facilitating water table replenishment through rainwater infiltration (Kusumastuti *et al.*, 2019).

2 Importance of permeable paving systems

Front gardens and lawns have great importance in the context of climate change. Although they are designed to create pleasant townscapes, they also help to reduce flooding risks by soaking up the stormwater and absorbing carbon dioxide from the atmosphere (Alexander, 2015). Increased car ownership, pressure on roadside parking and change of fashion in pavement design resulted in new paving systems (Alexander, 2015). In addition, a BBC article stated that people in the UK tend to move on to paved gardens as it is easier to maintain when compared with grass lawns (Low and Heyden, 2015). However, many studies stated that increased hard surfacing on land had major drawbacks (Harvey *et al.*, 2014; Kelly, 2018). Initially, paving systems prevented rainwater infiltration, leading to increased flood risk by increasing the surface runoff (Lee and Heaney, 2003; Willems *et al.*, 2012). This risk is expected to increase with time since rainfall is predicted to become more frequent and intense in the future (Murphy *et al.*, 2009) as a study in the United Kingdom stated that a current 1 in 100-year rainfall might occur as frequently as 1 in 25-year by the 2080s (Sanderson, 2010).

The other main concern of pavement systems is the development of the heat island effect due to hard surfacing generated by pavement systems (Mohajerani et al., 2017). A study in 2008 stated that the average urban surface spread in four metropolitan areas in the USA is as follows: 29-41% vegetation, 19-25% roofs, and 29-39% in paved surfaces (Akbari and Rose, 2008). The above values show that over 60% of urban surfaces are covered with manmade hardscapes. Furthermore, this percentage can be expected only to increase with time. Therefore, this development of the heat island effect leads to many environmental issues for the urban population (Yang et al., 2015). Such as critical impacts on human comfort, health and wellbeing, and the local atmosphere (Grimmond, 2007; Ichinose et al., 2008; Synnefa et al., 2011; Yang et al., 2015).

Therefore, developing a paving system should ensure that it allows stormwater penetration to the ground surface and reduces the impact on the urban heat island effect. The following section describes several permeable paving systems currently used in the industry to prevent the aforementioned adverse impacts.

3 Different paving systems

Several paving systems were identified which can be used to mitigate the aforementioned adverse impacts and satisfy the requirements of a paving system. A detailed description of each paving system and its advantages and disadvantages are discussed in subsections 3.1 to 3.4.

3.1 Porous Asphalt Paving

Porous Asphalt Paving (PAP) can be defined as asphalt pavement developed with materials screened to reduce the percentage of fines (Goh *et al.*, 2012). Which eventually allows for better rainwater infiltration. The thickness of a wearing surface of porous asphalt pavement varies from 75 mm to 180 mm, depending on the traffic load the pavement is expected to bear (Dreelin et al., 2006). The void percentages in most Porous Asphalt Pavements were around 15% (Sangiorgi *et al.*, 2017). In 1970 Franklin institute of Philadelphia improved this method to reduce drainage structures (Cahill, Adams and Marm, 2003). In addition, a geotextile can be applied under the aggregate to filter pollutants and fines (Cahill et al., 2003). Some advantages of porous asphalt pavement are as follows: reduction of stormwater systems, reduction in street flow during inclement weather, and reduction of night glare and splash visibility during inclement weather increased (Hossain et al., 1991; Younger et al., 1994). Furthermore, a Taiwan study stated that porous asphalt is more cost-effective when compared with open-graded asphalt, and cost can be further reduced by using sustainable materials such as steel slag, which is technically viable and environmentally friendly (Chen et al., 2019).

However, although the porous asphalt pavements illustrated promising performances in stormwater management, it has many concerns regarding economic aspects as it requires higher installation and maintenance costs compared with other pavement systems (Nicholls and Carswell, 2001; Yildirim *et al.*, 2006). It also has limitations when meeting freezing and thawing cycles (Goh *et al.*, 2012). A Swedish study in 2000 confirmed this fact by stating that if the moisture content of the soil is higher, it has increased the thawing effect rapidly in PAP, and it is more resilient to freezing when compared with conventional pavement (Backstrom, 2000). A Switzerland study also stated that, for winter maintenance, porous asphalt needs deicing salts and thawing products as same as conventional asphalt pavements. However, due to the higher void content of the asphalt layer, there is a tendency that these deicing salts can penetrate to the bottom through the voids, resulting in ice staying longer on the surface. (Iserning et al., 1990). Finally, although PAP can be considered for public street paving, it is not feasible to use it for household gardens and roads due to its required installation resources.

3.2 Permeable concrete Paving

Permeable Concrete Paving (PCP) is also another similar pavement to PAP. PCP is created by mixing Portland cement with less fine aggregate, increasing the void percentage and allowing water to drain easily. Therefore, PCP can be defined as a concrete pavement that provides a network for stormwater infiltration into the subbase and base layers (Wanielista *et al.*, 2007; Ullate *et al.*, 2010; Lee *et al.*, 2013). An ASTM is yet to be designed to PCP with the porous concrete's complexity. However, previous studies have used ASTM C39 to test compressive strength in PCP (Xie, Akin and Shi, 2019). A typical PCP was found to inhibit a permeability from 20 to 500 m/day, compressive strength of 5.5 to 20 MPa, and air voids of about 15% to 30% (Schaefer *et al.*, 2006; Weiss *et al.*, 2017).

In urban environments, PCP can be very beneficial as it enables the dissipation of stormwater runoff and improves the water quality concerning metals, nitrogen, phosphorus, and suspended solids (McCain and Suozzo, 2010; Holmes et al., 2017; Kim et al., 2017). In addition to stormwater runoff reduction, an Indian study stated that the PCP could reduce the heat island effect and the generated traffic noise (Chandrappa and Biligiri, 2016). Also, it was found that the cement consumption is relatively low in PCPompared with conventional concrete pavements (Xie, Akin and Shi, 2019). Moreover, a life cycle assessment in Greece stated that permeable concrete emits only 2% of conventional concrete's CO_2 produced, producing 19.5 kg CO_2 / m^3 than 903 kg CO_2 / m^3 (Anastasiou et al., 2017).

Although PCP can bring the benefits mentioned above, its effectiveness and durability are major drawbacks in the long run. A winter study carried in the USA identified some of the factors: premature failure, deterioration of pavement characteristics when exposed to chemical and physical attacks, and clogging of the PCP from sand applied on the pavement (McCain Jr and Dewoolkar, 2010). It was also found that clogging of PCP can occur due to the transportation of sand by traffic and stormwater runoff from the adjacent lands (Kia *et al*., 2017; Weiss et al., 2017).

3.3 Permeable Interlocking Concrete Paving

The permeable Interlocking concrete paving (PICP) system has been widely used for the past 25 years as one of the famous permeable paving systems (Lucke and Beecham, 2011). PICP is being used in the industry as an eco-friendly and cost-effective paving alternative that is durable, has low maintenance, and is highly versatile (Tirpak *et al.*, 2020). Specifically, these blocks can prevent rainwater gathering and resultant flooding and provide a solid surface that provides better runoff for chemicals, oils, and other liquids (Tirpak *et al.*, 2020). Furthermore, PICPs can be easily used for multiple landscaping applications such as stormwater reusing and vegetation (Tirpak *et al.*, 2020). PICP is the system where concrete paving blocks are designed and laid with sufficient spacing between blocks so that stormwater can infiltrate the base layer (Mullaney and Lucke, 2014a). The joints and spaces between pavers are kept void without filling them with sand or any binding material, as shown in Figure 1, and the structural strength is obtained by its interlocking behaviour. Therefore, the void percentage of the paving system is 8 to 20% of the paving area (Hunt and Collins, 2008) which allows for better stormwater infiltration. Figure 2 illustrates the sub-structure of a PICP in which the joints between pavers allow water to infiltrate the bedding layer. This bedding layer is usually a 2-5mm aggregate layer laid on a geotextile (Scholz and Grabowiecki, 2007). This geotextile is used to improve the inflow water quality (Puehmeier and Newman, 2008).

Figure 1: Permeable interlocking concrete pavement

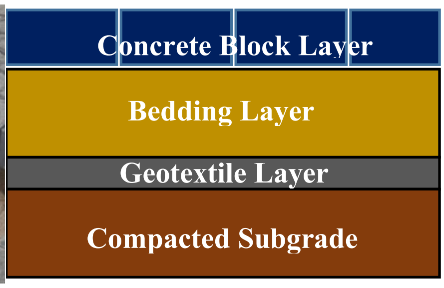

Figure 2: Substructure of PICP Pavement

PICP has been a main focus area for research for the last few decades because of its ability to construct using vast materials. Researchers have made many attempts to reduce the construction cost by replacing aggregate with: mud, fly ash (Kumar and Kumar, 2013; Udawattha et al., 2017), ceramic tiles (Penteado et al., 2016) and even waste materials (Ganjian et al., 2015). A Chinese study stated that in creating paving blocks recycled coarse concrete aggregate can be used up to 60%, and recycled concrete fine aggregate can be used up to 20% (Wang et al., 2019).
Researchers also attempted to customize the blocks' appearance to meet customer satisfaction by changing their shape (Rachmat and Salsabilla, 2019), creating the paving blocks using different materials such as granite and natural rocks (Boonen and Smets, 2019) and finally introducing vast pigments (Lee et al., 2003). However, although many attempts were made, there is still room for innovative designs to meet the aesthetic satisfaction of customers.

3.4 Plastic Grid Paving System

Plastic Grid Paving (PGP) is a system where interconnected plastic grids are laid on top of a prepared surface and later filled with gravel or topsoil planted with grass. The functionality of PGP is similar to that of PICP, where the voids in the pavement allow to disperse of runoff water into the bottom surface. However void percentage in PGP is higher than PICP, as shown in Figure 3, to have a better infiltration of stormwater runoff. For PGP, the void percentage varies from 90 to 98% compared with 8 to 20% in PICP (Mullaney and Lucke, 2014). These grids are often created by lightweight injection molded plastic, and these can be created with 100% post-consumer plastic (High-Density Poly Ethylene) with added 3% carbon black for UV protection (GrassPave, 2021). These grids should be able to carry a load of 402 kg/cm^2 (5700psi) when filled with sand over a depth of road base (GrassPave, 2021).

Figure 3: Plastic Grid Pavement filled with grass and gravel

4 Past research findings addressing the characteristics of permeable paving systems

4.1 Infiltration of Surface Water

Compared with traditional pavements, pervious pavements systems had significantly reduced stormwater runoff and peak flow rates in urban catchments. A USA study measured the removal rates of PC and PICP compared with an impervious asphalt surface. The permeable surfaces showed a mean runoff reduction of 98% compared to 35% on impervious surfaces (Collins et al., 2008). Regarding PGP, a study conducted in the USA stated that PGP filled with topsoil and grass had shown around 93% runoff reduction compared to a conventional asphalt surface (Dreelin et al., 2006). Also, a study conducted in North Carolina found a rational runoff coefficient of 0.2 - 0.5 on a pavement created by PGP (Hunt et al., 2002). Jayasuriya and Kadurupokune conducted a more detailed study in Melbourne, where they found: that peak discharges were reduced by 40 – 55% in PICP and by 45 – 60% in PGP, runoff volumes were reduced by 43 – 55% in PICP and by 52 – 62% in PGP and for the runoff to occur a traditional asphalt pavement needed only 3 mm rainfall where it had required a rainfall of 13 mm for PICP and 18 mm for PGP (Jayasuriya and Kadurupokune, 2010). In Belgium, another fascinating study was carried out where they measured the effect of laying grass in PGP. They concluded by stating that greened PGP performances were beneath open jointed PGP, and the recovery time had increased to two days, where the open jointed PGP dried in a few hours (Straet et al., 2008). Several studies have been conducted to find the runoff coefficient for PICP, and they came up with several conclusions. Two studies in 1995 and 1997 stated that 60% of the runoff volumes and peak flow rates had been reduced by the PICP when compared with traditional asphalt pavements (Pratt et al., 1995; Pratt, 1997). Later, a USA study in 2006 stated that the runoff coefficient reduction could be as high as 72% in PICP pavements compared to asphalt pavements (Gilbert et al., 2006). Additionally, an Australian study stated that the imperviousness of streets could be reduced by 42% by installing PICP (Rankin et al., 2004).

4.2 Clogging of pavement

Past research indicates that clogging and failure of permeable pavement can occur due to many reasons, such as poor design, poor construction, poor maintenance, low permeability of the soil, and lack of sediment erosion control during construction (Pratt, 1997; Fassman et al., 2010; Lucke et al., 2011). A German study in 2006 found that the infiltration rate is affected by the pavement's age, mainly due to the filling of joints and pores of the permeable pavement with mineral and organic fines. It also stated that the infiltration rate would decrease and become steady after 10 years to 20 – 25% of the initial infiltration (Borgwardt, 2006). A 17-week model for permeable paving systems was conducted in Australia to analyze the effects of up to 17 years of operation. It found that the removal of almost 100% of the Total Suspended Solids (TSS) of the stormwater can be expected from permeable pavements. These TSS would accumulate at the bottom of the pavement, leading to clogging and ponding. It also stated that PICP is more likely to pond after 5 years of operation due to its geotextile layer at the bottom, and PAP is likely to pond after 8.5 years of operation (Yong *et al.*, 2008). However, a Spanish study found that in fully clogged PICP, 81% infiltration could be achieved when rainfall intensity is at 55 mm/h, and the maximum infiltration rate was found to be 64 mm/h at a rainfall intensity of 125 mm/h (González-Angullo *et al.*, 2008). An Australian study also stated that in a PICP system, infiltration could be fully functional, although the appearance seemed clogged, and 92% of the sediments lie in the paving layer and bedding layer of the pavement (Lucke and Beecham, 2011). A study was also conducted for 20 PCP car parks, to find the depth of sedimentation, with the use of a CT scanner, and they concluded by stating that a reduction of porosity of PCP was found on the top 25 mm of the PCP, which can be due to clogging (Kayhanian *et al.*, 2012).

4.3 Maintenance of Pavement

Permeable pavements allow infiltration of stormwater through joints and voids. However, these joints and voids get clogged with sediment and fines after some time. Hence, preventive and restorative measurements are required to uphold the hydrological benefits of permeable pavements (Sehgal *et al.*, 2018). A UK study stated that PAP and PCP were susceptible to clogging within the first 3 years of usage and the top layer needs to be replaced and reinstated after each period for proper drainage (Scholz et al., 2007). Various researchers have opted out that maintenance for PICP should be carried out by removing pollutants from the pavers and replacing the bedding layer from time to time to maintain proper stormwater infiltration (Pratt, 1990; Colandini et al., 1995; Mullaney et al., 2014). However, a Canadian study stated that infiltrations would increase by removing the top 10-20 mm of joint filler for low daily traffic areas, and removal depth should be increased to 20-25mm for areas with high traffic (Gerrits et al., 2002). Studies also state that proper maintenance can improve the infiltration of PICP by up to 65% (Bean *et al.*, 2004; Dierkes *et al.*, 2007). For PICP, vacuuming and yearly sweeping improved the pavement's hydrological characteristics (Pezzaniti et al., 2009). The same was found with PCP. However, pressure washing was highly effective with PCP (Chopra et al., 2010). Even though pressure washing was effective, Fassman stated that dislodging sediments should not be recommended as those can be washed to a reticulate system (Fassman et al., 2010). Some USA authorities encourage routine sweeping up to three or more times a year. However, Australia and Europe discourage frequent maintenance as they consider it unnecessary (Shackel, 2010). Moreover, an eight-year-old and a 6-year-old study stated that hydrological performances were satisfactory for PICP when no maintenance was carried out despite significant clogging (Hess et al., 2011; Lucke et al., 2011).

5 Guidelines and testing

When developing permeable pavement systems, there are many standards and tests that you need to follow. Table 1 represents some test procedures followed in past studies while developing permeable pavement systems.

Table 1: Standard structural tests which were followed in developing permeable pavement systems

Test	Standard, if followed	References
Abrasion resistance	ASTM C418, ASTM C779	(Ramesh et al., 2014; Parangi et al., 2020; Tempa et al., 2021)
Durability test	BS EN 1338, ASTM C1262	(Udawattha et al., 2017)
Efflorescence test	ASTM C67	(Dinesh et al., 2016)
Fire resistance test		(Dinesh et al., 2016)

Hardness test	IS 1500: 2005	(Dinesh et al., 2016; Tempa et al., 2021)
Impact resistance		(Parangi et al., 2020)
Run over vehicle test		(Mashudi *et al.*, 2020)
Saturated water content	ASTM C140	(Yogananth *et al.*, 2019)
Sieve analysis of aggregate		(Yogananth *et al.*, 2019)
Skid resistance test	BS EN 1338:2003	(Udawattha et al., 2017)
Strength loss after freeze and thaw cycle	ASTM D560	(Yogananth *et al.*, 2019)
Strength loss after being immersed in acid solution	ASTM C289-07	(Yogananth *et al.*, 2019)
Strength loss after immersed in Salt, alkaline solution	ASTM C1152 M-04	(Yogananth *et al.*, 2019)
Strength loss after wetting and drying cycles	ASTM D6611	(Yogananth *et al.*, 2019)
Tensile splitting strength	BS EN 1338:2003	(Udawattha et al., 2017)
Transverse strength		(Parangi et al., 2020)
Water absorption	ASTM C936	(Dinesh et al., 2016; Udawattha et al., 2017; Parangi et al., 2020; Tempa et al., 2021)
Wet and dry compressive strength	EN 772, ASTM C936	(Dinesh et al., 2016; Udawattha et al., 2017; Yogananth et al., 2019; Citra et al., 2020; Mashudi et al., 2020; Tempa et al., 2021)
Wet and dry density	ASTM C140	(Yogananth *et al.*, 2019; Caronge *et al.*, 2020)
Wet and dry flexural strength	ASTM C1609	(Yogananth *et al.*, 2019)
Setting time	IS 4031: (Part 5)- 1988	(Tempa *et al.*, 2021)
Outdoor temperature effect	IS 15658: 2006	(Tempa *et al.*, 2021)

6 Discussion and Conclusion

Out of the paving systems considered, PAP can be considered a pavement system that could be widely used for public car parks and urban streets since construction depends on machinery and equipment availability. However, its machinery has a higher rental/purchase cost which is not feasible to be equipped by private households or to pave small quantities (Nicholls et al., 2001; Yildirim et al., 2006). In addition, it was also found that the PAP is not resistant to freezing and thawing cycles and needs deicing salts to melt the ice on the pavement (Iserning et al., 1990). Therefore, PAP is highly suitable for large-scale constructions with more significant volumes, such as public car parks, Industrial factory driveways, and public streets. However, using PAP for small-scale, low-traffic pavement systems has many drawbacks.

PCP is also very similar to PAP. It also has a satisfactory hydrological performance for draining the stormwater out of the pavement. It was also found that PCP has a lesser impact on the heat island effect when compared with traditional concrete pavements and asphalt pavements (Chandrappa et al., 2016). In addition, the PCP does not need any special machinery equipment such as PAP, allowing the customers to use this paving system in local households. However, the construction cost of the PCP is higher when compared with other pavement systems. Hence, it is less likeable for the PCP to be utilized by many customers. Similar to PAP, PCP too requires skilled labour to lay the pavement layer (Sartipi et al., 2019). Moreover, PAP and PCP were susceptible to being clogged after the end of 3 years, which would drastically affect their hydrological performance. Hence we can see that these two paving systems are not preferable to use in home gardens and private spaces.

When considering PICP, it provides stormwater infiltration for the base layer by allowing the stormwater to penetrate through the joints between the blocks. PICP contains a void percentage that varies from 8 to 20%. Some blocks have been developed by keeping spaces in the middle of the blocks to increase their void percentage, which some researchers have addressed as concrete grid pavers (Mullaney et al., 2014). Moreover, these pavers are much more suitable for paving home gardens and private spaces as not much-skilled expertise is required in laying the pavers and can be easily laid through an unskilled worker (Shackel, 2010), minimizing the installation cost for the pavement. Moreover, since these pavements are created with precast blocks, the cost per block can be reduced with large-scale manufacturing, and the construction time would be much reduced compared to PAP and PCP (Chen et al., 2016). Another advantage of PICP is the ability to change the block's appearance to meet the customers' aesthetic satisfaction. PGP is a product of the numerous research carried out under the PICP where they came up with open plastic grids increasing the void percentage up to 98%, allowing improved hydrological performance (Mullaney et al., 2014). However, these voids are often filled with grass or gravel (Brattebo et al., 2003; Mullaney et al., 2014). The grass covering is often famous with PGP as it gives a natural paving atmosphere improving the structural strength of the pavement. Similar to PICP, PGP also does not need skilled labour and could be easily installed by an unskilled worker, making this paving system much more suitable for home gardens. However, unlike PICP, PGP cannot have many customized outlooks as it can only be planted with grass or filled with a course material to maintain its permeability, which limits the possibility of satisfying many customers aesthetically. Furthermore, the frequent maintenance requirement of grass-filled PGP is also a major drawback in adapting this paving system.

Therefore, the most suitable paving system for home gardens with light-weight traffic can be suggested as PICP.

7 References

Akbari, H. and Rose, L.S. (2008) ‘Urban Surfaces and Heat Island Mitigation Potentials’, *Journal of the Human-Environment System*, 11(2), pp. 85–101. Available at: https://doi.org/10.1618/JHES.11.85.

Alexander, D.A. (2015) ‘The environmental importance of front gardens’, *http://dx.doi.org/10.1680/muen.2006.159.4.239*, 159(4), pp. 239–244. Available at: https://doi.org/10.1680/MUEN.2006.159.4.239.

Anastasiou, E.K., Liapis, A. and Papachristoforou, M. (2017) ‘Life Cycle Assessment of Concrete Products for Special Applications Containing EAF Slag’, *Procedia Environmental Sciences*, 38, pp. 469–476. Available at: https://doi.org/10.1016/J.PROENV.2017.03.138.

Anderson, L.M. and Cordell, H.K. (1985) ‘Residential Property Values Improved by Landscaping with Trees’, *Southern Journal of Applied Forestry*, 9(3), pp. 162–166. Available at: https://doi.org/10.1093/SJAF/9.3.162.

Backstrom, M. (2000) ‘Ground temperature in porous pavement during freezing and thawing’, *Journal of Transportation Engineering*, 126(5), pp. 375–381. Available at: https://doi.org/10.1061/(ASCE)0733-947X(2000)126:5(375).

Bean, E.Z. *et al.* (2004) ‘STUDY ON THE SURFACE INFILTRATION RATE OF PERMEABLE PAVEMENTS’.

Boonen, E. and Smets, S. (2019) 'High-quality materials for road paving of natural stone: results of the PREMANAT research project', *OCW mededelingen = Bulletin CRR* [Preprint], (120).

Borgwardt, S. (2006) 'LONG-TERM IN-SITU INFILTRATION PERFORMANCE OF PERMEABLE CONCRETE BLOCK PAVEMENT'.

Brattebo, B.O. and Booth, D.B. (2003) 'Long-term stormwater quantity and quality performance of permeable pavement systems', *Water Research*, 37(18), pp. 4369–4376. Available at: https://doi.org/10.1016/S0043-1354(03)00410-X.

Bretz, S., Akbari, H. and Rosenfeld, A. (1998) 'Practical issues for using solar-reflective materials to mitigate urban heat islands', *Atmospheric Environment*, 32(1), pp. 95–101. Available at: https://doi.org/10.1016/S1352-2310(97)00182-9.

Cahill, T., Adams, M. and Marm, C. (2003) 'POROUS ASPHALT : THE RIGHT CHOICE FOR POROUS PAVEMENTS', *HMAT: Hot Mix Asphalt Technology*, 8(5).

Caronge, M.A. *et al.* (2020) 'Development of eco-friendly paving block incorporating co-burning palm oil-processed tea waste ash', *IOP Conference Series: Earth and Environmental Science*, 419(1). Available at: https://doi.org/10.1088/1755-1315/419/1/012158.

Chandrappa, A.K. and Biligiri, K.P. (2016) 'Pervious concrete as a sustainable pavement material-Research findings and future prospects: A state-of-the-art review', *Construction and Building Materials*, 111, pp. 262–274. Available at: https://doi.org/10.1016/J.CONBUILDMAT.2016.02.054.

Chen, J.H., Yang, L.R. and Tai, H.W. (2016) 'Process reengineering and improvement for building precast production', *Automation in Construction*, 68, pp. 249–258. Available at: https://doi.org/10.1016/J.AUTCON.2016.05.015.

Chen, J.S., Yang, C.H. and Lee, C. te (2019) 'Field evaluation of porous asphalt course for life-cycle cost analysis', *Construction and Building Materials*, 221, pp. 20–26. Available at: https://doi.org/10.1016/J.CONBUILDMAT.2019.06.072.

Chopra, M.B., Stuart, E. and Wanielista, M.P. (2010) 'Pervious Pavement Systems in Florida—Research Results', *Low Impact Development 2010: Redefining Water in the City - Proceedings of the 2010 International Low Impact Development Conference*, pp. 193–206. Available at: https://doi.org/10.1061/41099(367)18.

Citra, A.D.P., Purwanto, P. and Soenoko, H.R. (2020) 'Life Cycle Assessment and Quality of Utilization of Paint Waste as a Raw Material of

Paving Block', *Journal of Ecological Engineering*, Vol. 21(nr 2), pp. 89–94. Available at: https://doi.org/10.12911/22998993/116342.
Colandini, V., Legret M., Brosseaud Y., Baladès J., (1995) 'Metallic pollution in clogging materials of urban porous pavements', *Elsevier* [Preprint].
Collins, K.A., Hunt, W.F. and Hathaway, J.M. (2008) 'Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina', *Journal of Hydrologic Engineering*, 13(12), pp. 1146–1157. Available at: https://doi.org/10.1061/(ASCE)1084-0699(2008)13:12(1146).
Dierkes, C. Kuhlmann L., Kandasamy J., Angelis G., (2007) 'Pollution Retention Capability and Maintenance of Permeable Pavements'.
Dinesh, S., Dinesh, A. and Kirubakaran, K. (2016) 'UTILISATION OF WASTE PLASTIC IN MANUFACTURING OF BRICKS AND PAVER BLOCKS', *International Journal of Applied Engineering Research*, 11(3).
Dreelin, EA., Fowler, L. and Carroll, C.R.. (2006) 'A test of porous pavement effectiveness on clay soils during natural storm events', *Water research*, 40(4), pp. 799–805. Available at: https://doi.org/10.1016/J.WATRES.2005.12.002.
Fassman, E.A. and Blackbourne, S. (2010) 'Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils', *Journal of Hydrologic Engineering*, 15(6), pp. 475–485. Available at: https://doi.org/10.1061/(ASCE)HE.1943-5584.0000238.
Ganjian, E., Jalull, G. and Sadeghi-Pouya, H. (2015) 'Using waste materials and by-products to produce concrete paving blocks', *Construction and Building Materials*, 77, pp. 270–275. Available at: https://doi.org/10.1016/J.CONBUILDMAT.2014.12.048.
Garrett, Eckbo. (1964) *Urban landscape design*. McGraw-Hill.
Gerrits, C. and James, W. (2002) 'Restoration of Infiltration Capacity of Permeable Pavers', *Global Solutions for Urban Drainage*, pp. 1–16. Available at: https://doi.org/10.1061/40644(2002)77.
Gilbert, J.K. and Clausen, J.C. (2006) 'Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut', *Water Research*, 40(4), pp. 826–832. Available at: https://doi.org/10.1016/J.WATRES.2005.12.006.
Goh, S.W., You Z., (2012) 'Mechanical Properties of Porous Asphalt Pavement Materials with Warm Mix Asphalt and RAP'. Available at: https://doi.org/10.1061/(ASCE)TE.
Gomez-Ullate, E., Castillo-Lopez E., Castro-Fresno D., Bayon J.R., (2010) 'Analysis and Contrast of Different Pervious Pavements for Management of Storm-Water in a Parking Area in Northern Spain', *Water*

Resources Management 2010 25:6, 25(6), pp. 1525–1535. Available at: https://doi.org/10.1007/S11269-010-9758-X.

González-Angullo, N.., Castro D., Rodríguez-Hernández, J., Davies, J. W., (2008) 'Runoff infiltration to permeable paving in clogged conditions', *Urban Water Journal*, 5(2), pp. 117–124. Available at: https://doi.org/10.1080/15730620701723538.

GrassPave (2021) *GrassPave | Grass Paver | Permeable Grass Surface | ACF Env.* Available at: https://acfenvironmental.com/products/stormwater-management/permeable-porous-paving/grass-pave2-grass-paver/ (Accessed: 30 September 2021).

Grimmond, S. (2007) 'Urbanization and global environmental change: local effects of urban warming', *Geographical Journal*, 173(1), pp. 83–88. Available at: https://doi.org/10.1111/J.1475-4959.2007.232_3.X.

Harvey, J., Saboori A., Dauvergne M., Steyn W., Jullien A., Li H., (2014) 'COMPARISON OF NEW PAVEMENT CONSTRUCTION GHG AND ENERGY IMPACTS IN DIFFERENT REGIONS'.

Hess, T. and Ibe, C. (2011) *Evaluation of the performance of permeable pavement at Lamb Drove FINAL - PDF Free Download*. Departmentof Environmental Science and Technology, Cranfield University.

Holmes, R.R., Hart, M.L. and Kevern, J.T. (2017) 'Enhancing the Ability of Pervious Concrete to Remove Heavy Metals from Stormwater', *Journal of Sustainable Water in the Built Environment*, 3(2), p. 04017004. Available at: https://doi.org/10.1061/JSWBAY.0000823.

Hossain, M. and Scofield, L.A. (1991) 'Porous pavement for control of highway run-off', (FHWA/AZ91-352).

Hunt, B., Stevens, S. and Mayes, D. (2002) 'Permeable Pavement Use and Research at Two Sites in Eastern North Carolina', *Global Solutions for Urban Drainage*, pp. 1–10. Available at: https://doi.org/10.1061/40644(2002)39.

Hunt, W.F. and Collins, K.A. (2008) 'Permeable Pavement: Research Update and Design Implications', *NORTH CAROLINA COOPERATIVE EXTENSION SERVICE* [Preprint]. Available at: https://nacto.org/docs/usdg/urban_waterways_permeable_pavement_hunt.pdf (Accessed: 23 September 2021).

Ichinose, T., Matsumoto, F. and Kataoka, K. (2008) 'Counteracting Urban Heat Islands in Japan', *Urban Energy Transition*, pp. 365–380. Available at: https://doi.org/10.1016/B978-0-08-045341-5.00015-3.

Iserning, T., Koster, H. and Scazzrca, I. (1990) 'Experiences with Porous Asphalt in Switzerland', *Transportation Research Record*, Transporta(1265).

Jayasuriya, N. and Kadurupokune, N. (2010) ‘Comparative performance of permeable and porous Pavements’.

Kayhanian, M., Anderson D., Harvey J., Jones D., Muhunthan B., (2012) ‘Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots’, *Journal of Environmental Management*, 95(1), pp. 114–123. Available at: https://doi.org/10.1016/J.JENVMAN.2011.09.021.

Kelly, D.A. (2018) ‘Impact of paved front gardens on current and future urban flooding’, *Journal of Flood Risk Management*, 11, pp. S434–S443. Available at: https://doi.org/10.1111/JFR3.12231.

Kia, A., Wong, H. and Cheeseman, C. (2017) ‘Clogging in permeable concrete: A review’, *Journal of environmental management*, 193, pp. 221–233. Available at: https://doi.org/10.1016/J.JENVMAN.2017.02.018.

Kim, G.M. Jang J. G., Khalid H. R., Lee H. K., (2017) ‘Water purification characteristics of pervious concrete fabricated with CSA cement and bottom ash aggregates’, *Construction and Building Materials*, 136, pp. 1–8. Available at: https://doi.org/10.1016/J.CONBUILDMAT.2017.01.020.

Kumar, A. and Kumar, S. (2013) ‘Development of paving blocks from synergistic use of red mud and fly ash using geopolymerization’, *Construction and Building Materials*, 38, pp. 865–871. Available at: https://doi.org/10.1016/J.CONBUILDMAT.2012.09.013.

Kusumastuti, C., Chandra H. P., Wibisono K., Hartono A.C., (2019) ‘Eco Drainage System for Surface Runoff Reduction in Indonesia’, *Civil Engineering Dimension*, 21(1), pp. 29–35. Available at: https://doi.org/10.9744/CED.21.1.29-35.

Lee, H.S., Lee, J.Y. and Yu, M.Y. (2003) ‘Influence of iron oxide pigments on the properties of concrete interlocking blocks’, *Cement and Concrete Research*, 33(11), pp. 1889–1896. Available at: https://doi.org/10.1016/S0008-8846(03)00209-6.

Lee, J.G. and Heaney, J.P. (2003) ‘Estimation of Urban Imperviousness and its Impacts on Storm Water Systems’, *Journal of Water Resources Planning and Management*, 129(5), pp. 419–426. Available at: https://doi.org/10.1061/(ASCE)0733-9496(2003)129:5(419).

Lee, M., Tia M., Chuang S., Huang Y., Chiang C., (2013) ‘Pollution and Purification Study of the Pervious Concrete Pavement Material’, *Journal of Materials in Civil Engineering*, 26(8), p. 04014035. Available at: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000916.

Low, H. and Heyden, T. (2015) ‘The decline of the British front garden - BBC News’, *BBC News Magazine*, 15 May. Available at:

https://www.bbc.com/news/magazine-32780242 (Accessed: 21 September 2021).
Lucke, T. and Beecham, S. (2011) 'Field investigation of clogging in a permeable pavement system', *http://dx.doi.org/10.1080/09613218.2011.602182*, 39(6), pp. 603–615. Available at: https://doi.org/10.1080/09613218.2011.602182.
Mashudi, I., Suardana N.P.G., Thanaya I.N.A., Adnyana, I.W.B., Kencanawati, C.I.P.K. (2020) 'Compressive strength and truck run over ability of plastic/sand paving block composites', *IOP Conference Series: Materials Science and Engineering*, 839(1), p. 012011. Available at: https://doi.org/10.1088/1757-899X/839/1/012011.
McCain, G.N. and Suozzo, M. (2010) 'A Laboratory Study on the Effects of Winter Surface Applications on the Hydraulic 1 Conductivity of Porous Concrete Pavements 2 3', *undefined* [Preprint].
McCain Jr, G.N. and Dewoolkar, M.M. (2010) 'Effects of Winter Surface Applications on Hydraulic Conductivity of Porous Concrete Pavements'.
Mohajerani, A., Bakaric, J. and Jeffrey-Bailey, T. (2017) 'The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete', *Journal of Environmental Management*, 197, pp. 522–538. Available at: https://doi.org/10.1016/J.JENVMAN.2017.03.095.
Mullaney, J. and Lucke, T. (2014a) 'Practical Review of Pervious Pavement Designs', *CLEAN – Soil, Air, Water*, 42(2), pp. 111–124. Available at: https://doi.org/10.1002/CLEN.201300118.
Mullaney, J. and Lucke, T. (2014b) 'Practical Review of Pervious Pavement Designs', *CLEAN – Soil, Air, Water*, 42(2), pp. 111–124. Available at: https://doi.org/10.1002/CLEN.201300118.
Murphy, J.M., Sexton D.M.H., Jenkins G.J., Jenkins G.J., (2009) *UK Climate Projections Science Report: Climate Change Projections*. Available at: https://www.researchgate.net/publication/313212734_UK_Climate_Projections_Science_Report_Climate_Change_Projections (Accessed: 21 September 2021).
Nicholls, J.C. and Carswell, I.G. (2001) 'THE DESIGN OF POROUS ASPHALT MIXTURES TO PERFORMANCE-RELATED CRITERIA', *TRL REPORT 497* [Preprint].
Olayinka, S.A., Adekunle, O.S. and Musa, H.A. (2020) 'Exploring the Effect of Landscaping on Property Value in Meeting the Contemporary Sub-Sahara Environment', *Env. Design & Construction Mgt. (JECM-4)*, 18(4).

Parangi, B., Gagan and Hallur, M.S. (2020) 'REUSE OF PLASTICS WASTE FOR THE PRODUCTION OF FLOOR TILES', *Journal of Seybold Report*, 15(8 2020).

Pawsey, M.R. (1982) 'Providing Campus Environmental Coherence by Landscaping.', *Planning for Higher Education*, 11(1), pp. 25–29.

Penteado, C.S.G., Viviani De Carvalho, E. and Lintz, R.C.C. (2016) 'Reusing ceramic tile polishing waste in paving block manufacturing', *Journal of Cleaner Production*, 112, pp. 514–520. Available at: https://doi.org/10.1016/J.JCLEPRO.2015.06.142.

Pezzaniti, D., Beecham, S. and Kandasamy, J. (2009) 'Influence of clogging on the effective life of permeable pavements', *Proceedings of the Institution of Civil Engineers: Water Management*, 162(3), pp. 211–220. Available at: https://doi.org/10.1680/WAMA.2009.00034.

Pratt, C. (1990) 'Permeable pavements for stormwater quality enhancement', *cedb.asce.org* [Preprint].

Pratt, C.J. (1997) 'Design Guidelines for Porous/Permeable pavements', in *Sustaining Urban water resources in the 21st century*.

Pratt, C.J., Mantle, J.D.G. and Schofield, P.A. (1995) 'UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality', *Water Science and Technology*, 32(1), pp. 63–69. Available at: https://doi.org/10.1016/0273-1223(95)00539-Y.

Puehmeier, T. and Newman, A.P. (2008) 'Oil Retaining and Treating Geotextile for Pavement Applications'.

Rachmat, M. and Salsabilla, T.N. (2019) 'Analysis of hexagonal paving block as a better paving shape', *IOP Conference Series: Materials Science and Engineering*, 527(1), p. 012068. Available at: https://doi.org/10.1088/1757-899X/527/1/012068.

Ramesh Kumar, G. and Kumar Sharma, U. (2014) 'Standard Test Methods for Determination of Abrasion Resistance of Concrete', *International Journal of Civil Engineering Research*, 5(2), pp. 155–162.

Rankin, K. and Ball, J.E. (2004) 'A Review of the Performance of Permeable Pavers'.

Sanderson, M. (2010) 'Changes in the frequency of extreme rainfall events for selected towns and cities'.

Sangiorgi, C., Eskandarsefat S., Tataranni P., Simone A., Vignali V., Lantieri C., Dondi G., (2017) 'A complete laboratory assessment of crumb rubber porous asphalt', *Construction and Building Materials*, 132, pp. 500–507. Available at: https://doi.org/10.1016/J.CONBUILDMAT.2016.12.016.

Sartipi, M. and Sartipi, F. (2019) 'Stormwater retention using pervious concrete pavement: Great Western Sydney case study', *Case Studies in*

Construction Materials, 11, p. e00274. Available at: https://doi.org/10.1016/J.CSCM.2019.E00274.

Schaefer, V., Eskandarsefat S., Tataranni P., Simone A., Vignali V., Lantieri C., Dondi G., (2006) *MIX DESIGN DEVELOPMENT FOR PERVIOUS CONCRETE IN COLD WEATHER CLIMATES*.

Scholz, M. and Grabowiecki, P. (2007) 'Review of permeable pavement systems', *Building and Environment*, 42(11), pp. 3830–3836. Available at: https://doi.org/10.1016/J.BUILDENV.2006.11.016.

Sehgal, K., Drake J., Seters T.V., Linden W.K.Y., (2018) 'Improving Restorative Maintenance Practices for Mature Permeable Interlocking Concrete Pavements', *Water 2018, Vol. 10, Page 1588*, 10(11), p. 1588. Available at: https://doi.org/10.3390/W10111588.

Shackel, B. (2010) 'THE DESIGN, CONSTRUCTION AND EVALUATION OF PERMEABLE PAVEMENTS IN AUSTRALIA', in. 24th ARRB Conference – Building on 50 years of road and transport research, Melbourne, Australia 2010 .

Straet, F., Beckers, E. and Degre, A. (2008) 'Hydraulic behaviour of greened porous pavements: a physical study TERRA-multiscale soil systems View project GISER Gestion Intégrée sol érosion Ruissellement View project', in. 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Synnefa, A., Karlessi T., Gaitani N., Santamouris M., Assimakopoulos D. N., Papakatsikas C., (2011) 'Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate', *Building and Environment*, 46(1), pp. 38–44. Available at: https://doi.org/10.1016/J.BUILDENV.2010.06.014.

Tempa, K., Chettri M., Thapa G., Phurba, Gyeltshen C., Norbu D., Gurung D., Wangchuk U., (2021) 'An experimental study and sustainability assessment of plastic waste as a binding material for producing economical cement-less paver blocks', *Engineering Science and Technology, an International Journal* [Preprint]. Available at: https://doi.org/10.1016/J.JESTCH.2021.05.012.

Tirpak A., Winston R.J., Feliciano M., Feliciano M., (2020) 'Stormwater quality performance of permeable interlocking concrete pavement receiving run-on from an asphalt traffic lane in a cold climate', *Environmental science and pollution research international*, 27(17), pp. 21716–21732. Available at: https://doi.org/10.1007/S11356-020-08707-2.

Udawattha, C., Galabada, H. and Halwatura, R. (2017) 'Mud concrete paving block for pedestrian pavements', *Case Studies in Construction Materials*, 7, pp. 249–262. Available at: https://doi.org/10.1016/J.CSCM.2017.08.005.

Wang, X., Chin, C.S. and Xia, J. (2019) 'Material Characterization for Sustainable Concrete Paving Blocks', *Applied Sciences 2019, Vol. 9, Page 1197*, 9(6), p. 1197. Available at: https://doi.org/10.3390/APP9061197.

Wanielista, M. Chopra M., Spence J., Ballock C., (2007) 'Hydraulic Performance Assessment of Pervious Concrete Pavements for Stormwater Management Credit'.

Weiss, P.T., Kayhanian M., Gulliver J.S., Khazanovich L., (2017) 'Permeable pavement in northern North American urban areas: research review and knowledge gaps', *https://doi.org/10.1080/10298436.2017.1279482*, 20(2), pp. 143–162. Available at: https://doi.org/10.1080/10298436.2017.1279482.

Willems, P., Arnbjerg-Nielsen K.., Olsson, J., Nguyen V.T.V., (2012) 'Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings', *Atmospheric Research*, 103, pp. 106–118. Available at: https://doi.org/10.1016/J.ATMOSRES.2011.04.003.

Xie, N., Akin, M. and Shi, X. (2019) 'Permeable concrete pavements: A review of environmental benefits and durability', *Journal of Cleaner Production*, 210, pp. 1605–1621. Available at: https://doi.org/10.1016/J.JCLEPRO.2018.11.134.

Yang, J., Wang Z.H., Kaloush K.E., (2015) 'Characteristics of indoor air quality at urban elementary schools in Seoul, Korea: Assessment of effect of surrounding environments', *Atmospheric Pollution Research*, 6(6), pp. 1113–1122. Available at: https://doi.org/10.1016/j.apr.2015.06.009.

Yang, J., Wang, Z.H. and Kaloush, K.E. (2015) 'Environmental impacts of reflective materials: Is high albedo a "silver bullet" for mitigating urban heat island?', *Renewable and Sustainable Energy Reviews*, 47, pp. 830–843. Available at: https://doi.org/10.1016/J.RSER.2015.03.092.

Yildirim, Y., Dossey T., Fults K.W., Trevino M., (2006) 'Winter Maintenance Issues Associated with New Generation Open-Graded Friction Courses'.

Yogananth, Y., Thanushan K., Sangeeth P., Coonghe J.C., Sathiparan N., (2019) 'Comparison of strength and durability properties between earth-cement blocks and cement–sand blocks', *Innovative Infrastructure Solutions*, 4(1). Available at: https://doi.org/10.1007/S41062-019-0238-8.

Yong C.F., Deletic A., Fletcher T.D., Grace M., (2008) 'The clogging behaviour and treatment efficiency of a range of porous pavements', in *11 th International Conference on Urban Drainage, Edinburgh,* *Scotland, UK*. 11 th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Younger, K., Hicks, R.G. and Gower, J. (1994) 'EVALUATION OF POROUS PAVEMENTS USED IN OREGON. FINAL REPORT. VOLUME II - APPENDICES'.

Annex 2

Assessment of the optimum dimensions for cobble-type paving blocks using finite element modeling

N.R.KUMARAGE
Department of Civil Engineering
University of Moratuwa
Sri Lanka
kumaragenipun@gmail.com

C. JAYASINGHE
Department of Civil Engineering
University of Moratuwa
Sri Lanka
chintha@uom.lk

K.P.H. PERERA
Department of Civil Engineering
University of British Colombia
Canada
piyaruwan@gmail.com

K.K.G.K.D. KARIYAWASAM
Department of Civil Engineering
University of Moratuwa
Sri Lanka
kasund@uom.lk

S. HERATH
Department of Civil Engineering
University of Moratuwa
Sri Lanka
sumuduh@uom.lk

***Abstract*— A numerical model was developed to investigate the deflection of permeable interlocking concrete blocks. In this study, the acceptance of paving blocks with extensive plan areas was tested. ABAQUS finite element modeling software which is commercially available was used and a static, linear perturbation analysis was carried out. Three alternative block dimensions were determined according to the guidelines provided in ASTM C936 and were modeled. Mesh sensitivity analysis was carried out on each alternative to identify the optimum global element size for each model. Although all three tested models resulted in vertical deformations less than the threshold, the results indicated a positive association between the exposed plan area and the vertical deformation. Finally, it can be concluded as the SLS 1425 recommended paving block dimensions resulted in the most favorable results.**

Keywords—Finite Element Modelling, Pavement design, Paving blocks, Cobble type, Stretcher bond

I. INTRODUCTION

Landscaping has gained immersed attention during the past few years, affecting the total property value [1]. One of the significant landscaping components is land paving [2]. Although land paving is known to create pleasant townscapes, one major drawback of these pavement systems is the prevention of the infiltration of rainwater, resulting in higher runoff and increasing the risk for flooding [3], [4]. This forced engineers to change from traditional paving systems to permeable pavement systems such as porous asphalt, permeable concrete, and permeable interlocking concrete paving [5]–[7].

The Permeable Interlocking Concrete Paving (PICP) system has been widely used in the recent past as one of the famous paving systems [5]. PICP is the system where concrete paving blocks are designed and laid with sufficient spacing between blocks so that stormwater can infiltrate the base layer through the spacing provided [6]. The joints and spaces between pavers are kept void without filling with sand or any binding material, and the structural strength is obtained by its interlocking behavior. The void percentage of the paving system is 8 to 20% of the paving area, which allows for better infiltration of stormwater [7]. Guidelines have been developed by many authorities creating restrictions on dimensions and physical properties to ensure the permeable properties of PICP [8], [9]. These PICP blocks are developed in many shapes such as cobble and uni-style [10]. The Cobble type paving shape is widely used with various dimensions developed according to ASTM C936 standard [9]. This paper is based on analyzing the deflections and interlocking behaviour for cobble type paving blocks when the block is created with more extensive exposed plan area as per ASTM guidelines with a FEM approach.

II. OBJECTIVE

The main research objective was to determine the optimum dimensions of the cobble-type paving blocks through the use of FEM.

III. FINITE ELEMENT MODELING

Finite Element Modelling (FEM) is one of the main approaches to conducting a numerical analysis for many engineering applications. It is extensively used in engineering as it reduces costs and shortens design cycles compared with prototype testing. In FEM, the analysis can either be conducted in 2D or 3D according to preference. FEM analysis was conducted using ABAQUS/CAE software for this research which can easily create, edit, monitor, and visualize advanced finite element models [11]. The following section describes the details of the developed model.

A. Properties of the block and subgrade layers

A 1 m x 1 m square plane was used for the study. It was defined with subgrade layers, base course, sand bed, and concrete block layer at the top, as shown in Figure 1. Three cobble-type block sizes were tested in this analysis. A steel loading plate of 69,750 mm^2 (225 mm x 310 mm) was used at the model's center for loading, equal to a single wheel-tire contact area [12].

B. Development of the Abaqus FEM model

The model was developed using the material properties given in Table 1, which were identified in the literature [13], [14]. A stretcher bond was used for the paving block layer.

Table 1: Material properties

	Subgrade	Base	Sand	Concrete
Density (kg/m^3)	1600	1800	1680	2400

Youngs Modulus E (GPa)	0.12	0.24	0.01	23.2
Poisson ratio	0.40	0.30	0.26	0.20

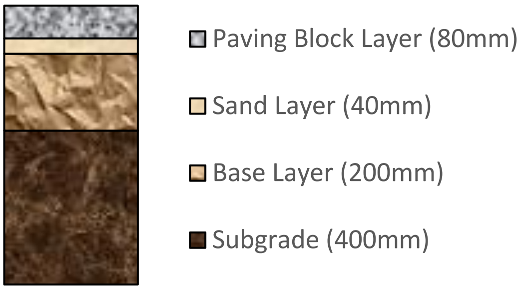

Figure 1: Section view of the model

Boundary conditions were developed according to Mampearachi and Prageeth [14]. It was defined by having restrained the horizontal movement of each layer at the boundaries allowing vertical displacement and defining an encastre boundary condition at the bottom of the subgrade, as shown in Figure 2. In addition, a tie constraint was provided in all vertical contact surfaces to define a collective settlement for the entire model. The developed ABAQUS model is shown in Figure 3.

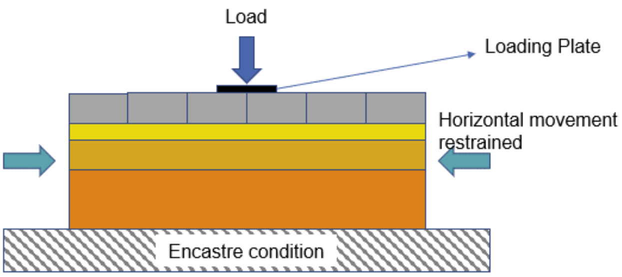

Figure 2: Boundary and loading conditions

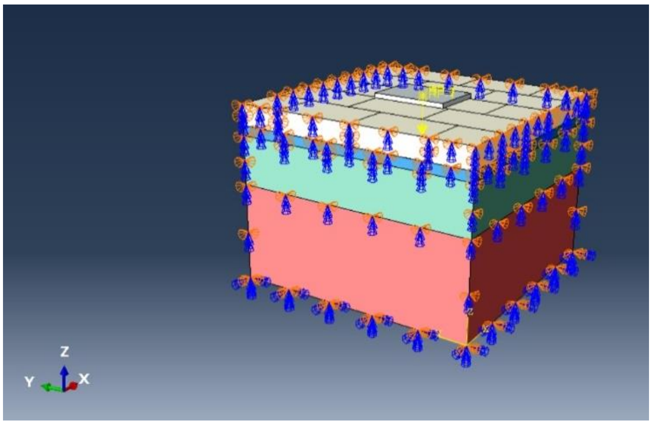

Figure 3: Boundary conditions of the ABAQUS model

C. Loading conditions

The loading of the model was conducted through a loading plate. The loading plate had a plan area of 69,750 mm^2 (225 mm x 310 mm) which is approximately equal to the contact area of a single tire [12]. A point load of 60 kN was applied at the center of the plate, as shown in Figure 2.

D. Validation of the model

Mampearachchi and Gunarathna conducted a similar FEM approach for smaller paving blocks (210 mm x 100 mm x 60 mm) using ANSYS FEM software validated with a physical model [14]. Hence, to validate the ABAQUS model in this paper, the same model was developed using ABAQUS FEM software, and deflections were compared for loads of 10 kN, 40 kN, and 60 kN, as shown in the following Figure 4.

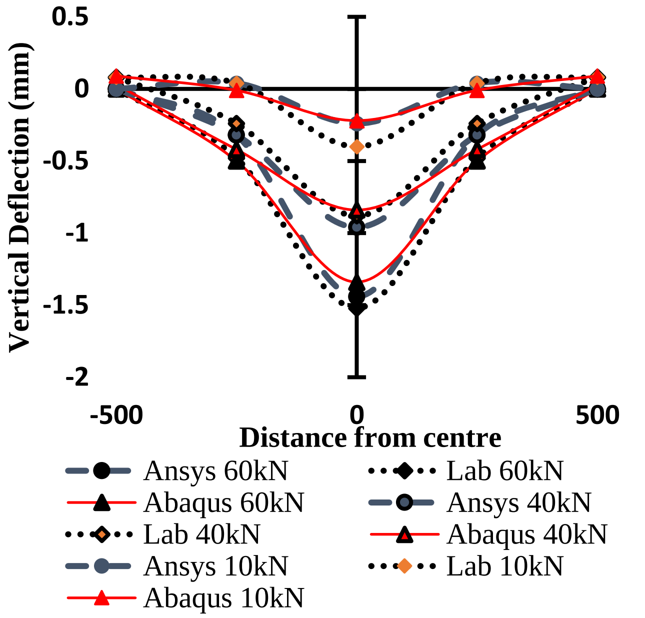

Figure 4: Verification of the ABAQUS model

With the given results we could see that the ABAQUS model corresponds almost similar to the laboratory model and the Ansys model which were obtained from the literature. Hence we could conclude that the model is valid.

E. Development of the three alternative block dimensions

American Society for Testing and Materials (ASTM) developed a standard for determining dimensions for solid concrete interlocking paving units (ASTM C936) [15]. According to the standard, there are several guidelines when defining paving block sizes as follows,

- Exposed face area $\leq$ 0.065 m^2
- The overall length divided by thickness $\leq$ 4
- The minimum thickness shall be 60mm

The first alternative was defined according to the dimensions given in SLS 1425 standard [16] which also aligns with the ASTM C936 standard, and the final two alternative block sizes were defined to have a maximum plan area with optimum thickness as given in Table 2 according to the guidelines discussed in ASTM C936 [9]. Note that each dimension was rounded off to the nearest 5mm, considering practicality.

Table 2: Alternative block sizes

Alternative	Length (mm)	Width (mm)	Thickness (mm)
1	200	100	80
2	300	200	75
3	250	250	65

F. The meshing of the model

Mesh sensitivity analysis was conducted to find the correct mesh size for each model. Mesh sizes were changed by adjusting the global element size of each part/ layer and adjusting the total number of elements. The total number of elements varied from 117 elements to 56708 elements for the mesh sensitivity analysis. Initially, an attempt was made to use a finer mesh for the topmost layers and gradually increase the mesh size to a coarser mesh when moving to the bottom layers. However, it was more convenient to maintain a uniform mesh throughout the model since mesh ratios between the layers had to be maintained constant for the mesh sensitivity analysis. Hence, a uniform mesh was used for the entire model, as shown in Figure 5.

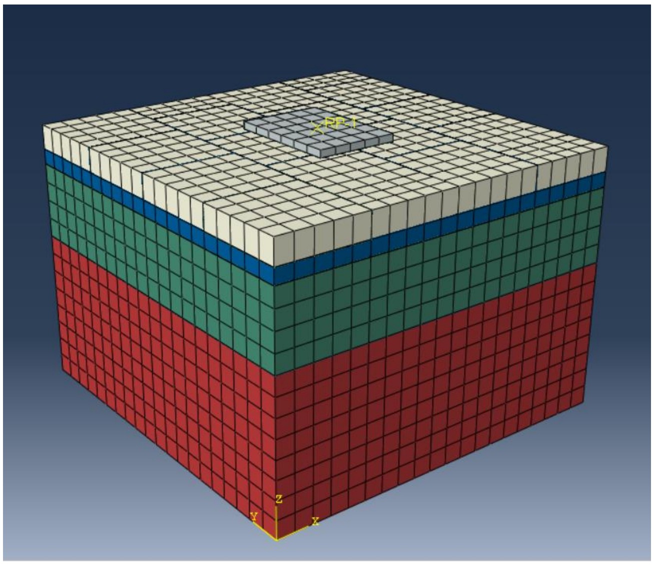

Figure 5: Meshing of the model

G. Surface tolerance standard

The surface tolerance is not mentioned in the ASTM standard. However, many institutions such as Interlocking Concrete Pavement Institute and The Indian Roads Congress have provided the surface tolerance/ surface flatness to be maintained less than 10 mm for any 3 m interval [17], [18] and therefore this value was used as the threshold for the model.

H. Analysis

Linear properties such as elasticity and Poisson's ratio were included in the model and a static, linear perturbation analysis was carried out for the model to obtain the results.

IV. Results and Discussion

Three finite element models were developed for the three alternative block dimensions. A mesh sensitivity analysis was initially conducted for each alternative to find the optimum mesh size for the analysis. Figure 6 indicates the mesh sensitivity conducted for alternative 1, in which the deflections converged at a global element size of 0.05 m, which approximately resulted in 5000 total elements. Similarly, mesh sensitivity analysis was conducted for the other two alternatives in which the deflections converged at 2000 elements and 1000 elements, respectively.

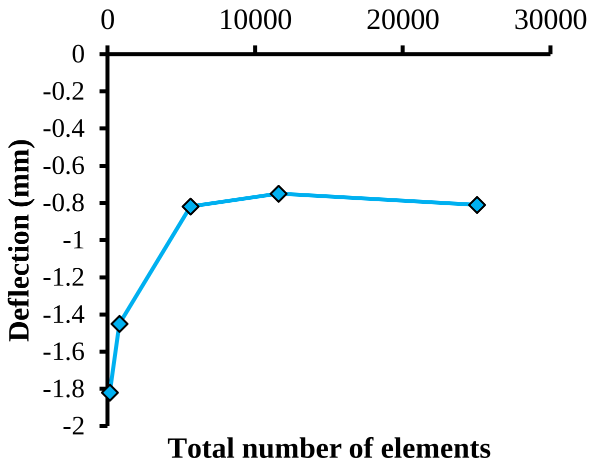

Figure 6: Mesh sensitivity analysis for alternative 1

For Alternative 1, since the model converged at a global size of 0.05 m with 5000 total elements, the same mesh size was used to measure the vertical deflection. The vertical deflection of the Alternative 1 occurred as shown in Figure 7, and the deflection shape was similar to that in Gunathilake and Mampearachchi [10]. The maximum deflection was visible at the center under the loading plate, which was common for all three alternatives. A cross-section at the center of the pavement was used to identify the maximum deflection at the center, as shown in Figure 8. A vertical deformation scale factor of 60 was used for clear visibility.

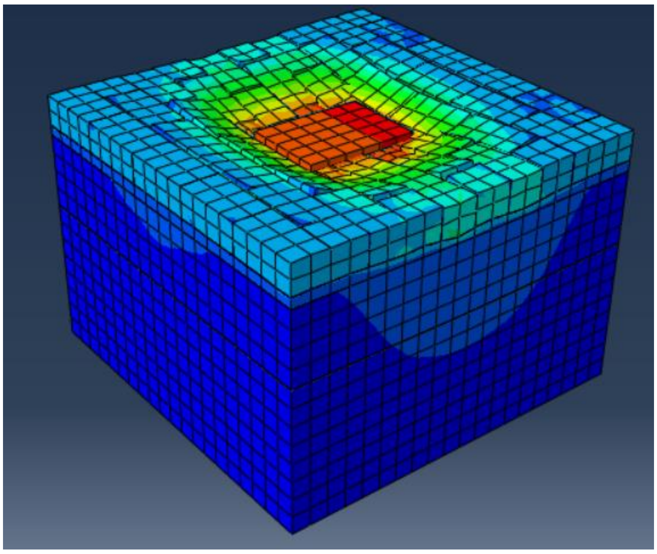

Figure 7: Vertical deflection of ABAQUS FEM for alternative 1

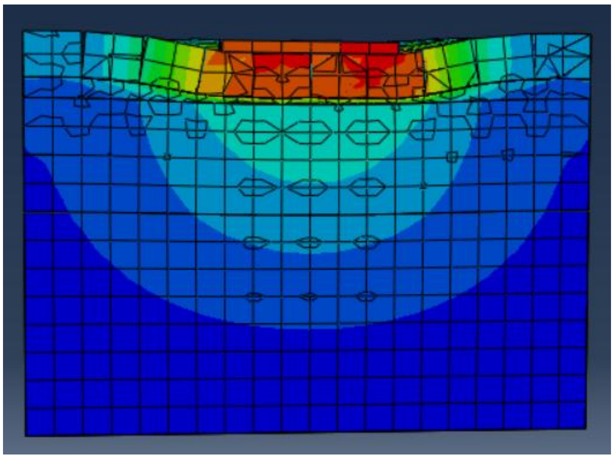

Figure 8: Vertical deflection at the center cross-section of alternative 1

Similar steps were carried out for the other two alternatives, and the resulted maximum vertical deflection was summarized as shown in Figure 9.

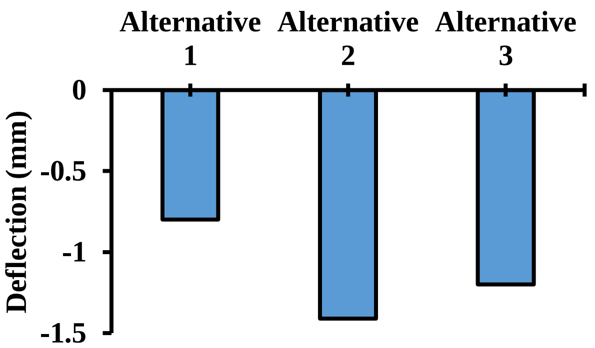

Figure 9: Maximum vertical deflection

The results showed that Alternative 1 (the SLS recommended paving block size) resulted in the lowest vertical deflection, 0.8 mm, and for Alternatives 2 and 3, vertical deflections were 1.4 mm and 1.2 mm, respectively. The exposed plan areas of the three alternative blocks are 0.02 m^2, 0.06 m^2, and 0.0625 m^2, respectively. There is a plan area increment of 200% and 212.5% for alternatives 2 and 3 concerning alternative 1 and the deformations have also increased by 75% and 50% respectively. The lower plan area of a block implies a higher number of blocks will be used and a higher number of joints for a given area of blocks, thus higher permeability. Therefore Alternative 1 has shown the most desirable properties of the potential for highest permeability and lowest deflection.

Additionally, larger paving blocks will result in a higher weight. Which might need a higher labor requirement in installation and can be a potential drawback in handling and installing the paving blocks.

V. Conclusion

This paper presented a linear finite element model developed to estimate the deformation of three different alternative sizes of cobble-type paving blocks. A validation model of a block (210 mm x 100 mm x 60 mm) was conducted, and the model results agreed with the experimental results available in the literature. Out of the three alternative block sizes considered, results obtained from the finite element model indicated that the smaller-sized SLS 1425 recommended paving block had the lowest vertical deflection of 0.8 mm, compared to other blocks with plan area higher by 200%, which had deflections higher than 50%. However, according to surface tolerance standard, all the deflections were acceptable, and there is no clear evidence not to use paving blocks with extensive plan area. Hence, all the paving block sizes can be recommended. However. using the smallest/SLS 1425 recommended paving block will have lesser deformations, will be easy in installation and will have a higher joint concentration leading for a higher permeability in the pavement.

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References

[1] S. Olayinka, O. Sulaiman Adekunle, and H. Ahmed Musa, “Exploring the Effect of Landscaping on Property Value in Meeting the Contemporary Sub-Sahara Environment,” *Env. Design & Construction Mgt. (JECM-4)*, vol. 18, no. 4, Oct. 2020.

[2] M. R. Pawsey, “Providing Campus Environmental Coherence by Landscaping.,” *Planning for Higher Education*, vol. 11, no. 1, pp. 25–29, 1982.

[3] J. G. Lee and J. P. Heaney, “Estimation of Urban Imperviousness and its Impacts on Storm Water Systems,” *Journal of Water Resources Planning and Management*, vol. 129, no. 5, pp. 419–426, Sep. 2003, doi: 10.1061/(ASCE)0733-9496(2003)129:5(419).

[4] P. Willems, K. Arnbjerg-Nielsen, J. Olsson, and V. T. V. Nguyen, “Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings,” *Atmospheric Research*, vol. 103, pp. 106–118, Jan. 2012, doi: 10.1016/J.ATMOSRES.2011.04.003.

[5] T. Lucke and S. Beecham, “Field investigation of clogging in a permeable pavement system,” *http://dx.doi.org/10.1080/09613218.2011.602182*, vol. 39, no. 6, pp. 603–615, 2011, doi: 10.1080/09613218.2011.602182.

[6] J. Mullaney and T. Lucke, “Practical Review of Pervious Pavement Designs,” *CLEAN – Soil, Air, Water*, vol. 42, no. 2, pp. 111–124, Feb. 2014, doi: 10.1002/CLEN.201300118.

[7] W. F. Hunt and K. A. Collins, “Permeable Pavement: Research Update and Design Implications,” *NORTH CAROLINA COOPERATIVE EXTENSION SERVICE*, 2008, Accessed: Sep. 23, 2021. [Online]. Available: https://nacto.org/docs/usdg/urban_waterways_permeable_pavement_hunt.pdf

[8] “EUPAVE is the European Concrete Paving Association - Find out more about the benefits of concrete pavements.” https://www.eupave.eu/ (accessed Mar. 07, 2022).

[9] *ASTM Standards*. 2021. Accessed: Jan. 09, 2022. [Online]. Available: https://www.astm.org/about/overview.html

[10] D. Gunatilake and W. K. Mampearachchi, "Finite element modelling approach to determine optimum dimensions for interlocking concrete blocks used for road paving," *https://doi.org/10.1080/14680629.2017.1385512*, vol. 20, no. 2, pp. 280–296, Feb. 2017, doi: 10.1080/14680629.2017.1385512.

[11] "Abaqus CAE - SIMULA™ by Dassault Systèmes®." https://www.3ds.com/products-services/simulia/products/abaqus/abaquscae/ (accessed Feb. 11, 2022).

[12] B. C. Panda and A. K. Ghosh, "Structural Behavior of Concrete Block Paving. I: Sand in Bed and Joints," *Journal of Transportation Engineering*, vol. 128, no. 2, pp. 123–129, Mar. 2002, doi: 10.1061/(ASCE)0733-947X(2002)128:2(123).

[13] M. Hafezolghorani, F. Hejazi, R. Vaghei, M. S. bin Jaafar, and K. Karimzade, "Simplified damage plasticity model for concrete," *Structural Engineering International*, vol. 27, no. 1, pp. 68–78, Feb. 2017, doi: 10.2749/101686616X1081.

[14] W. Mampearachchi, P. Gunarathna, W. K. Mampearachchi, and W. P. H. Gunarathna, "Finite-Element Model Approach to Determine Support Conditions and Effective Layout for Concrete Block Paving Design and Development of a Portable Wireless Axle Load Measuring System View project Finite-Element Model Approach to Determine Support Conditions and Effective Layout for Concrete Block Paving," 2010, doi: 10.1061/(ASCE)MT.1943-5533.0000118.

[15] "ASTM International - Standards Worldwide." https://www.astm.org/ (accessed Aug. 12, 2021).

[16] SLS, "SLS 1425," 2011. Accessed: Apr. 08, 2022. [Online]. Available: http://slsi.lk/index.php?lang=en

[17] Interlocking Concrete Pavement Institute, "Construction Tolerances and Recommendations for Interlocking Concrete Pavements."

[18] THE INDIAN ROADS CONGRESS, *GUIDELINES FOR THE USE OF INTERLOCKING CONCRETE BLOCK PAVEMENT*. 2004. Accessed: Apr. 09, 2022. [Online]. Available: https://law.resource.org/pub/in/bis/irc/irc.gov.in.sp.063.2004.pdf