

1 **Material Characterisation and Design of Alternative Pavement Surfacing for Steep Hilly**
2 **Sections of Low-Volume Roads in Ghana**

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1 **ABSTRACT**

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3 Identifying appropriate pavement design options for higher-risk sections of low-volume roads is a crucial
4 part of Ghana's strategy to improve sustainable all-season rural access. This paper investigates the
5 suitability of alternative surfacing for steep hilly sections of low-volume roads in Ghana with gradients
6 above 12%. Typically, these roads are constructed with weak natural gravel as the wearing course. To
7 address the persistent drainage and erosion problems on these steep sections, four alternative rigid
8 pavement options were designed and proposed. These were interlocking concrete block paving (ICBP),
9 roller compacted concrete (RCC), thin mesh reinforced concrete (TMRC), and non-reinforced concrete
10 (NRC). We present the material selection, pavement designs, and life-cycle economic analysis of these
11 four cost-effective pavement options. The present worth of cost life-cycle cost appraisal of the options
12 considering the initial cost, probable maintenance cost, and salvage value of the road asset over a 25-year
13 service life, with a pavement design life of 15 years and an analysis period of 25 years are discussed. The
14 results indicate that all four alternative surfacing types are economically feasible and comparable,
15 although RCC has the lowest cost, while the ICBP option is relatively the most expensive.

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18 **Keywords:** Low-Volume Roads, Steep Gradients, Interlocking concrete block paving, Roller Compacted
19 Concrete, Thin Mesh Reinforced Concrete, Non-Reinforced Concrete

1 INTRODUCTION

2 Steep slopes (gradients above 12%) on low-volume feeder roads in Ghana are at high risk of
3 slope failure, erosion, and drainage-related problems, which ultimately affect rural communities by
4 causing traffic delays, safety issues, damage to natural resources, and hindering access to social and
5 economic activities. These problems are mainly attributed to prolonged rainy seasons, coupled with weak
6 natural gravels commonly used as a wearing course on feeder roads. Cost-effective rehabilitation and
7 maintenance of these roads are crucial for Ghana's agricultural development, economic recovery and
8 growth, poverty alleviation, and food security. Recent research has shown that most earth and gravel
9 roads in Ghana are uneconomical and unsustainable. Therefore, identifying appropriate design options for
10 high-risk sections of low-volume roads is essential for improving sustainable all-season rural access in
11 Ghana. Steep hill sections (gradients above 12%) of these roads are particularly vulnerable to slope
12 failure, erosion, and drainage issues, which negatively impact rural communities.

13 As part of the UK Government DFID-funded Africa Community Access Partnership (AfCAP)
14 Research for Community Access Partnership (ReCAP) programme, alternative road surfacing materials
15 and pavement structures were investigated for steep hilly road sections in Ghana. Currently, over 70% of
16 Ghana's feeder roads are built on mountainous or rolling terrains. Feeder roads make up approximately
17 62% of the entire 68,124 km road network. However, only 5% of these roads have bituminous surfacings,
18 with the remaining 95% being either earth or gravel roads (1, 2). The Department of Feeder Roads (DFR)
19 oversees the administration, control, development, and maintenance of feeder roads in Ghana. The
20 rehabilitation and maintenance of feeder roads are crucial for supporting Ghana's socio-economic
21 development. These roads are essential for rural socio-economic growth and are a vital component of the
22 government's rural poverty reduction strategies. Well-maintained feeder roads ensure all-weather, year-
23 round access for communities, which is particularly important for Ghana's agriculture-based economy.
24 Poor rural roads undermine economic growth, making the rehabilitation and maintenance of feeder roads
25 vital for agricultural development, economic recovery, poverty alleviation, and food security.

26 Previous studies have shown that significant quantities of local materials are available for road
27 building in Ghana. For example, lateritic gravels have been extensively used in surfacing and gravel
28 roads. However, high rainfall areas and steep hill sections (gradient >12%) on feeder roads are prone to
29 high surface run-off, erosion, and flash flooding. Therefore, special attention must be given to installing
30 effective drainage systems and implementing measures to control erosion. Engineered paved surfacing
31 would mitigate these problems more effectively than gravel-wearing courses, especially on steep hills.
32 Moreover, the maintenance and rehabilitation costs of gravel roads are often high, with periodic re-
33 graveling operations costing between USD 500 and USD 2,000 per km per year (3) in many developing
34 countries. Compelling evidence indicates that lateritic materials not meeting standard specifications can
35 perform exceptionally well in road construction, even as a base course (4, 5). The geotechnical properties
36 of lateritic soils formed under tropical conditions, such as in Ghana, generally do not meet the
37 specification standards for road construction. A common practice to improve the engineering properties of
38 substandard natural road materials is through stabilization, which comes in various forms and methods (6
39 – 8).

40 The objective of this paper is to present the research outcomes investigating the suitability of four
41 alternative rigid pavement surfacings on steep gradients of low-volume roads to offer sustainable
42 solutions for drainage and erosion problems. The surfacings investigated were (1) modular concrete block
43 paving, (2) roller-compacted concrete, (3) thin mesh-reinforced concrete, and (4) non-reinforced concrete.
44 Other factors considered in the study included environmental friendliness and optimizing locally available
45 materials to create employment opportunities. The proposed alternatives aimed to provide cost-effective
46 designs allowing community participation and employment opportunities, especially for local residents.

47 **Figure 1** illustrates some of the problems. A prolonged rainy season (especially in southern
48 Ghana) coupled with weak natural (lateritic) soils exacerbates the issues facing hilly sections with
49 gradients over 12% on feeder roads in Ghana. Therefore, identifying appropriate surfacing options for
50 higher-risk sections on feeder roads is essential to the DFR's strategy for ensuring sustainable all-season
51 rural access in Ghana.

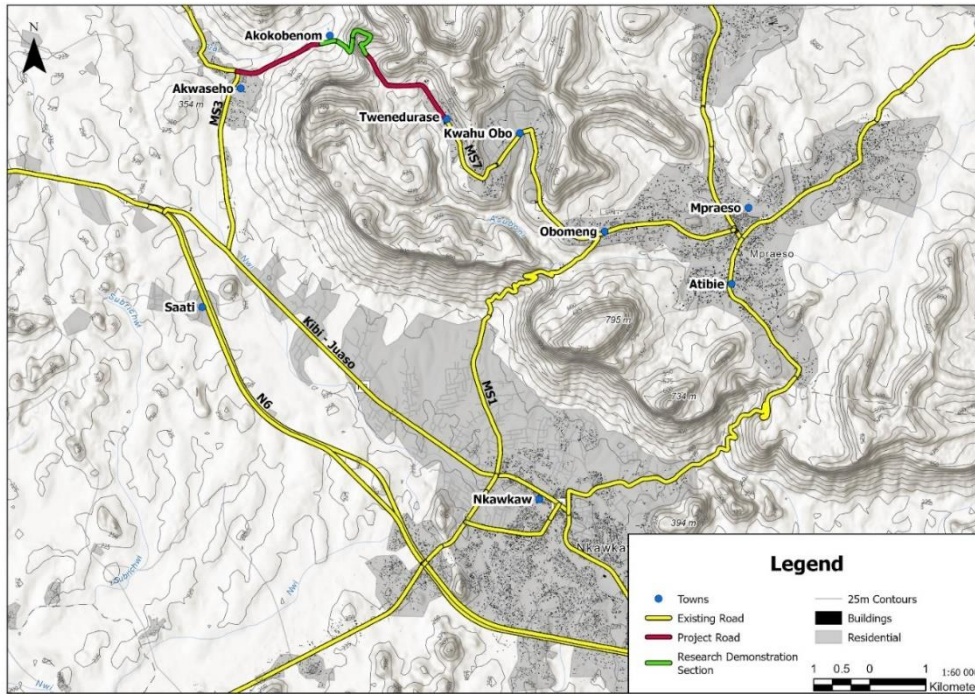


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Figure 1: Some problems associated with steep slope gravel roads in Ghana

STUDY AREA AND PROJECT ROAD CORRIDOR

The study area is located in the Eastern Region of Ghana, characterized by a mountainous terrain with an annual mean rainfall of 1,800 mm. This region contains several low-volume roads. The site was selected based on various factors, including traffic levels, terrain (gradients ranging from 12% to 22%), environmental sustainability, availability of local materials, and potential for employment generation. These considerations align with the framework proposed by (9). The relief of the study area includes rocks situated between 300 and 600 meters above mean sea level (AMSL). The project road runs from Akwesiho (geo-location: 6.617906N; 0.820665W; elevation 249 m) to Twenedurase (6.613102N; 0.787185W; elevation 570 m). The total length of this link road is 5.1 km (highlighted in red and green), with 1.6 km of steep hilly sections (Ch 1+900 to Ch 3+350; highlighted in yellow) designated as the research demonstration section. The hilltops in the area are flat to undulating and represent the eroded remnants of a former peneplain surface. **Figure 2** presents a topographical map of the study area, which includes the road linking Akwesiho and Twenedurase, as well as the beneficiary community of Akokobenum Nsu and the adjoining communities of Obo and Obomeng.



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Figure 2: Topographical map of the study area showing: (a) the research demonstration section (green) of the project road (red) and (b) the existing road (yellow) network connecting beneficiary communities

7 **Consideration of Design Factors and Assumptions**

8 Appropriate design factors and assumptions were considered for both geometric and pavement designs to
 9 achieve the project objectives. In addition to geometric and pavement design parameters, factors
 10 influencing material selection such as local availability, employment potential, environmental
 11 friendliness, and economic considerations were also taken into account. Traffic surveys conducted
 12 included screenline counts, turning movements, and loading studies. For the screenline counts, a 12-hour
 13 survey was performed over seven days at predetermined master stations. This data was analyzed using
 14 models recommended in (10), with adjustments made to determine the average daily traffic (ADT) for
 15 calculating traffic loading parameters. Geometric and structural design standards were selected to
 16 optimize the economic returns on construction investments. A key principle of this project was the use of
 17 locally available resources. Therefore, materials sourced locally were mapped and evaluated for
 18 suitability in the design of surfacing alternatives, in line with project objectives. It is important to note
 19 that the geometric design of the road is not covered in this paper. However, aspects related to geometric
 20 design, such as gradients, are implicitly addressed in the discussion of steep gradient values.

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22 **MATERIALS SELECTION AND DESIGN**

23 **Properties of Layer Materials**

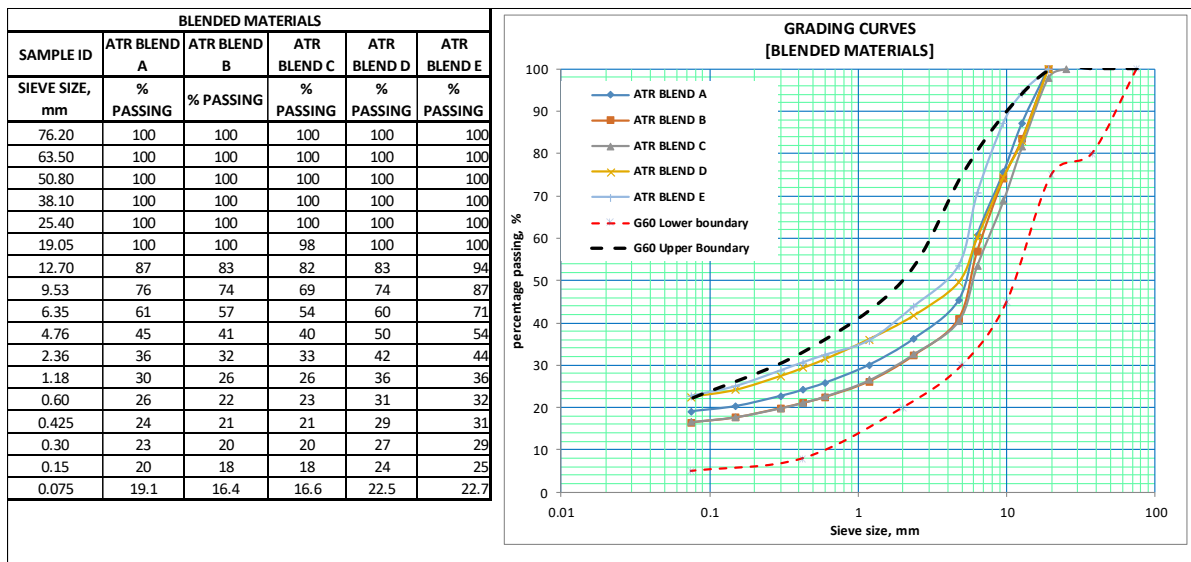
24 The research road, being a new construction project, required fresh pavement layer materials.
 25 Materials from two borrow pits near the project site designated BS1 and BS2, located 1.4 km and 11 km
 26 from the site respectively, were evaluated for their suitability. Laboratory test results indicated that the
 27 samples from these borrow pits were predominantly sand with varying proportions of clay, silt, and gravel
 28 (as per ASTM D 2487 classification). Given the high risk of erosion at the project site, both mechanical
 29 and chemical stabilization methods were considered for the underlying layer materials of the pavement
 30 structure. However, at the design stage, the use of these natural gravels (BS1 and BS2) was recommended
 31 for the pavement layers, though their high plasticity index ($PI > 10$) indicated the need for stabilization

1 (11, 12). Initially, a mechanical stabilization technique was proposed to blend the borrow pit materials
 2 with crusher sand sourced from the vicinity of the research site to improve material properties.
 3 Consequently, five blend options (A, B, C, D, and E) were formulated based on the properties of the
 4 individual borrow materials, their proximity to the project site, and the cost-effectiveness of transporting
 5 them. Table 1 presents these blend options along with their proportions. The blend materials were
 6 characterized to select an optimized blend for further assessment. A summary of their physical properties
 7 is also presented in Table 1. All blends were classified as sandy gravel with traces of clay and silt
 8 according to the BS 5930 classification, which is recommended for use in Ghana (13). The grading
 9 modulus of the blends ranged from 2.03 to 2.30, meeting the minimum specification value of 1.5 for
 10 typical base course materials used in road construction in Ghana. However, the plasticity modulus values
 11 of all blends (ranging from 302 to 450) did not meet the criteria set for base course materials (13). Figure
 12 3 illustrates the grading curves for the blend materials against the grading envelopes for a G60 material.
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14 **TABLE 1 Natural Gravels and Blend Proportions**

Natural gravel ID	Distance from the project site (km)	Estimated quantity (m ³)	PI value	
BS 1	11.4	15,000	22.9	
BS 2	1.4	25,000	17.2	
Blend options	Composition (%)			
	BS1	BS2	Quarry dust	
BLEND A	20	70	10	
BLEND B	25	65	10	
BLEND C	35	55	10	
BLEND D	40	50	10	
BLEND E	0	85	15	
Sample ID	Liquid Limit (%)	Plasticity Index (%)	Grading modulus (GM)	Plasticity modulus (PM)
BLEND A	44.8	16.0	2.21	387
BLEND B	43.2	14.4	2.30	302
BLEND C	43.4	15.3	2.30	324
BLEND D	42.0	15.1	2.07	443
BLEND E	44.7	14.7	2.03	450

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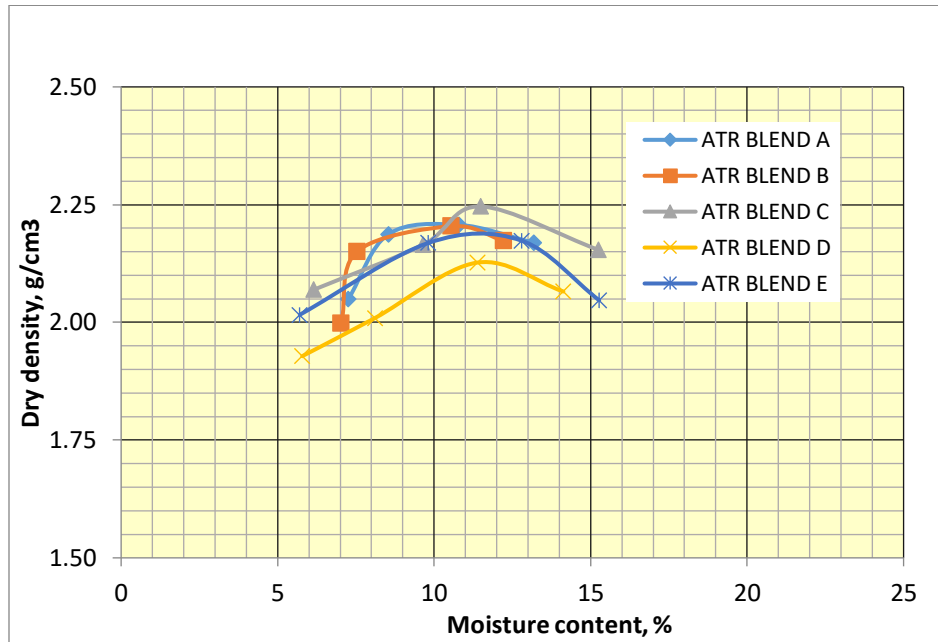
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Figure 3 Grading results of blended materials and G60 specification

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Moisture-Density Relationships

The moisture-density relationships for the blend materials were determined using the standard test procedures outlined in BS 1377-4:1990. A summary of the compaction test results for the five blends is illustrated as compaction curves in **Figure 4**. The maximum dry density (MDD) and optimum moisture content (OMC) of the blends ranged from 2.127 Mg/cm³ to 2.246 Mg/cm³ and 10.2% to 11.6%, respectively. Blend C exhibited the highest dry density at 2.246 Mg/cm³, whereas Blend D had the lowest density at 2.127 Mg/cm³. The results indicate that there is no significant difference in density among the five blends.



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Figure 4 Moisture density curves for the blend materials

CBR Test Results

CBR tests on the blend materials were performed according to BS 1377-4:1990 test procedures. The tests were conducted at three compaction levels (100% MDD, 98% MDD, and 95% MDD) and under three different moisture conditions (96 hours soaked and at OMC). The results, presented in **Table 2**, show that the CBR values of the blends ranged from 26% to 47%. The maximum swell value was negligible across all samples, with Blend A showing a swell of 0.13%. The CBR values for both borrow pit and blend samples were consistent across different compaction energies, with values at 98% and 95% MDD closely matching those at 100% MDD. Based on CBR values, the blend materials were classified as G40 and G30. Blend C and Blend D, with CBR values of 26% and 28%, respectively, marginally meet the specifications for G30 materials. It is noteworthy that the soaked CBR values for the borrow pit materials (BS1 and BS2) were 13 and 30, respectively, at 100% Mod AASHTO density, qualifying these materials as subgrade materials for pavement

1 **TABLE 2 CBR Test Results at Different Compaction Levels**

Sample ID	96 hrs soaked CBR values						GSSRB Classification	Pavement material type
	CBR @ 100%MDD		CBR @ 98%MDD		CBR @ 95%MDD			
	CBR, %	Swell, %	CBR, %	Swell, %	CBR, %	Swell, %		
BLEND A	47	0.13	46	0	42	0	G40	Base
BLEND B	36	0	35	0	32	0	G40	Base
BLEND C	26	0	25	0	23	0	G30	Subbase
BLEND D	28	0	28	0	25	0	G30	Subbase
BLEND E	41	0	40	0	37	0	G40	Base

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Laboratory Investigation of Stabilisation Material

To validate the design stage results and determine the need for stabilization, CBR and PI tests were conducted on both the natural gravels and blend materials. The verification tests confirmed high PI values, ranging from 14.4 to 22.4 (**Table 3**), indicating the necessity for chemical stabilization to reduce these values. Given the limited availability of lime in Ghana, cement stabilization was employed instead. Two types of cement stabilization techniques were investigated: Ordinary Portland Cement (OPC) and Pozzolana Modified Portland Cement (PPC), which comprises 70% cement and 30% pozzolana. Both OPC and PPC were tested at cementitious contents of 0%, 2%, 4%, and 6%. The PI and CBR values for these materials are detailed in **Table 3**. Typically, a well-stabilized material for base/subbase layers should have a PI of less than 10. CEM II 32.5 (Cement) was selected as the stabilizing agent due to the high PI values and the critical erosion concerns at the project site. Although the performance of pavements constructed with treated or blended lateritic gravel under complex field conditions remains to be fully explored (4), laboratory results indicated that BS2 with 4.5% cement was the most suitable and cost-effective option for achieving a PI of less than 10. Four concrete mix designs were developed, with each design having three variants, totalling 12 mix designs. The target for these mix designs was a minimum 28-day compressive strength of 30 N/mm², appropriate for the anticipated low to medium traffic on the project road. The compressive strength of the mix designs ranged from a minimum of 30.1 N/mm² to a maximum of 46.2 N/mm².

1 **TABLE 3 Properties of Natural Gravels and Blend Material**

SAMPLE ID	No additive	2% Cement	4% Cement	6% Cement	2% pozzolana-cement	4% pozzolana-cement	6% pozzolana-cement
PI Values of natural gravels and blend material							
BS1	22.4	18.2	12.8	11.5	18.1	16.1	13.0
BS 2	17.9	18.9	10.9	3.4	26.7	17.9	14.6
BLEND A	16.5	20	14.1	13.3	11.7	14.4	11.8
BLEND B	17.9	21.8	21.8	13.9	20.9	11.2	11.2
BLEND C	15.8	22.4	19.2	10.5	14.7	14.5	11.4
BLEND D	14.4	19.2	16.5	13.9	12.6	9.8	11.2
BLENDE E	15.3	17.3	12.5	10.9	11.3	14.0	11.0
CBR @ 95% MDD, 96 hrs soaked condition							
SAMPLE ID	No additive	2% Cement	4% Cement	6% Cement	2% pozzolana-cement	4% pozzolana-cement	6% pozzolana-cement
BS1	13	35	79	123	55	87	85
BS 2	30	79	109	119	90	81	99
BLEND A	42	74	144	155	78	116	110
BLEND B	32	69	139	149	75	82	94
BLEND C	23	71	92	102	97	110	105
BLEND D	25	94	118	126	84	109	110
BLENDE E	37	76	124	127	98	110	104

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Recommended Stabilization and Material Use

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Based on the test results, the most suitable material for the base/subbase layer is BS2 with approximately 4.5% cement, achieving a PI of less than 10. This aligns with common practice in Ghana, where a typical cement stabilization rate is 4%. In the event of a shortage of BS2 material, Blend D stabilized with 4% of a mix of 70% cement and 30% pozzolana, is recommended. This blend achieves a PI just below 10, making it a viable alternative. These stabilized materials are proposed for use in the subbase layer beneath the four surfacing options (interlocking concrete block pavement, roller-compacted concrete, thin mesh-reinforced concrete, and non-reinforced concrete). The CBR values for both BS2 and Blend D are greater than 100, indicating that these materials will provide adequate bearing capacity for the concrete sections, provided the sub-layers are properly prepared.

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Concrete Mix Design and Testing

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The concrete mix design was based on the standard methods from the Building Research Establishment (BRE) (1997) and supplemented with guidance from the American Concrete Institute's Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91, 2009). Three concrete specimens were produced for each proposed concrete product using the designed proportions. Once the mix was prepared, slump tests were performed to assess the workability of the fresh concrete. Compressive strength tests were conducted at two intervals: after 7 days and after 28 days. The 7-day testing was conducted in addition to the standard 28-day testing to evaluate early strength gains, which is

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1 useful for research purposes. The average compressive strength of three specimens from each trial mix
 2 was calculated, and the results are summarized in **Table 4**.

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TABLE 4 Summary of Compressive Strength Test Results

Trial Mix	Constituent	Specimen Type	Average f'_c (N/mm ²) @ 7 days	Average f'_c (N/mm ²) @ 28 days	Mean f'_c (N/mm ²) @ 28 days
NRC Mix1A	OPC, Sand, Coarse Aggregate from Quarry	150mm cube	20.2	36.8	34.8
NRC Mix2A	PPC, Sand, Coarse Aggregate from Quarry	150mm cube	17.3	31.6	
NRC Mix3A	OPC, Sand, Coarse Aggregate [70% Quarry + 30% In-situ rock]	150mm cube	19.8	36.1	
TMRC Mix1A	OPC, Sand, Coarse Aggregate from Quarry	150mm cube	25.3	46.2	39.1
TMRC Mix2A	PPC, Sand, Coarse Aggregate from Quarry	150mm cube	15.9	30.3	
TMRC Mix3A	OPC, Sand, Coarse Aggregate [70% Quarry + 30% In-situ rock]	150mm cube	22.5	40.9	
ICPB-Mix1A	OPC, Quarry Dust, Coarse Aggregate from Quarry	100mm ϕ Cylinder	21.6	40.1	37.2
ICPB-Mix2A	PPC, Sand, Coarse Aggregate from Quarry	100mm ϕ Cylinder	17.7	32.2	
ICPB-Mix3A	OPC, Quarry Dust, Coarse Aggregate [70% Quarry + 30% In-situ rock]	100mm ϕ Cylinder	22.0	39.2	
RCC-Mix1A	OPC, Quarry Dust, Coarse Aggregate from Quarry	100mm ϕ Cylinder	19.6	36.0	31.1
RCC-Mix2A	PPC, Sand, Coarse Aggregate from Quarry	100mm ϕ Cylinder	17.2	31.4	
RCC-Mix3A	OPC, Quarry Dust, Coarse Aggregate [70% Quarry + 30% In-situ rock]	100mm ϕ Cylinder	13.0	25.9	

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Compressive Strength Results

7 The compressive strength test results for the various concrete products in the initial trial mix generally
 8 exceeded the characteristic compressive strength of 30 N/mm² for TMRC (30.2 N/mm²) and ICBP (36.0
 9 N/mm²). In contrast, the overall average 28-day compressive strength for RCC was slightly below 30
 10 N/mm², at 28.7 N/mm². As anticipated, concrete mixes with only raw OPC achieved better results, with
 11 compressive strengths on the 28th day of 37 N/mm² for TMRC, 40.1 N/mm² for ICBP, and 36.0 N/mm²
 12 for RCC. Remarkably, all mix variants, except for RCC with a blend of OPC, Quarry Dust, and Coarse
 13 Aggregate (70% Quarry + 30% In-situ Rock), achieved 28-day compressive strengths greater than the
 14 target of 30 N/mm². The mean compressive strengths for NRC (34.8 N/mm²), TMRC (39.1 N/mm²),
 15 ICBP (37.2 N/mm²), and RCC (31.1 N/mm²) all surpassed the characteristic strength. These mean
 16 compressive strengths are crucial inputs for determining the concrete's properties.

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PAVEMENT DESIGN

Design Approach and Tools

19 The AASHTO Pavement Structures Design Guide (14 - 16) and local documents, such as the Ghana
 20 Highway Authority (GHA) Pavement Design Manual (17) and the Ghana Standard Specifications for
 21

1 Road and Bridge Works (18), were the primary pavement design references. *StreetPave* software,
2 developed by the American Concrete Pavement Association (ACPA), was used to verify the slab designs
3 of the rigid pavements. Supplementary documents consulted for road pavement ancillaries, such as road
4 furniture and signage to promote safety, including the Policy on Geometric Design of Highways and
5 Streets (19) and MRH Standard Details, Road Signs, and Markings for Urban and Trunk Roads (20).
6

7 **Topography, Geology, and Climatic Factors**

8 Complementary design factors included the project's catchment area's topography, geology, and climate.
9 The terrain of the project road is rolling for the first 500m, with an average gradient of 12.5%. The
10 geological beds within the project area comprise a thick sequence of white, highly matured quartzitic
11 sandstones, with bedding and jointing being common. The project area's climate is tropical, characterized
12 by a wet season with heavy rainfall and a dry season with minimal precipitation. The local temperature
13 averages 22.9°C, and the average annual rainfall is 1,584mm. Analyzes of 2006-2016 rainfall records
14 from Ghana Meteorological Services indicated an annual average of 1,362mm, with a maximum of
15 1,627mm and a minimum of 1,209mm. June typically recorded the highest rainfall, with a monthly
16 average of 209mm, while November through February recorded the lowest monthly rainfall, ranging from
17 20 to 55mm. Temperature records for 2006-2016 showed maximum temperatures of 37°C usually
18 occurring in February/March, while the annual minimum (25°C) occurred in September/October. Trend
19 analysis indicated a slightly extended period of maximum temperature from January through March.
20

21 **Traffic Loading Estimation**

22 As this was new construction, no traffic data was available for the project road, and alternative routes
23 served the two towns. A seven-day, 12-hour manual traffic count, including weekends, was conducted on
24 three probable alternative routes to estimate the projected base traffic for the proposed road. The average
25 daily traffic (ADT) was estimated to be 433 vehicles. The projected traffic mix was assumed to consist of
26 70% small vehicles (taxis and private cars), 27% medium vehicles (light and medium trucks – 20%; buses
27 – 7%), and 3% heavy vehicles. Due to the gradient of up to 22%, it was unlikely that a significant number
28 of heavy vehicles would use this road. However, heavy trucks with three or more axles might use the road
29 within the first five years of the project's implementation. A 50/50 split was assumed for pavement
30 design, and 1,972,530 equivalent standard axle loads (ESALs) were calculated and used for the pavement
31 designs.
32

33 *Sensitivity Analysis of Traffic Growth*

34 This analysis was critical because the project road was new with no historical data. A more accurate way
35 to estimate traffic growth is to predict future traffic based on an economic growth indicator model that
36 uses travel demand theory. Without valid economic data (e.g., income elasticity, demand, population and
37 per capita income growth, growth of the agricultural sector or industry/mining in the project catchment
38 area), a simplistic growth factor was used for the designs. The annual growth of 2% in commercial
39 vehicles over the design life of the pavements was approximately 2 million ESALs. Increasing the growth
40 from 2% to 6% by one percentage increment would increase the ESALs to about 2.7 million (an increase
41 of 35%, which was unlikely on the project road). Although the 2% growth rate appears low, a 6% growth
42 rate seemed exceedingly high based on existing data from the DFR. A growth rate of 4% (corresponding
43 to 2.3 million ESALs) was recommended for the pavement design. Based on sensitivity analysis, the
44 anticipated future traffic indicated that the cumulative traffic volume could range between 1.9 million and
45 2.7 million ESALs in 15 years from the base year (**Figure 5**). Thus, the expected traffic on the project
46 road falls within the same traffic-loading class of 1 to 3 million ESALs.
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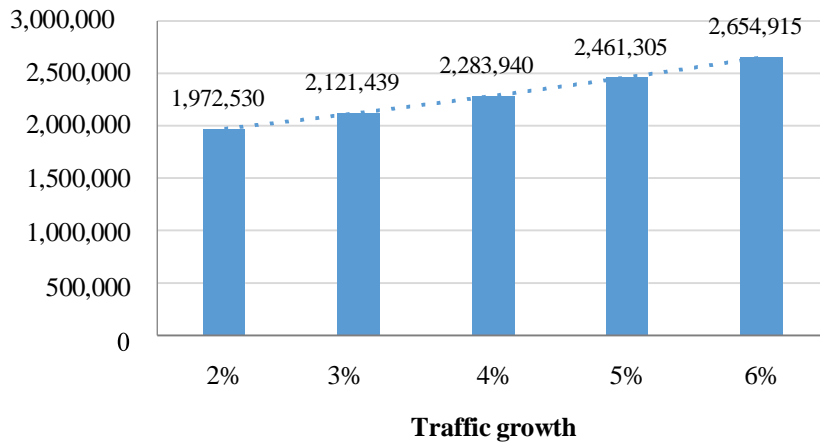


Figure 5 Sensitivity analysis of traffic growth rate

Pavement Structural Design

The material properties for the structural designs were based on laboratory test results for the soil and gravel materials and the mix design of modular and concrete pavement options. The modular paving option is classified as a flexible pavement and is thus designed according to the AASHTO Pavement Design Guide (16). A design life of 15 years and an analysis period of 25 years were used for the designs. These values were based on the performance of similar pavements in Ghana. Based on average daily traffic, ESALs, and a growth rate of 4%, the cumulative ESAL over the 15-year design life used for pavement design was 2.3 million. The value recommended by AASHTO for the initial design serviceability index of flexible pavements is 4.2. A terminal serviceability value of 2.0 was considered for the design, resulting in a design serviceability loss of 2.2. The AASHTO Design Guide suggests reliability levels ranging from 50% to 99.9% for various functional classifications, from local roads to interstate/freeways. Since the project road was in a rural location where daily traffic was not expected to exceed half its capacity, an 80% reliability level was selected for the design. The value recommended by the AASHTO Design Guide for flexible pavements is 0.40 to 0.50; thus, an average value of 0.45 was used for the design.

Effective Subgrade Resilient Modulus

Based on field assessment results, a minimum CBR of 15% was used for the pavement design. The roadbed resilient modulus (MR) was calculated based on the popular correlation (**Equation 1**) for unbound materials. $MR = 17.629 \times CBR^{0.64}$ (MPa) (1)

The effective subgrade MR was calculated for the design based on relative damage (uf), a concept used by AASHTO for flexible pavement design and defined in **Equation 2**.

$$uf = 1.18 \times 10^8 \times MR^{-2.32} \quad (2)$$

According to the Ghana Pavement Design Manual, areas with a minimum annual rainfall between 1,000 and 1,500 mm generally have four wet and eight dry months. The Manual recommends reducing the calculated modulus value by 20% for each month of the rainy season. The project catchment area had a minimum annual rainfall of 1,209 mm. Hence, the effective subgrade MR was determined for the dry season (Nov-Feb; 100 MPa) and wet season (Mar-Oct; 80 MPa). With a uf of 0.01 for the 12 months, the seasonal design subgrade modulus was 85 MPa.

1 *Design of Interlocking Paving Block Pavement*

2 The structural number design approach, as recommended in the AASHTO Design Guide (16),
 3 was used to determine the thickness of the interlocking block paving (semi-rigid pavement). The design
 4 input parameters for the semi-rigid pavement are as follows: estimated future traffic of 2.3 million
 5 ESALs, design reliability of 85%, overall standard deviation of 0.45, effective subgrade modulus of 85
 6 MPa, and serviceability loss of 2.2. The layer coefficients for the material layers are cement-stabilized
 7 base course (0.23), granular base course of crushed/natural material (0.14), and granular subbase course
 8 of natural gravel (0.10). Based on the project road environment (climate) conditions, it was assumed that
 9 the pavement would be exposed to moisture levels always approaching saturation of 5% to 25%. Hence, a
 10 drainage coefficient of 0.8, a suitable safety factor, was selected for both the base and subbase layers.

11
 12 *Design of Rigid Pavement Options*

13 The AASHTO Design Guide (16) was used to design the concrete pavements. It was assumed that load
 14 transfer would be achieved via aggregate interlock, so dowels were not considered. The traffic levels used
 15 were the same as those for semi-rigid modular pavement. The recommended initial design serviceability
 16 index for rigid pavements is 4.5, and a terminal serviceability value of 2.0 was used for the design,
 17 resulting in a design serviceability loss of 2.5. An 85% reliability level was selected for the rigid
 18 pavement design. The recommended value of the overall standard deviation for rigid pavements is 0.30 to
 19 0.40, and a conservative average value of 0.35 was used for the design.

20 In the AASHTO Design Guide (16), the primary input properties for concrete are flexural
 21 strength and elastic modulus. Well-established American Concrete Institute (ACI) correlations are
 22 available for these two properties. We used the average values for the 28-day compressive strength
 23 obtained from the mix design in the laboratory to derive the flexural strength and elastic moduli for the
 24 concrete designs. The concrete slab thicknesses for the options were further designed as required. The
 25 pavement structures designed for the alternative options are summarized in **Table 5**.

26
 27 **TABLE 5 Summary of Specifications and Design Parameters**

Pavement surfacing	Description of section	Structural design details			
Interlocking concrete block paving (ICBP)	Chainage 2+395 to 2+480. Total length of section is 85 m, constructed on an average gradient of 12.9%.	Materials and properties:			
		* 75mm interlocking concrete block paving.			
		* Concrete made from OPC, sand and quarry stones. Minimum 28-day characteristic compressive strength of 30 MPa			
		* Approximate size; 300 x 220 x 75 mm (H x W x T)			
		* 150mm layer stabilised with cement (4-4.5%); PI <10; CBR = 100 (soaked)			
		* 150mm drainage layer 19 to 37mm stone			
		* Subgrade/formation: Natural gravel, min CBR = 15 (soaked)			
		Layer	Material	Thickness	Strength
		Surfacing	ICBP	75 mm	C30
		Bedding	SBL	25 mm	-
		Base	Cement stabilised	150 mm	UCS = 1.5- 3.0 MPa
		Subgrade	Natural gravel	150 mm	CBR (soaked) = 15
Roller-compacted concrete (RCC)	Chainage 2+480 to 2+735. Total length of section is 255 m; three different surfacing mixes (85 m	Materials and properties:			
		* Concrete made from OPC, pozzolana, sand, quarry stones, and screened natural. Minimum 28-day characteristic compressive strength of 30 MPa			

	long each, average gradient of 17.2%).	<ul style="list-style-type: none"> * 150mm layer stabilised with cement (4-4.5%); PI <10; CBR = 100 (soaked) * 150mm drainage layer 19 to 37mm stone * Subgrade/formation: Natural gravel, min CBR = 15 (soaked) <table border="1"> <thead> <tr> <th>Layer</th> <th>Material</th> <th>Thickness</th> <th>Strength</th> </tr> </thead> <tbody> <tr> <td>Surfacing</td> <td>RCC</td> <td>110 mm</td> <td>C30</td> </tr> <tr> <td>Base</td> <td>Cement stabilised</td> <td>150 mm</td> <td>UCS = 1.5- 3.0 MPa</td> </tr> <tr> <td>Subgrade</td> <td>Natural gravel</td> <td>150 mm</td> <td>CBR (soaked) = 15</td> </tr> </tbody> </table>	Layer	Material	Thickness	Strength	Surfacing	RCC	110 mm	C30	Base	Cement stabilised	150 mm	UCS = 1.5- 3.0 MPa	Subgrade	Natural gravel	150 mm	CBR (soaked) = 15
Layer	Material	Thickness	Strength															
Surfacing	RCC	110 mm	C30															
Base	Cement stabilised	150 mm	UCS = 1.5- 3.0 MPa															
Subgrade	Natural gravel	150 mm	CBR (soaked) = 15															
Thin mesh-reinforced concrete (TMRC)	Chainage 2+735 to 2+990. Total length of section is 255 m; three different surfacing mixes (85 m long each, average gradient of 17.9%).	<p>Materials and properties:</p> <ul style="list-style-type: none"> * Concrete made from OPC, pozzolana, sand, quarry stones, and screened natural. Minimum 28-day characteristic compressive strength of 30 MPa * High yield strength steel reinforcement bars > 400 MPa, 6 mm diameter @ 150mm c/c in longitudinal and transverse directions. * 150mm layer stabilised with cement (4-4.5%); PI <10; CBR = 100 (soaked) * 150mm drainage layer 19 to 37mm stone * Subgrade/formation: Natural gravel, min CBR = 15 (soaked) <table border="1"> <thead> <tr> <th>Layer</th> <th>Material</th> <th>Thickness</th> <th>Strength</th> </tr> </thead> <tbody> <tr> <td>Surfacing</td> <td>TMRC</td> <td>75 mm</td> <td>C30</td> </tr> <tr> <td>Base</td> <td>Cement stabilised</td> <td>150 mm</td> <td>UCS = 1.5- 3.0 MPa</td> </tr> <tr> <td>Subgrade</td> <td>Natural gravel</td> <td>150 mm</td> <td>CBR (soaked) = 15</td> </tr> </tbody> </table>	Layer	Material	Thickness	Strength	Surfacing	TMRC	75 mm	C30	Base	Cement stabilised	150 mm	UCS = 1.5- 3.0 MPa	Subgrade	Natural gravel	150 mm	CBR (soaked) = 15
Layer	Material	Thickness	Strength															
Surfacing	TMRC	75 mm	C30															
Base	Cement stabilised	150 mm	UCS = 1.5- 3.0 MPa															
Subgrade	Natural gravel	150 mm	CBR (soaked) = 15															
Non-reinforced concrete (NRC)	Chainage 2+990 to 3+245. Total length of section is 255 m; three different surfacing mixes (85 m long each, average gradient of 17.1%).	<p>Materials and properties:</p> <ul style="list-style-type: none"> * Concrete made from OPC, pozzolana, sand, quarry stones, and screened natural. Minimum 28-day characteristic compressive strength of 30 MPa * 150mm layer stabilised with cement (4-4.5%); PI <10; CBR = 100 (soaked) * 150mm drainage layer 19 to 37mm stone * Subgrade/formation: Natural gravel, min CBR = 15 (soaked) <table border="1"> <thead> <tr> <th>Layer</th> <th>Material</th> <th>Thickness</th> <th>Strength</th> </tr> </thead> <tbody> <tr> <td>Surfacing</td> <td>RCC</td> <td>110 mm</td> <td>C30</td> </tr> <tr> <td>Base</td> <td>Cement stabilised</td> <td>150 mm</td> <td>UCS = 1.5- 3.0 MPa</td> </tr> <tr> <td>Subgrade</td> <td>Natural gravel</td> <td>150 mm</td> <td>CBR (soaked) = 15</td> </tr> </tbody> </table>	Layer	Material	Thickness	Strength	Surfacing	RCC	110 mm	C30	Base	Cement stabilised	150 mm	UCS = 1.5- 3.0 MPa	Subgrade	Natural gravel	150 mm	CBR (soaked) = 15
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ECONOMIC ANALYSIS OF PROPOSED ALTERNATIVES

The Present Worth of Cost (PWOC)

Present worth or present value economic analyses are considered the best methods for evaluating pavement design or rehabilitation alternatives. The main question is usually which design alternative results in the lowest total cost over the life of the project and the user-cost impacts of alternative strategies. The PWOC life-cycle cost appraisal of the proposed pavement options was conducted, considering the initial cost, probable maintenance cost, and salvage value of the road assets over a 30-year service life. The life-cycle cost analysis included the initial construction cost, the cost of future maintenance standards and associated activities over the analysis period, and a salvage value, estimated as

1 a percentage of the initial construction cost for each alternative option, based on empirical data and
 2 research. The basic equation for determining present worth is presented in **Equation 3**:

$$3 \quad PWOC = C + \sum_{i=1}^m M_i \left(\frac{1}{1+r}\right)^{n_i} - S \left(\frac{1}{1+r}\right)^Z \quad (3)$$

4 where

5 $PWOC$ = Present Worth of Cost.

6 C = Present Cost of initial design or rehabilitation activity.

7 m = Number of maintenance or rehabilitation activities.

8 M_i = Cost of the i th maintenance or rehabilitation alternative in terms of present cost, i.e., constant
 9 dollars.

10 r = Discount rate.

11 n_i = Number of years from the present of the i th maintenance or rehabilitation activity.

12 S = Salvage value at the end of the analysis period.

13 Z = Length of analysis period in years.

14 $\left(\frac{1}{1+r}\right)^n$ = is commonly called the single payment present worth factor in most engineering economic
 15 publications.
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18 **Comparison of the Four Pavement Options**

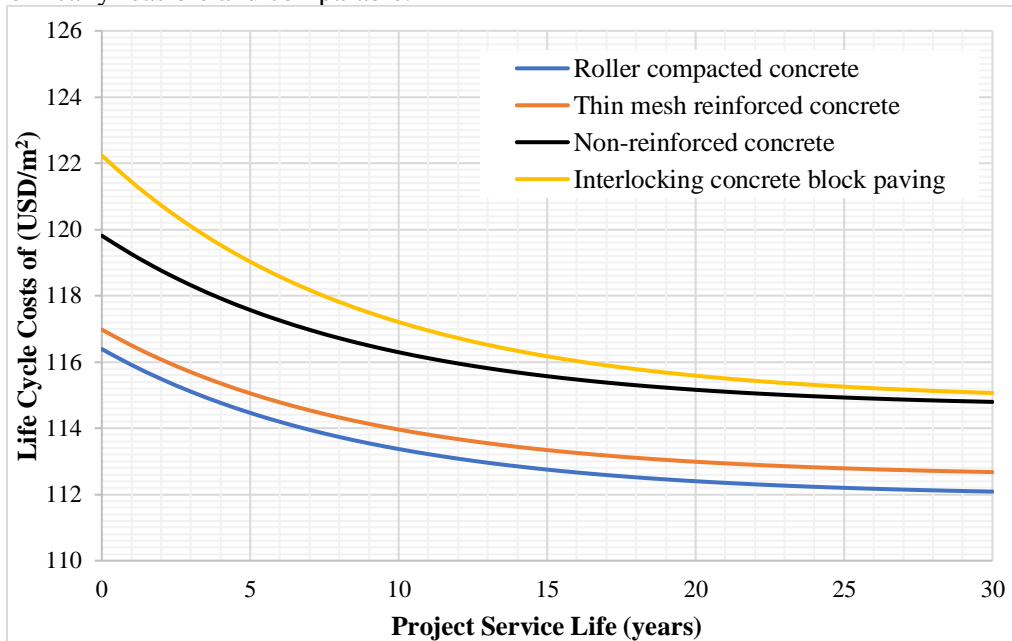
19 The project service life for all paving options in this analysis is 15 years. A discount rate of 12%
 20 has been extensively used for the economic cost analysis of international projects, including World Bank
 21 projects from six countries. This uniform service life allows for a direct comparison of maintenance costs,
 22 initial costs, salvage value, and overall life-cycle costs, as presented in **Table 6**. Maintenance costs vary
 23 significantly among the paving options due to differences in material and repair methods. Interlocking
 24 concrete block paving (ICBP) incurs the highest maintenance cost, reflecting the more extensive repairs
 25 required for this type of surfacing, which is commonly used in Ghana. Despite its higher initial and
 26 maintenance costs, the ICBP option has a competitive life cycle cost due to its higher salvage value.
 27 However, it still ranks as the most expensive option in terms of life-cycle cost.

28 Unlike the typical concrete-based counterparts, the ICBP is expected to undergo at least three
 29 structural maintenance activities during its service life of up to 30 years. The relatively low maintenance
 30 cost, coupled with the high potential of residual road assets valued at USD 22.65 per square meter (20%
 31 of initial construction cost), makes the roller-compacted concrete (RCC) the most cost-effective option of
 32 all the alternatives. Similarly, the life-cycle cost of the thin mesh-reinforced concrete (TMRC) pavement
 33 option is lower than the initial construction cost due to the lower cost of less frequent maintenance
 34 activities and a higher potential of residual road assets as salvage value at the end of the pavement service
 35 life. The non-reinforced concrete (NRC) ranks third on the life-cycle cost scale with a unit cost of USD
 36 115.57. The overall maintenance cost over an analysis period of 25 years (with an expected service life of
 37 up to 30 years) and a salvage value of USD 20.85 per square meter, estimated at 18% of its initial
 38 construction unit cost of USD 115.85, contribute to its ranking. The residual value of 18% is based on
 39 empirical data of typical mass concrete pavements, which is slightly lower than that of a reinforced
 40 counterpart like the TMRC.
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1 **TABLE 6 Life-Cycle Cost of Concrete Surfacing Alternatives**

Surfacing Type	Structural Maintenance	Maintenance Cost (USD/m ²)	Initial Cost (USD/m ²)	Salvage %	Salvage value (USD)	Life-Cycle Cost (USD/m ²)
Roller compacted concrete (RCC)	Repair all cracks and broken edges	4.45	113.27	20	22.65	112.75
Thin mesh reinforced concrete (TMRC)	Repair all cracks and broken edges	4.45	113.87	20	22.77	113.34
Non-reinforced concrete (NRC)	Repair all cracks and broken edges	5.19	115.85	18	20.85	115.57
Interlocking concrete block paving (ICBP)	Half-depth pavement repairs	7.42	116.18	20	23.24	116.17

2
 3 **Figure 6** shows the results of a model of the four alternative pavements based on the PWOC life-
 4 cycle cost appraisal. The figure discriminates the life-cycle costs of the pavement options investigated.
 5 After 25 years of project life, the model curves for all four options flatten, implying that all significant
 6 maintenance costs associated with the pavements have been incurred, and there are no expected major
 7 expenditures or changes in cost beyond this point. The percentage differences between the RCC, TMRC,
 8 and NRC options compared to the ICBP option are 3.03%, 2.50%, and 0.52%, respectively. From a
 9 practical standpoint, if the difference in the present worth of costs between two design or rehabilitation
 10 alternatives is 10% or less, it is normally assumed to be insignificant, and the present worth of the two
 11 alternatives can be considered the same. The life-cycle costs show that all four alternative surfacing types
 12 are economically feasible and comparable.



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 14
 15 **Figure 6 Present worth of cost model for four alternative pavements over 30 years analysis period**
 16

1
2 **CONCLUSIONS**

3 The selection of alternative pavement/surfacing options was presented. The approach used
4 includes material selection, pavement designs, and life-cycle economic analysis of four pavement options.
5 The following conclusions are drawn based on the results of this study.

- 6 • Successful utilization of naturally occurring and locally produced materials, such as calcined clay
7 pozzolana or screened lateritic gravels and concrete (both thin mesh-reinforced and roller-
8 compacted) mix designs for the project will reduce construction costs when these surfacing
9 techniques are fully implemented on steep sections of feeder roads.
- 10 • Adequate laboratory investigation has been undertaken to establish material properties for the
11 selected road materials. The engineering properties of the materials are discussed. The database
12 established from the final designs will support the development of a road material database for
13 use at national levels.
- 14 • To optimize the use of naturally occurring materials, attention must be paid to the compatibility
15 between the pavement structure, the materials used, the type of surfacing, construction processes,
16 and, above all, control of moisture through effective drainage.
- 17 • Since the project catchment area experiences high annual rainfall, the granular base materials
18 (gravels) are potentially susceptible to erosion, leading to poor performance of the concrete
19 pavement sections. Under these circumstances, and as proposed in the design, placing the
20 concrete surfacing on a stabilized layer/lean concrete would be more ideal than on the proposed
21 granular base layers.
- 22 • This project includes the application of new technologies (e.g., RCC and TRMC) that have never
23 been used in Ghana. The use of a contractor with extensive experience in road construction and
24 qualified technical staff is paramount.
- 25 • It is established that all four proposed pavement/surfacing options are economically feasible and
26 comparable. However, the choice of paving option should consider these costs alongside other
27 factors such as expected traffic loads, environmental conditions, and specific project
28 requirements. Road performance monitoring and evaluation of demonstration sections are
29 required to assess the actual maintenance strategies and derive the full economic benefits of the
30 proposed pavements.

31
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38
39 **AUTHOR CONTRIBUTIONS**

40 The authors confirm contribution to the paper as follows: study conception and design: J Anochie
41 Boateng, E Debrah, G. Mvelase, P Agyekum, and D. Asenso-Gyambibi; data collection: J Anochie
42 Boateng, E Debrah, G. Mvelase, P Agyekum, and D. Asenso-Gyambibi; analysis and interpretation of
43 results: X J Anochie Boateng, E Debrah, G. Mvelase, P Agyekum, and D. Asenso-Gyambibi; draft
44 manuscript preparation: J Anochie Boateng, E Debrah, G. Mvelase, P Agyekum, and D. Asenso-
45 Gyambibi. All authors reviewed the results and approved the final version of the manuscript.

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