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Evaluation of Strength Performance of Cement Treated Graded Crushed Stones (GCS) for High Traffic Volume Roads Construction in Kenya

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Abstract

This study evaluates the strength performance of cement-treated Graded Crushed Stone (GCS) of 0/30 mm and 0/40 mm gradations, commonly used in Kenyan for construction of roads carrying over 10 million equivalent standard axles (MESA). While cement is often added to bind GCS fines, its effect on road performance had not been analyzed. This research assessed the Unconfined Compressive Strength (UCS) of GCS from three quarries, treated with 1%–5% cement and cured for 7, 14, and 28 days. Results showed that the 0/40 mm gradation outperformed 0/30 mm in UCS, with strength increasing steadily up to 4% cement content. Greatest UCS development occurred within the first 14 days of curing. A strong correlation (R^2 = 0.893) was found between UCS and the variables studied. The study recommends using 0/40 mm gradation, extended curing periods, and optimized cement content to meet performance requirements for roads with heavy traffic.

Keywords: Graded crushed stone, cement, UCS, high traffic volume roads

INTRODUCTION

The development and maintenance of durable and sustainable road infrastructure are vital to national economic development, particularly in developing countries such as Kenya. Gravel sources are depleting rapidly, and gravel is becoming more expensive with changes in land use in Kenya. However, good quality stones are abundant and readily available in most parts of the country. Graded crushed stone (GCS) offers a good alternative owing to its inherent strength properties and availability.

The Kenya Road Design Manual Part III, (MoT&C, 1987) and the Standard Specifications for Road and Bridge Construction (MoR&PW, 1986) provide for use of class A neat (untreated) GCS of 0/30 mm for base and class B 0/40 mm for subbase construction, under heavy traffic loading.

In early 1990s, premature failures were noted on Rodi Kopany–Karungu and Nakuru–Timboroa roads, due to loss of fines and gradation during construction through moistening and handling, which highlighted the susceptibility of untreated GCS. This resulted in introduction of cement to GCS, despite the standards specifying only the use of neat GCS.

Untreated GCS relies on aggregate interlock and inter-particle friction for strength. Proper performance therefore requires continuous gradation, sufficient compaction, and provision of an adequate supporting layer to ensure proper compaction and hence strength. Nonetheless, loss of fines during construction compromises its structural integrity, rendering it inadequate for heavy traffic roads.

Cement treatment binds the fines, enhances strength, and improves durability. The mechanical properties of cement-treated GCS are influenced by aggregate gradation, cement content, compaction, and curing conditions (Thompson & Naidoo, 2001; Little et al., 2005). However, limited research has been conducted within the Kenyan context.

Cement-treated GCS has been used in the

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construction of heavy traffic roads, such as national highways, urban arterials and rural roads, where structural reliability and durability are critical. In addition to enhanced structural performance, cement-treated GCS significantly improves moisture resistance and fatigue life, reduces shrinkage, and enhances long-term durability of roads. Further, it offers a better alternative to gravels that are rapidly depleting and becoming more expensive with changes in land use. These performance and sustainability benefits justify further exploration and application of cement-treated GCS for heavy traffic roads in Kenya's growing highway and urban road network.

This study evaluates the strength performance of two commonly specified GCS gradations—0/30 mm and 0/40 mm—treated with varying cement contents and conditioned at varying curing and soaking durations. Materials were sourced from three active Kenyan quarries used for construction of major road in the source regions. The primary objective of the study is to characterize the strength properties of cement-treated GCS of the two gradations. The study correlates the strength properties of cement treated GCS with varying cement dosages and curing periods and evaluates the impact of varied GCS grading on the strength properties of GCS treated with cement and conditioned to different curing periods. The findings of the study will guide improvements of specifications and promote adoption of performance-based design and construction of roads using cement treated GCS.

THEORY

Kenya's Pavement Design Guideline for Low Volume Sealed Roads PDG 1 (MoTIHUD, 2017) imply the use of cement-treated GCS through structural layer coefficients. The guideline defines two classes of cement bound material (CBM): CB1 with UCS values of 3.0 – 6.0 MPa and a structural layer coefficient, ai, of 0.18; CB2 with UCS values of 1.5–3.0 MPa and (ai) of 0.13, based on minimum UCS performance.

(TRH4, 1996) defines cemented GCS classes C1 and C2, with UCS targets of 6 – 12 MPa and 3.5 – 6 MPa, respectively, based on parent material quality. Similarly, (Austroads 2019) classifies cement-stabilized materials into modified (UCS <1 MPa), lightly bound (UCS 1 – 2 MPa), and bound (UCS >2 MPa) categories.

Recent research highlights the significant impact of cement content on material strength. (Deschenes, 2020) found that cement-stabilized crushed stone base courses with UCS greater than 5 MPa achieved a structural coefficient (a2) of 0.21, suggesting that 4 – 5% cement content is optimal. (Okonkwo et al., 2020) demonstrated that 5% cement significantly enhanced the CBR of crushed ironstone and improved durability against moisture damage. (Mutua and Wambua, 2021) established that high cement dosage resulted in enhance strength of stabilised material. Similarly, (Priastiwi et al., 2023) reported that 4% cement content yielded optimal UCS for cement treated base (CTB) in Indonesia, with aggregate quality and preparation methods significantly influencing performance outcomes.

Further studies show that cement stabilization improves fatigue behavior, reduces shrinkage, and enhances water resistance of GCS. Lim and Zollinger, (2003) proposed equations to estimate UCS and Resilient Modulus development in cement-treated aggregate bases, suggesting a consistent relationship regardless of aggregate type. (Sheng, 2011) correlated cement dosage with mechanical performance indicators such as fatigue life, shrinkage behavior, and permeability. Similarly, (Hossain et al., 2017) concluded that aggregate properties influence cement treated aggregates (CTA) performance, recommending a structural layer coefficient of 0.2 for CTA with 7-day UCS greater than 600 psi (4.1 MPa).

Jiang et al., (2022) emphasized the role of compaction methods and cement content in achieving significant improvements in UCS, splitting strength, and resilient modulus (RM), with the most notable strength gains occurring within the first 14 days of curing. (Mwaura and Gichaga, 2018) concluded that 14- and 28-day strength gain in cemented materials was more pronounced that 7 days and underscored the need for sufficient curing time to achieve long-term strength and stability. (Austroads 2019) also guides that a 21-day minimum curing period is required for load-bearing performance layers.

Aggregate size and distribution also affect strength development. (Rahman and Ullah, 2018) found that while larger aggregates generally increase concrete strength, excessive oversize aggregates may cause segregation and reduce strength. Similarly, (Kamau and Ochieng, 2022) suggested that the aggregate gradation influenced the variation of optimal cement content for the determined UCS for granular materials.

- The reviewed literature therefore demonstrates that the strength performance of cement-treated graded crushed stones (GCS), determined from unconfined compressive strength (UCS), resilient modulus (RM), and structural layer coefficients, are significantly influenced by cement content, curing duration, aggregate properties such as gradation and type, and the applied compaction method. For this study, the considered independent variables, also known as predictors, are cement content, curing time and aggregate gradation while the corresponding dependent variable representing strength performance, is UCS. The relationship between these variables is supported by mechanistic pavement design theory, which proposes that optimizing material input parameters such as cement content, good aggregates gradation, and sufficient curing time, results in improved mechanical strength and durability. This theoretical basis underscores the importance of strength performance evaluation to ensure that cement-treated GCS layers meet the structural and durability requirements of roads with high traffic volumes in Kenya.

To determine the correlation between the variables, a linear regression analysis was used to examine the influence of each factor on the resultant unconfined compressive strength (UCS) of cement-treated granular construction soil (GCS). A multiple linear regression (MLR) model was also adopted to assess the combined influence of the independent variables, including cement content (%), curing time (days), and gradation type, on the dependent variable, UCS. The MLR model was considered most suited for the study due to the following reasons:

- *Variable types:* UCS is a continuous outcome, making it well-suited for linear regression. The predictors include both continuous variables (cement content and curing time) and categorical variables (gradation type), which can be handled effectively using appropriate encoding techniques such as dummy variables (Hadi and Chatterjee, 2023; Montgomery et al.,, 2021).
- *Research objective:* The model is designed to quantify how individual and combined input variables affect the UCS of cement-treated GCS, which aligns with the purpose of multiple regression analysis (Montgomery et al., 2021).
- *Theoretical and empirical support:* Previous research and mechanistic design theories have shown that linear or near-linear relationships exist between these factors and UCS within standard engineering practice (Zhou et al., 2023; Stasinopoulos et al., 2024).
- *Ease of interpretation:* Each regression coefficient clearly indicates how much UCS is expected to change with a unit change in the corresponding predictor while holding other variables constant, which supports its practical use in engineering modeling (Hadi and Chatterjee, 2023).
- *Practical application:* In engineering contexts, MLR provides a balance between analytical accuracy and simplicity, making it highly effective for developing construction specifications and predictive models (Zhou et al., 2023).

Therefore, this study contributes to the development of optimized GCS specifications to enhance road durability and performance under heavy traffic conditions.

RESEARCH METHODS

This research involved laboratory experimentation. Graded Crushed Stone (GCS) materials sourced from three Kenyan quarries actively used in the ongoing and completed road construction projects. The quarries represent diverse geological profiles and their usage ensures the practical relevance of this study for high traffic volume roads. Ordinary Portland Cement of 42.5 N/mm^2 mortar strength was used for GCS treatment at varying dosages, cured for 7, 14 and 28 days in a room of free-flowing air then soaked for 7 days prior to testing. The 7-days curing was necessary to simulate the ongoing field practice of curing cement treated GCS layers.

Graded Crushed Stone (GCS) Sourcing

Graded Crushed Stone (GCS) materials were sourced from three Kenyan quarries actively used in the ongoing and completed road construction projects. The quarries represent diverse geological profiles and their usage ensures the practical relevance of this study for high traffic volume roads.

H Young Quarry in Katani, Machakos County is located on GPS coordinates 1°21'11.02''S and 37°00'41.01''E. The dominant rocks at the quarry site are the Nairobi Phonolites that are banded to have formed within the Lower Trachyte Division of Tertiary volcanic activities (Fairburn, 1963). Aggregate sampled was all-in for 0/30 and adjusted by addition of 0/3 mm and 28/37.5 mm single sizes for grading correction and attainment of 0/40 mm.

This quarry has been used in several projects around Nairobi, by Kenya Urban Roads Authority, KURA, including the rehabilitation and upgrading of 3.1 km First Avenue Eastleigh and 2 km General Waruinge Roads in Nairobi. The scope of works involved construction of 175 mm, 2% cement improved GCS base-quality subbase of 0/30 mm gradation, compacted to 95% MDD (AASHTO T180) on subgrade class S3, and supporting 125mm Dense Bitumen Macadam (DBM) base and 50 mm Asphalt Concrete (AC) type I surfacing (KURA, 2015).

China Wu Yi Quarry in Kirinyaga County is located on GPS coordinates 0°44'06.68''S and 37°17'49.29''E. The dominant rocks at the quarry site are the Basalts and Basaltic Agglomerates formed within the "Simbara Type Basalts" (Fairburn, 1966). Single size aggregates of 0/6 mm, 6/10 mm, 10/14 mm, 14/20 mm, 20/28 mm and 28/37.5 mm were sampled. This quarry has been used in several projects in Central Region of Kenya for Asphalt Concrete production by Kenya Rural Roads Authority, KeRRA, as well as GCS construction by Kenya National Highways Authority, KeNHA, including rehabilitation and upgrading of Sagana – Marua (A2) Road. The project's scope of works involved construction of 175 mm cement improved GCS base-quality subbase compacted to 95% MDD (AASHTO T180) on subgrade class S5, and supporting 150 mm DBM and 50 mm AC (KeNHA, 2024).

Sino Hydro Awasi (Pala) Quarry in Kisumu County is located on GPS coordinates 0°12'33.29''S and 35°06'48.17''E with dominant rocks at the quarry site being part of the Kericho Group of Phonolites (Binge, 1962). Single size aggregates of 0/6 mm, 6/10 mm, 10/14 mm, 14/20 mm, 20/28 mm and 28/37.5 mm were sampled. Materials were sampled following Kenyan and international procedures to ensure consistency and representativeness. This quarry was used in the construction of Kericho - Nyamasaria (B1) Road and is currently being used in the rehabilitation and upgrading of Mamboleo – Kipsitet (C34) Road. The scope of works involves construction of 225mm G30 material on subgrade class S5, 175 mm 2% cement improved class A GCS base-quality subbase of 0/30 mm gradation, 150 mm DBM and 50 mm AC (KeNHA, 2021).

Cement Sourcing

Simba cement complying with KS EAS 18-1: 2017 for Ordinary Portland Cement was used for the research.

Laboratory Testing and Procedures

Testing procedures were carried out to the following standards:

- **Gradation/Sieve Analysis:** AASHTO T27, BS 1377, and adapted procedures from Austroads AGPT02 and SANRAL TRH14 for continuous grading control.
- **Plasticity Index (PI):** BS 1377 Part 2 and COTO standards to confirm non-plasticity.
- **Mechanical Strength Tests:** Was used to classify the GCS in accordance with SSRBC (1986)
    i. Aggregate Crushing Value (BS 812-110)
    ii. Los Angeles Abrasion (ASTM C131)
    iii. Water Absorption (ASTM C127)
    iv. Flakiness Index (BS 812-105)
    v. 10% FACT (BS 812-111)
- **Unconfined Compressive Strength (UCS):** Moulding, Curing, Soaking and Testing in accordance with BS 1377-4:1990 and ASTM D1633.

Specimen Molding and Cement Treatment

Cement treatment was done at 1 – 5% dosage. The mass of cement for mixing in the GCS was determined as a percent of the aggregates MDD determined at OMC. Mixing in cement and water was done using a mechanical mixer in order to achieve homogeneity. UCS test specimens were molded using cylindrical split moulds of 152 mm diameter and 177 mm height, cast and compacted to a controlled thickness of 127 mm – 133 mm using a vibrating hammer (BS 1377: Part 4).

At each cement content, three specimens were prepared for each of the three curing durations.

Specimens Curing and Soaking
Curing of the cement treated samples was achieved by using air tight moisture bags kept at room temperature in a room with free circulation of air. Curing was done for 7, 14 and 28 days. At the end of the curing period for each group of specimens, the specimens were carefully removed and placed in a soaking tank, fully immersed in water, for a period of 7 days prior to testing. These durations align with recommendations in Austroads (2019) and SANRAL (TRH4,1996) guidelines to achieve early and ultimate strength performance under high traffic applications.

UCS Testing and Data Analysis
Unconfined Compressive Strength was tested in accordance with ASTM D1633 and BS 1377: Part 4 procedures. A digital compression machine of 250 kN capacity was used for the UCS testing. The molded specimens were tested in batches upon attainment of the curing periods. At each curing period, results for the 3 specimens were recorded and the average reported. Data analysis included:

- Descriptive statistics (mean/average)
- Pearson correlation (cement content (%), curing time (days), gradation)
- Multiple linear regression modeling (predictive UCS framework)

RESULTS AND DISCUSSIONS

Sieve Analysis and Grading Compliance
The gradation curves of best fit derived from proportioning of the single size aggregates from Awasi and Kirinyaga and all-in aggregates from Katani are compared against the Standard Specifications for Road and Bridge Construction, SSRBC (MoR&PW, 1986) limits. **Tables 1** and **2** present the GCS gradations for 0/30 mm and 0/40 mm and **Figures 1** and **2** illustrate the grading curves for 0/30 mm and 0/40 mm respectively.

All sources complied with the grading requirements for 0/30 mm and 0/40 mm and were within the grading envelopes. The aggregates were deficient in the finer sizes and fitted on the margin of the lower grading specifications. Sino Hydro quarry (Awasi) generally had a more uniform gradation within the envelopes.

Mechanical Properties and GCS Classification
The results of mechanical properties presented in **Table 3** confirms that GCS materials from the three sources are class A, based on ACV, LAA, SSS, FI and CR and complies with the requirements for materials for base and/or base quality subbase specifications under heavy to very heavy traffic loading.

Sino Hydro Awasi quarry had the lowest LAA and

TABLE 1
0/30 mm GCS Grading for Awasi, Kirinyaga and Katani quarries

GRADED CRUSHED STONE (0/30 mm) GRADING					
BS SIEVES (mm)	PERCENT (%) PASSING EACH SIEVE			GRADING SPECIFICATIONS (ENVELOPE)	
	AWASI	KIRINYAGA	KATANI	LOWER SPECS	UPPER SPECS
50	100.0	100.0	100.0	100	100
37.5	100.0	100.0	100.0	100	100
28	100.0	94.8	95.9	90	100
20	93.0	88.0	79.3	65	95
10	51.7	60.5	57.5	40	70
6.3	43.9	47.9	48.2	30	55
2	28.9	25.7	29.1	20	40
1	23.7	15.7	18.3	15	32
0.425	13.7	7.8	11.2	10	24
0.075	5.0	1.9	5.2	4	10

Source: Field Survey, 2025

TABLE 2
0/40 mm GCS Grading for Awasi, Kirinyaga and Katani quarries

GRADED CRUSHED STONE (0/30 mm) GRADING					
BS SIEVES (mm)	PERCENT (%) PASSING EACH SIEVE			GRADING SPECIFICATIONS (ENVELOPE)	
	KATANI	AWASI	KIRINYAGA	LOWER SPECS	UPPER SPECS
50	100.0	100.0	100.0	100	100
37.5	93.6	100.0	92.7	90	100
28	90.9	93.1	80.4	75	95
20	73.6	82.3	76.4	60	90
10	50.0	60.9	62.3	40	75
6.3	46.3	51.8	52.3	30	63
2	32.8	37.8	31.6	20	45
0.425	16.1	18.0	17.7	15	31
0.075	6.6	5.9	6.4	5	15

Source: Field Survey, 2025

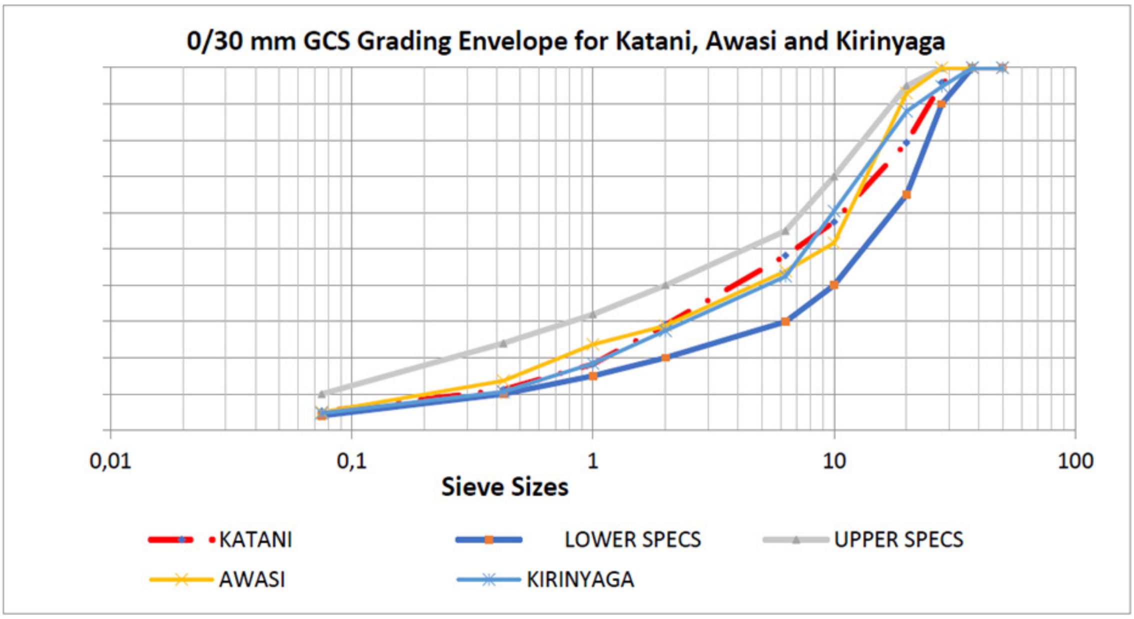

FIGURE 1
0/30 mm GCS Grading Envelope for Katani, Awasi and Kirinyaga
Source: Field Survey, 2025

Water Absorption, suggesting superior aggregate durability.

UCS Results
Three samples were molded at each cement content for each gradation and at each curing duration. The average UCS for each cement content, curing and soaking duration and gradation were as presented in **Table 4**.

UCS versus Cement Content
The study found a strong correlation between UCS and cement content. Across all three sources and gradations, UCS values increased with increasing cement dosages. For instance, H Young Katani's 0/30 mm mix improved from 2.5 MPa at 1% cement to 9.4 MPa at 5% with the 0/40 mm gradation achieving even greater improvement of up to 13.9 MPa. This trend is consistent

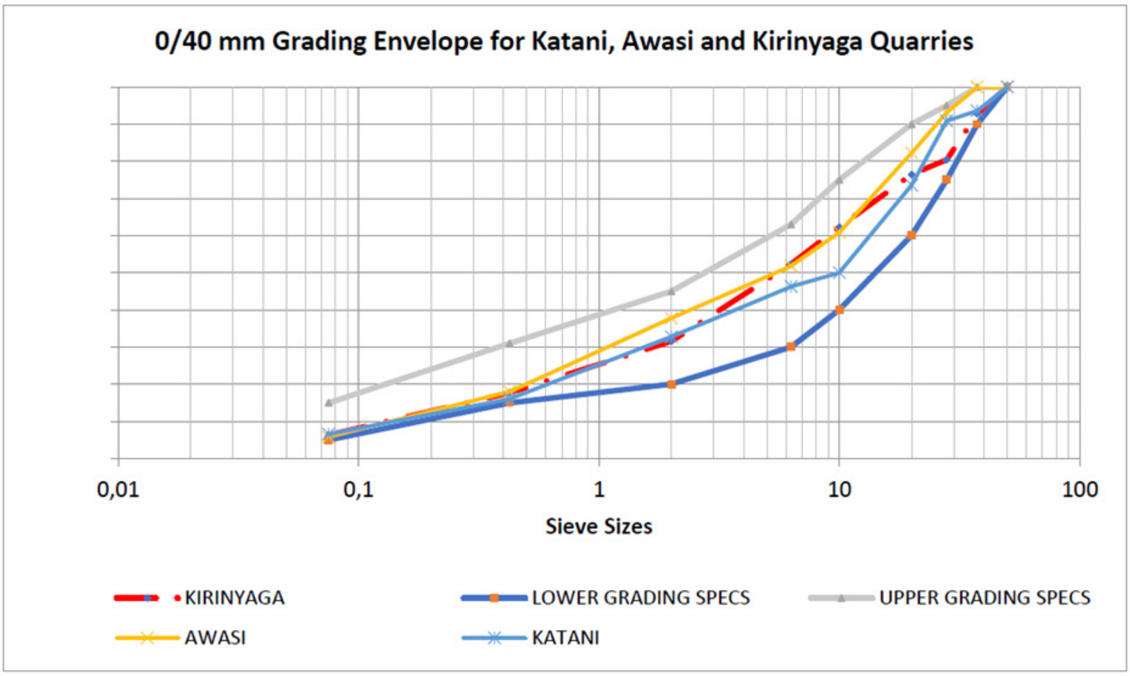

FIGURE 2
0/40 mm Grading Envelope for Katani, Awasi and Kirinyaga
Source: Field Survey, 2025

TABLE 3
Mechanical Properties of GCS Aggregate from Katani, Kirinyaga and Awasi

Property	Mechanical Properties of Aggregate Sources			Class A Specification (SSRBC)
	H Young Katani Quarry	China Wu Yi Kirinyaga Quarry	Sino Hydro Quarry Awasi	
ACV	24.8	13.0	12.6	Max. 25
LAA	19.5	15.4	12.0	Max. 30
SSS	1.1	1.2	0.8	Max. 12
FI	18.6	12.0	18.0	Max. 25
CR (Crushing Ratio)	100	100	100	Min. 100
Water Absorption	3.3	1.3	0.5	
Plasticity Index	0.0	0.0	0.0	
AIV	19.0	11.6	12.0	

Source: Field Survey, 2025

with findings from Mutua & Wambua (2021), confirming the strengthening effect of increased cement dosage.

The effectiveness of cement content on UCS is attributed to improved bonding between aggregate particles and the formation of calcium-silicate-hydrate (C-S-H) gel, which enhances inter-particle friction and stiffness. Beyond 4%, there was marginal gain in UCS, suggesting an optimal cement content range for economic efficiency.

Figure 3 illustrates the UCS trends for the cement content, gradations and curing period for HYoung Katani quarry. A similar trend was exhibited by all the three sources.

The significant increase in UCS with cement contents across all materials sources and gradations, confirms the findings of Deschenes (2020), which highlighted the positive impact of cement treatment on strength and stiffness of cement treated GCS. Strength gains however diminished

TABLE 4
Average UCS for each cement content, curing period and gradation

Aggregate Sources	Aggregate Gradation	Cement Content (%)	Average UCS (MPa) for Curing + Soaking Duration		
				14+7	28+7
Source 1: H Young Katani Quarry	**0/30 mm Gradation**	1%	2.5	2.8	3.4
		2%	3.1	4.0	4.8
		3%	3.8	5.6	6.4
		4%	4.9	6.2	7.4
		5%	7.6	8.4	9.4
	0/40 mm Gradation	1%	3.0	4.2	5.2
		2%	5.8	6.8	7.7
		3%	8.0	8.4	9.5
		4%	9.7	10.5	12.4
		5%	11.1	12.6	13.9
Source 2: China Wu Yi Kirinyaga Quarry	**0/30 mm Gradation**	1%	2.9	3.2	3.6
		2%	4.3	4.3	5.3
		3%	5.1	5.3	6.9
		4%	5.8	6.9	8.6
			7.6	8.6	10.3
	0/40 mm	1%	3.5	3.8	4.2
		2%	5.6	7.1	8.2
		3%	6.9	8.5	9.3
		4%	8.0	9.8	11.2
		5%	9.1	11.4	13.5
Source 3: Sino Hydro Quarry Awasi	**0/30 mm Gradation**	1%	3.1	3.5	3.8
		2%	4.3	5.1	5.7
		3%	6.0	6.9	7.8
		4%	7.5	8.8	9.1
		5%	8.9	9.6	11.5
	0/40 mm Gradation	1%	3.4	3.8	4.1
		2%	5.8	7.5	8.2
		3%	7.8	8.7	9.3
		4%	9.8	12.6	14.4
		5%	11.8	14.4	15.3

Source: Field Survey, 2025

beyond 4%, supporting recommendations from TRH4 (1996) and Austroads (2019) on economical cement usage.

Table 5 presents linear regression analysis for UCS as a function of cement content at a curing duration of 28+7 days for each source and gradation is presented.

The results show a strong linear correlation between cement content and UCS. Notably, Sino Hydro (0/40 mm) displays the steepest slope, indicating the highest strength gain per unit of cement. Generally, 0/40 mm gradation

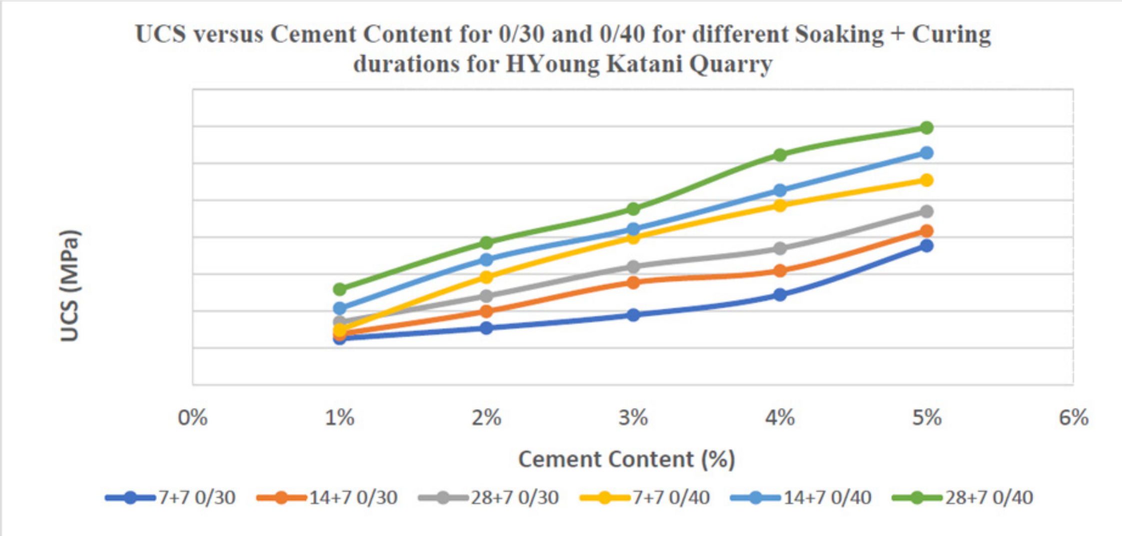

FIGURE 3
Typical UCS versus Cement Content for 0/30 and 0/40 for different Soaking + Curing durations for HYoung Katani Quarry
Source: Field Survey, 2025

TABLE 5
Regression Analysis: UCS vs Cement Content (28+7 Days)

Aggregate Source	Gradation	Slope	Intercept	R^2 Value
H Young Katani	0/30 mm	1.36	2.00	0.923
China Wu Yi	0/30 mm	1.67	1.93	1.000
Sino Hydro	0/30 mm	1.88	1.94	0.994
H Young Katani	0/40 mm	2.31	2.61	0.986
China Wu Yi	0/40 mm	2.16	2.80	0.963
Sino Hydro	0/40 mm	2.86	1.68	0.955

Source: Field Survey, 2025

outperforms 0/30 mm in UCS development.

UCS versus Curing Duration
Curing duration affected UCS development for all the sources. Early-age strength (7 days cure + 7 days soak) was considerably lower than the 14 days cure +7-day soak and 28 days cure +7-day soak. However, strength gain diminished with time, indicating that most hydration reactions occurred within the first 21 days. For example, UCS for Sino Hydro Awasi's 0/40 mm at 5% cement increased from 11.8 MPa at 14 days to 15.3 MPa at 28 days.

This pattern aligns with Mwaura, F. M., & Gichaga, J. F. (2018) finding that 14- and 28-day strength gain was more pronounced that 7 days in cemented materials, underscoring the need for sufficient curing time to achieve long-term strength and stability. The finding also confirms the Austroads (2019) guidance that stresses a 21-day minimum curing period for load-bearing performance layers.

Table 6 presents linear regression analysis for UCS as a function curing duration at fixed cement content levels for each aggregate source.

The results indicate a strong correlation with high R^2 values, confirming that UCS generally increases with curing duration. Higher cement content levels resulted in steeper slopes, indicating faster strength development over time.

TABLE 6
Analysis of UCS vs Curing Duration

Aggregate Source	Cement Content (%)	Slope	Intercept	R^2 Value
H Young Katani	1	0.043	1.90	1.000
H Young Katani	2	0.078	2.16	0.951
H Young Katani	3	0.114	2.60	0.842
H Young Katani	4	0.114	2.60	0.842
H Young Katani	5	0.084	6.51	0.984
China Wu Yi	1	0.033	2.47	0.988
China Wu Yi	2	0.051	3.44	0.893
China Wu Yi	3	0.090	3.67	0.947
China Wu Yi	4	0.132	4.03	0.996
China Wu Yi	5	0.128	5.86	0.998
Sino Hydro	1	0.032	2.73	0.928
Sino Hydro	2	0.063	3.56	0.928
Sino Hydro	3	0.083	4.97	0.964
Sino Hydro	4	0.068	6.87	0.739
Sino Hydro	5	0.126	7.07	0.995
H Young Katani	1	0.100	1.80	0.942
H Young Katani	2	0.036	5.60	0.481
H Young Katani	3	0.072	6.94	0.995
H Young Katani	4	0.130	7.84	0.998
H Young Katani	5	0.128	9.56	0.947
China Wu Yi	1	0.033	3.07	0.988
China Wu Yi	2	0.116	4.29	0.900
China Wu Yi	3	0.106	5.76	0.862
China Wu Yi	4	0.145	6.29	0.933
China Wu Yi	5	0.201	6.64	0.954
Sino Hydro	1	0.032	3.03	0.928
Sino Hydro	2	0.105	4.71	0.829
Sino Hydro	3	0.067	7.03	0.910
Sino Hydro	4	0.228	6.26	0.964
Sino Hydro	5	0.152	10.29	0.800

Source: Field Survey, 2025

Effect of Gradation

The three sources offered a good comparison on the influence of gradation considering GCS from the three sources were class A, based on mechanical properties. The aggregate gradation influenced the variation of optimal cement content for the determined UCS values as suggested by Kamau & Ochieng (2022). The 0/40 mm gradation outperformed 0/30 mm across all cement contents and curing durations. This trend was most distinct at higher cement contents. The coarser gradation provided better interlock, reduced voids and higher densities, facilitating better cement paste distribution and compaction. These results support the hypothesis that optimal gradation contributes to higher UCS and reduced cement demand, thus promoting material efficiency and cost savings in construction. SANRAL and Austroads similarly prefer coarser, continuously graded materials in base layers. Overally, a regression equation below, based on average UCS for each test number, yielded an R^2 of 0.893, indicating a strong correlation and predictive power of the variables to UCS. The model can be used as a faster estimation of the UCS based on mix design parameters.

UCS (MPa) = -1.5936 + 1.7672(Cement %) + 0.0962(Curing Period) + 2.5533(Gradation Category)

CONCLUSION

From the study findings, it is concluded that cement treated class A 0/40 mm GCS performs better than class A 0/30 mm GCS and is most suitable for high traffic volume roads. The GCS aggregates source factors such as mechanical strength and crushing also affect the performance of cement treated GCS for similar classes and gradation. Further, there is variability of UCS at constant cement dosages for the different aggregate sources implying impracticality of adopting a constant cement content across different sources. UCS strength development for cement treated GCS is optimal at 21 days indicating that longer on-site curing durations, beyond the 7 days prescribed, is required for effective performance of cement treated GCS.

RECOMMENDATIONS

Based on the study findings the following recommendations are drawn:

i. Compared to class A 0/30 mm GCS, cement treated class A 0/40 mm GCS gradation is recommended for high traffic volume roads.
ii. On-road curing duration for cement treated GCS should be enhanced beyond the current 7- days practice to a minimum 21-days before allowing traffic passage over a constructed layer to enable optimum strength development.
iii. Performance-based mix designs for cement treated GCS is recommended instead of a constant cement content for all classes of GCS, for local road construction specifications due to the variability in the strengths obtained for the different sources at each cement dosage for the different GCS gradation.
iv. Field validation of laboratory UCS models using in-situ testing such as Plate loading, Light Weight and Falling Weight Deflection testing should be conducted to corroborate the laboratory findings.
v. Evaluation of the long-term fatigue and durability behavior of cement-treated GCS under actual traffic loading for in-service performance assessment.
vi. Laboratory trials using other/alternative stabilizers (e.g., pozzolanic cements, lime, slag) recommended for materials stabilization for road works.
vii. Comparison of Modified Proctor and Vibratory Hammer compaction methods for cement treated GCS.

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Appendices

The comprehensive UCS test results that support the findings of this research are openly available in this link:

https://docs.google.com/document/d/1dbNKyjLJ9aK9MdSqMzsALMTzCucFBxlN/edit?usp=sharing&ouid=102666240614201540330&rtpof=true&sd=true