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Case study

Stress-strain characteristics of concrete containing quarry rock dust as partial replacement of sand

Charles K. Kankam, Bismark K. Meisuh*, Gnida Sossou, Thomas K. Buabin

Civil Engineering Department, KNUST, Kumasi, Ghana

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ABSTRACT

The paper presents results of study on concrete using quarry dust to replace sand at levels of 0%, 25%, and 100% by weight. Design mixes were prepared to achieve concrete grades C25, C30, C35, C40 and C45 for each of the three replacement levels. Prismatic specimens were prepared to study the stress-strain behaviour of the concrete. It was observed that the stress-strain curves were similar for all sand replacement levels and that concrete with 100% quarry dust had the maximum strain values. The results of the study showed that for all concrete grades, 25% sand replacement level gave higher (7.9%) modulus of elasticity (MoE) while 100% sand replacement level gave lower (8.6%) MoE relative to 0% sand replacement level. The estimated MoE was compared with values obtained from the formulas proposed by the BS, ACI and IS for estimating the MoE using the compressive strength of concrete. It was found that blending sand and quarry dust produces concrete of enhanced mechanical properties.

1. Introduction

Natural sand has been the conventional fine aggregate in concrete production for many decades. However, there has been extensive research into alternative materials suitable to replace sand in concrete. The need to find replacement for sand stems from the fact that in most parts of the world, there is growing concern about the depletion of sand deposits, environmental and socio-economic threats associated with extraction of sand from river banks, coastal areas and farm lands. Some alternative materials which have been studied for use as partial replacement for sand include fly ash, slag limestone, silica stone, furnace bottom ash and recycled fine aggregate [1–3]. Among the many materials investigated, quarry rock dust (QD) appears to be the most suitable because it is available in large quantities in most parts of the world. The annual production and consumption rate of quarry aggregates in Great Britain and USA is estimated to be 230 million tonnes and 1.73 billion tonnes respectively [4,5]. The use of quarry dust as a building material has been accepted in the advanced countries in the past three decades [6,7]. The level of utilization stems from sustained research work carried out regarding increasing application of quarry fine aggregate.

Studies into the properties of fresh concrete have shown that there is decrease in workability with quarry dust in concrete [2]. The decrease in workability is mostly attributed to high percentage of fines in the quarry dust and also the angular shape and rough texture of the dust particles which result in high water demand.

Investigation into the durability of quarry dust concrete carried out by Ilangovana et al. [6] showed that quarry dust concrete dry shrinkage strains were larger at early ages (below 7 days) but lower at later ages compared with sand concrete. Also, Shanmugavadivu and Malathy [8] reported lower water permeability, chloride-ion penetration, strength and weight loss due to acid-chloride ion attack for concrete with 70% sand replacement with QD. Improved impact resistance of concrete has also been reported [9].

* Corresponding author.
E-mail address: bisuh2004@yahoo.com (B.K. Meisuh).

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Table 1
Physical Properties of Aggregates.

Aggregate	Bulk Density (kg/ m^3)	Fines Content (%)	Fineness Modulus	Water Absorption (%)	Moisture Content (%)	Specific Gravity	Crushing Value
River sand	1600	3.89	2.66	6.8	3.56	2.66	–
Quarry dust	1650	10.45	3.54	10.6	0.54	2.64	–
Coarse Agg.	1625	–	–	0.54	0.09	2.71	18.3

Studies conducted to investigate the effect of QD on the strength properties of a wide range of concrete grades from C20 to C45 and at varied sand replacement levels showed that the compressive, flexural and split tensile strengths of concrete increased to a maximum at optimum blend of QD and sand. The optimum blend varied greatly from 90:10 to 25:75 (Sand: QD) due to the variability in the properties of materials used for the various studies conducted at different parts of the world. However, in general, an increase of about 8–20% in strength has been reported at optimum sand replacement [2,10–16].

While considerable amount of research has been conducted to study the rheological, strength and durability properties of quarry dust concrete, no work has been carried out on the stress-strain characteristics of concrete with quarry dust. There is therefore the need to study the strength and stress–stress characteristics of concrete with quarry dust.

2. Experimental program

2.1. Materials

Portland limestone cement as the hydraulic binding agent, river sand and quarry rock dust both of 2 mm maximum size as fine aggregate, and 14 mm crushed rock coarse aggregate were used for the concrete. The physical properties of the fine and coarse aggregates are shown in Table 1. The fine and coarse aggregates satisfied the BS 882 [17] specification requirements.

2.2. Mix proportions and preparation of specimens

Three replacement levels of 0%, 25% and 100% quarry dust were used in the concrete mixes. The 25% is the optimum replacement percentage achieved by carrying out strength studies for 0%, 25%, 50%, 75% and 100% sand replacement levels. The respective 28-day strengths were 24.49, 27.91, 24.64, 21.33 and 19.40 N/mm^2 [18]. The mixes were designed to achieve five different target strengths. The concrete mixes were designed to have a near constant slump in the range of 60–180 mm; and as such, the water-cement ratio varied. The procedure used for the mix design was in accordance with that outlined in "Design of Normal Concrete Mixes" [19]. Table 2 shows the detailed mix proportions.

The cement and aggregates were first mixed together in a mixing pan. Water was then added and mixing was continued until a uniform and homogenous matrix was obtained. The mix for each sand replacement level of particular concrete grade was cast in 100 × 100 × 100 mm [20] and 100 × 100 × 200 mm [21] wooden moulds and compacted with a tamping rod in three layers. The specimens were de-molded after 24 hours and cured by immersion in water at a room temperature of 27 °C for 28 days. The prisms were used to obtain the stress–strain curves, and the cubes were used to obtain the compressive strength of the concrete.

Table 2
Mix Proportions of Concrete Mixes.

Mix notation	TCS (N/ mm^2)	SRL (%)	w/c ratio	Free water (kg/ m^3)	Cement(kg/ m^3)	River sand (kg/ m^3)	Quarry dust (kg/ m^3)	Coarse aggregate (kg/ m^3)
RSC25	25	0	0.60	222	370	583	–	1210
RSC30	30	0	0.56	222	397	557	–	1210
RSC35	35	0	0.52	222	427	530	–	1210
RSC40	40	0	0.48	222	463	502	–	1200
RSC45	45	0	0.44	222	505	473	–	1185
SQC25	25	25*	0.60	233	388	517	173	1034
SQC30	30	25*	0.56	233	416	496	166	1035
SQC35	35	25*	0.52	233	448	474	158	1032
SQC40	40	25*	0.48	233	485	451	151	1025
SQC45	45	25*	0.44	233	530	427	143	1012
QDC25	25	100	0.60	240	400	–	789	926
QDC30	30	100	0.56	240	429	–	759	927
QDC35	35	100	0.52	240	462	–	727	926
QDC40	40	100	0.48	240	500	–	695	921
QDC45	45	100	0.44	240	546	–	659	910

TCS is Target characteristic strength; SRL is sand replacement level; 25* is optimum percentage level [18].

Fig. 1. Stress-strain experimental set-up.

2.3. Test setup and method

On each day of testing, the specimens were taken out of the curing tanks and left in the open air for about 2 hours before testing. The cube and prism specimens were tested under static unconfined uniaxial compression using a 1000 kN capacity Universal Testing Machine (UTM). The specimens were subjected to continuous loading at a constant loading rate of 2 kN/s until failure.

The UTM was fitted with a digital dial gauge to measure the axial deformation (Fig. 1). The loading platens of the UTM remained planar, rigid and un-deformed throughout the tests. Hence, one dial gauge was found sufficient for accurate measurement of the deformation of the specimens. The displacement readings were used in calculating the strain for each specimen. The axial deformation was recorded at 20 kN load interval. Loading and axial deformation measurements were carefully controlled. The axial strain was determined by dividing the change in length by the original length.

3. Results and discussion

3.1. Failure behaviour and patterns

The failure behaviour was similar for all concrete specimens with 0%, 25%, 100% sand replacement. The failure behaviour was characterized by three stages, namely, initiation of cracks, propagation of cracks and finally, failure of the specimen. The test specimens did not show cracks initially until the increase of axial compression loading began to cause small micro-cracks to gradually form in the test specimens. Cracks were observed at comparatively lower stress in concrete with 100% sand replacement than in concretes with 0% and 25% sand replacement. The propagation of cracks was gradual until failure of specimen was reached. Crack propagation was faster in concrete with 0% sand replacement compared to concretes with 25% and 100% sand replacement.

The crack pattern developed was basically diagonal in nature for all specimens with concrete of 0% and 25% sand replacement levels showing a somewhat conical crack pattern (Fig. 2). The angle of inclination with respect to the centroidal vertical axis was about 40°, 45° and 25° for concrete with 0%, 25%, and 100% sand replacement respectively. Most of the concrete specimens with no

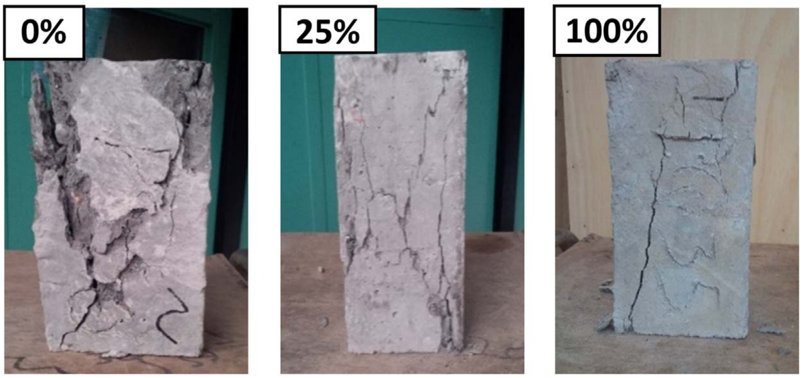

Fig. 2. Failure patterns of concrete with 0%, 25% and 100% sand replacement.

sand replacement failed by emitting loud splitting sound at failure.

3.2. Compressive strength

The prism compressive strength is the peak stress of the prismatic specimens tested under uniaxial compression. The cube compressive strength, f_{cu}, and the prism compressive strength, f_c, for the three sand replacement levels are given in Table 3. The ratios of the prism compressive strength to cube compressive strength are also presented. It can be seen that the prism compressive strength increases with increasing cube strength. The results also show that concrete with 25% sand replacement gave relatively higher compressive strength compared to the other two replacement levels.

The average f_c/f_{cu} ratios for 0%, 25% and 100% sand replacement are 0.79, 0.81 and 0.80, respectively, which fall within the range generally adopted for estimating prism or cylindrical compressive strength, that is, 75–85% of the cube compressive strength.

3.3. Stress-strain curves

Typical stress–strain curves (SSC) of grades C25 and C45 concrete with 0%, 25% and 100% quarry dust contents are shown in Fig. 3. Incorporation of quarry dust as fine aggregate in concrete has noticeable influence on the SSC of concrete. Nonetheless, the shape of the stress–strain curve for all the concrete with quarry dust fine aggregate was similar to that of the natural sand concrete, regardless of the replacement percentage. The curves are generally seen to have two parts: a lower linear portion up to about 35–45% of the failure stress and an upper nonlinear portion. This means that in principle no modifications are needed to be made in the structural design process to the application of the theory of elasticity for concrete with quarry dust. From Fig. 3, it is seen that strains were higher for 100% sand replacement than for 0% sand replacement. The grading properties and the fines content of quarry dust may have contributed to the characteristics of stress-strain curve of concrete with quarry dust. The maximum strains for 100% sand replaced concrete is about 15% higher than those of 0% sand replacement. The main cause of the increase in the peak strain is lower modulus of elasticity, which causes the concrete to undergo larger deformation.

3.4. Static modulus of elasticity

The static modulus of elasticity, E_c, is determined directly from the stress–strain curve. In this study, the secant modulus was estimated and taken as the static modulus of elasticity of the concrete. The secant modulus is generally evaluated as the slope of a line drawn from the origin to a point on the stress-strain curve corresponding to a stress 35–45% of the maximum stress. In this study, a stress of 40% of the maximum stress was used [22]. The initial tangent modulus (the slope of the tangent drawn at the origin of the

Table 3
Cube and Prism Compressive Strength Test Results (N/mm^2).

Concrete Grade	0% SRL			25% SRL			100% SRL		
	PCS, f_c	CCS, f_{cu}	$\frac{f_c}{f_{cu}}$	PCS, f_c	CCS, f_{cu}	$\frac{f_c}{f_{cu}}$	PCS, f_c	CCS, f_{cu}	$\frac{f_c}{f_{cu}}$
C25	20.80	26.70	0.75	22.00	26.10	0.84	21.50	26.90	0.80
C30	23.80	30.50	0.78	25.30	31.20	0.81	25.20	30.17	0.84
C35	28.30	36.17	0.78	29.00	38.00	0.76	28.70	35.53	0.81
C40	32.50	38.70	0.84	34.00	42.40	0.8	33.00	40.03	0.82
C45	36.50	44.43	0.82	39.50	46.40	0.85	34.80	47.27	0.74

SRL is sand replacement levels; PCS is prism compressive strength; CCS is cube compressive strength.

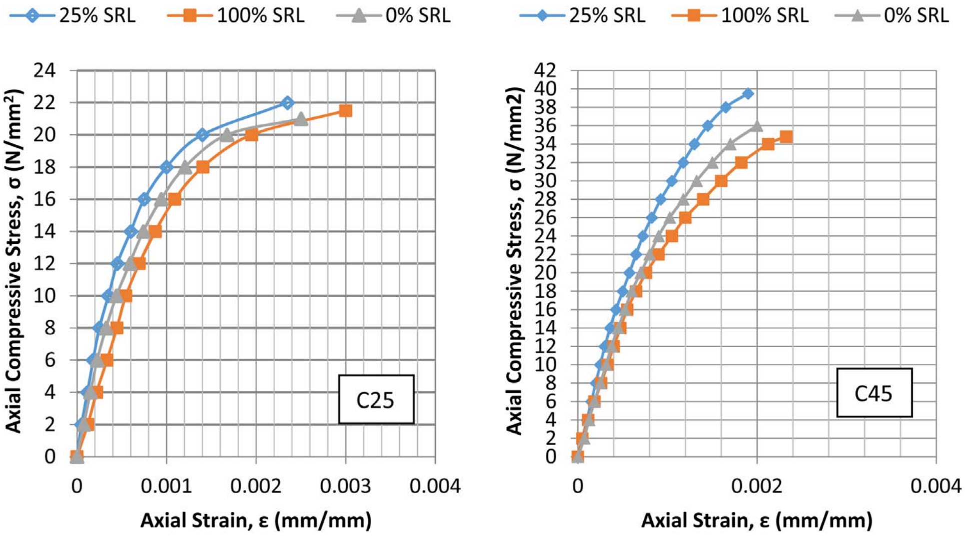

Fig. 3. Typical axial compressive stress-strain curves for concrete grades C25 and C45.

stress-strain curve) was also estimated. Table 4 shows the modulus of elasticity of concrete – secant and initial tangent moduli – for 0%, 25%, and 100% sand replacement levels. The cube compressive strength, f_{cu}, and maximum stress, f_c, of the prismatic test specimens are also presented. It can be seen that the modulus of elasticity of concrete with 100% sand replacement is lower than that of the concrete with no sand replacement. Concrete with 25% sand replacement is seen to have the highest elastic modulus. Averagely, the modulus of elasticity of concrete with 100% sand replacement was found to be 8.6% lower than concrete with no sand replacement whilst that of concrete with 25% sand replacement is 7.9% higher than concrete with no sand replacement. The variation in the modulus of elasticity is the consequence of better bonding of aggregate and cement particles due to the shape, texture and grading characteristics of the quarry rock dust. It is necessary to point out that the variation in the cube compressive strengths as well as the prism compressive strengths for the three concrete groupings corresponds with the trend observed with the modulus of elasticity.

3.5. Static modulus of elasticity and cube compressive strength relationship

Fig. 4 shows secant modulus of elasticity versus compressive strength of concrete with 25% and 100% sand replacements. The American Concrete Institute (ACI) Code, British Standard (BS) and Indian Standard (IS) formulas proposed for estimating the modulus of elasticity of normal weight concrete from 28-day compressive strength are also presented for comparison. These formulas have been modified to account for the difference between 100 mm cube compressive strength and 150 mm cube compressive strength for the IS and BS and cube compressive and cylindrical compressive strength for the ACI Code. Assuming a compressive strength modification factor of 0.9 for the former and 0.72 for the latter [23], the modified formulas are given as:

$$\text{ACI modified:} \quad \boldsymbol{E_c} = 3988\sqrt{\boldsymbol{f_{cu}}} \tag{1}$$

$$\text{BS modified:} \quad \boldsymbol{E_c} = 20000 + 180\boldsymbol{f_{cu}} \tag{2}$$

$$\text{IS modified:} \quad \boldsymbol{E_c} = 4458\sqrt{\boldsymbol{f_{cu}}} \tag{3}$$

Table 4
Results of Modulus of elasticity of Concrete (kN/mm²).

Concrete Grade	0% SRL				25% SRL				100% SRL			
	CCS, f_{cu}	PCS, f_c	SM,E_c	ITM, E_{it}	CCS, f_{cu}	PCS, f_c	SM, E_c	ITM, E_{it}	CCS, f_{cu}	PCS, f_c	SM, E_c	ITM, E_{it}
C25	26.70	20.80	24.00	31.20	26.10	22.00	25.39	32.94	26.90	21.50	21.65	28.15
C30	30.50	23.80	26.98	35.07	31.20	25.30	28.58	36.85	30.17	25.20	24.65	32.04
C35	36.17	28.30	28.91	37.00	38.00	29.00	31.90	40.83	35.53	28.70	26.80	34.30
C40	38.70	32.50	30.21	38.22	42.40	34.00	33.27	42.14	40.03	33.00	28.65	35.84
C45	44.43	36.50	31.28	39.12	46.40	39.50	34.38	43.01	47.27	34.80	29.28	36.57

SRL is sand replacement levels; PCS is prism compressive strength (N/mm²); CCS is cube compressive strength (N/mm²); SM is secant modulus; ITM is initial tangent modulus.

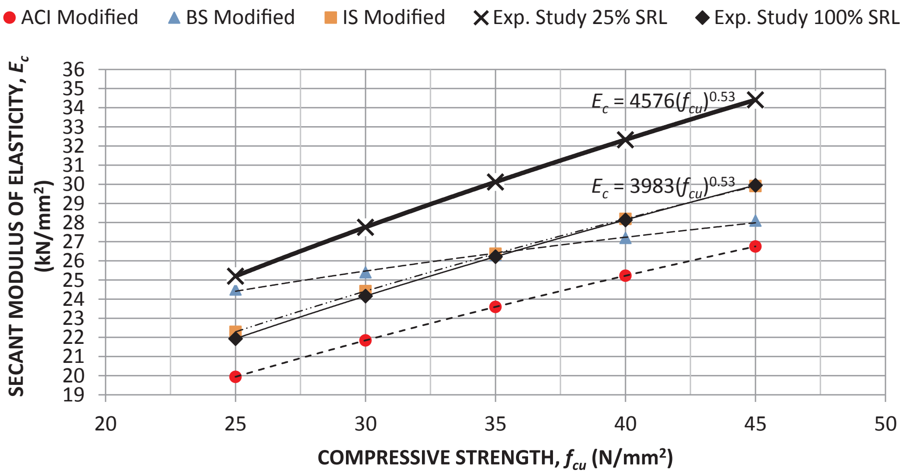

Fig. 4. Comparison of experimental static modulus of elasticity with standards.

where f_{cu} is cube compressive strength (N/mm^2) for 100 mm concrete cube specimen

Fig. 4 shows that the formulas proposed by the ACI and BS codes of practice cannot reliably be used to estimate the modulus of elasticity of concrete with quarry dust as fine aggregate. From Fig. 4 it is observed that the IS modified values relate closely with those of 100% sand replacement level. However, the 25% sand replacement level modulus of elasticity values are higher than those of the ACI, BS and IS formulas. For quarry dust concrete, the following formulas are proposed from the study:

$$\text{Optimum Blend 25: 75(QD: Sand):} \quad \boldsymbol{E_c} = 4576(\boldsymbol{f_{cu}})^{0.53} \tag{4}$$

$$\text{100\% Quarrydust:} \quad \boldsymbol{E_c} = 3983(\boldsymbol{f_{cu}})^{0.53} \tag{5}$$

4. Conclusions

Based on the results obtained and the analysis presented, the following conclusions can be drawn:

1. Generally, diagonal crack patterns were observed in all prismatic specimens tested to study the stress-strain behaviour. However, the crack patterns in specimens with 0% and 25% sand replacement levels were somewhat conical in nature.
2. The average ratio of prism compressive strength to the cube compressive strength is marginally higher for concrete with 25% sand replacement compared with that of 0% replacement.
3. The stress-strain curves (SSC) for concretes with quarry dust and river sand as fine aggregate showed similar behaviour. The SSCs for concrete with quarry dust showed higher maximum strains, 15% higher than those of conventional concrete. Based on the characteristics of the SSCs, it can be concluded that the structural design process of concrete with quarry dust within the elastic and inelastic range can be carried out normally without the need for modifications.
4. The modulus of elasticity of concrete with quarry dust was 8.6% lower than concrete with sand. However, concrete with 25% sand replacement gave the highest (7.9% higher than concrete with no sand replacement) modulus of elastic of concrete. The equations to predict modulus of elasticity of quarry dust concrete based on the compressive strength derived in this study varies greatly from those proposed in standard codes of practice.

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