scientific article
DOI: 10.18721/JEST.
УДК: 624.69-033

METAMORPHIC ROCKS FOR MANUFACTURED SAND AND COARSE AGGREGATE FOR CONC

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Аннотация. The present study is executed for determining the most applicable high-grade metamorphic rocks as the sources for manufactured sand and coarse aggregates production to apply in the construction industry. As the first stage of this study, representative samples of the most common ten types of metamorphic rock were collected and tested for mineralogical and chemical compositions to select the favorable rock types for the performance of concrete and mortar. XRD diffraction patterns and quantitative analysis results of XRF were referred for identifying the mineral and chemical contents respectively. Secondly among the favorable rock types, based on the geology, the area contribution by each rock was calculated and few abundantly available rocks were considered for further investigation. Finally, the compatibility of rocks was checked by analyzing the physical, mechanical and durability characteristics. As the physical parameters, the specific gravity, water absorption, loose and packing density and water content were checked. Mechanical properties of rocks was determined by investigating compressive and tensile strength, impact resistance, abrasion resistance and crushing value. Durability of rocks against weather fluctuations was probed through the slake durability indexes. Results from the first stage revealed that Charnockite, Hornblende-Gneiss, Intrusive Charnockite and Granitic-Gneiss as the favorable rocks which were rich with friendly minerals such as albite, k-feldspar and quartz for function of concrete and mortar. Among the above four rocks, Charnockite contributed around 40% and Hornblende-Gneiss covered approximately 9.5% of the area, which were then considered for the next stage of investigation. Charnockite and Hornblende-Gneiss showed similar porosities and water absorption in the range of 0.25 – 0.26 %. Each mechanical property of both rocks was complied with the requirements provided by the standards and they also manifested excellent durability performance against cyclic wetting and drying.

Ключевые слова: aggregates, concretes, mortar, construction industry, porosity, water absorption, compressive strength, tensile strength, mechanical properties, durability

Благодарности:

Ссылка при цитировании: . и др. METAMORPHIC ROCKS FOR MANUFACTURED SAND AND COARSE AGGREGATE FOR CONC // Инженерно-строительный журнал. №05(113).

scientific article

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METAMORPHIC ROCKS FOR MANUFACTURED SAND AND COARSE AGGREGATE FOR CONCRETE AND MORTAR

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Abstract: The present study is executed for determining the most applicable high-grade metamorphic rocks as the sources for manufactured sand and coarse aggregates production to apply in the construction industry. As the first stage of this study, representative samples of the most common ten types of metamorphic rock were collected and tested for mineralogical and chemical compositions to select the favorable rock types for the performance of concrete and mortar. XRD diffraction patterns and quantitative analysis results of XRF were referred for identifying the mineral and chemical contents respectively. Secondly among the favorable rock types, based on the geology, the area contribution by each rock was calculated and few abundantly available rocks were considered for further investigation. Finally, the compatibility of rocks was checked by analyzing the physical, mechanical, and durability characteristics. As the physical parameters, the specific gravity, water absorption, loose and packing density, and water content were checked. Mechanical properties of rocks were determined by investigating compressive and tensile strength, impact resistance, abrasion resistance, and crushing value. The durability of rocks against weather fluctuations was probed through the slake durability indexes. Results from the first stage revealed that Charnockite, Hornblende-Gneiss, Intrusive Charnockite, and Granitic-Gneiss the favorable rocks which were rich with friendly minerals such as albite, k-feldspar, and quartz for the function of concrete and mortar. Among the above four rocks, Charnockite contributed around 40% and Hornblende-Gneiss covered approximately 9.5% of the area, which were then considered for the next stage of the investigation. Charnockite and Hornblende-Gneiss showed similar porosities and water absorption in the range of 0.25 – 0.26 %. Each mechanical property of both rocks complied with the requirements provided by the standards and they also manifested excellent durability performance against cyclic wetting and drying.

Keywords: aggregates, concrete, mortar, construction industry, porosity, water absorption, compressive strength, tensile strength, mechanical properties, durability

Acknowledgements:

Citation: Arulmoly B. и др. Metamorphic Rocks for Manufactured Sand and Coarse Aggregate for Concrete and Mortar. Magazine of Civil Engineering. No. 05.

1. Introduction

The implementation of a proper alternative for river sand and natural coarse aggregate is the major problem that has risen now among the construction industries in most of the developing countries including Sri Lanka. River sand is currently being used as the main fine aggregate in most construction activities [1]. Many restrictions have been imposed on river sand mining due to the adverse impact on the environment and ecological systems. Excessive excavations near the riverbanks caused serious environmental threats not only in Sri Lanka but also in many countries that are still extracting river sand for infrastructure developments [2]. The most identified impacts on the environment are riverbank collapses, loss of vegetation on the bank of rivers, saline water intrusion, river buffer zone encroachment, erosion of riverbank land areas, and deterioration of river water quality and groundwater quality [2-5]. Presently, the construction companies are trying to introduce manufactured sand as an alternative to river sand for the construction activities to immediately mitigate the issues with river sand mining [1,6-8]. This leads to an increased number of quarries that are operated to supply the coarse aggregates as well as manufactured sand for both concrete and mortar works [9]. The source to produce manufactured sand is 'high-grade parent rock' which is a solid material with the collection of one or more mineralogical and chemical compositions [10-12]. Therefore, the quality of aggregates produced directly depends on the compositions of parent rocks, which may give positive and negative impacts on the performance of concrete and mortar [7,8,13].

Deliberation to manufactured sand production is crucial as the implications of finely crushed minerals in concrete and mortar are higher than coarse aggregates. It was identified that still, the question remains among the local construction industries, mining industries, and quarries on selecting appropriate rock types for manufactured sand production due to the inclusions of different minerals and chemicals present in the rocks as well as the performance of the rocks [14]. This problem is serious because the potentially deleterious mineralogical and chemical compositions in parent rocks may affect the long and short-term durability of concrete and mortar. Also, when the rock-derived materials used in concrete and mortar are not capable to resist higher stresses or withstand the climatic changes, may fail the structural elements. Therefore, it is a must to investigate the chemical, physical, mechanical, and durability properties of high-grade metamorphic rocks before utilizing them as the sources for aggregate production in the construction work.

This study is focused on determining suitable metamorphic rock types in Sri Lanka and their characteristics for use as the raw materials for producing manufactured sand. Therefore, the outcomes of this research are expected as the guide for selecting appropriate high-grade parent rocks for producing manufactured sand to enhance a durable and sustainable built environment.

Earth's crust is mainly composed of three major rock classes such as igneous rocks, sedimentary rocks, and metamorphic rocks [10,11]. Based on the simplified geology of Sri Lanka represented by Figure 1, the crust part (nine-tenths) is mainly underlain by 'Precambrian' age rocks which are subdivided into three major groups based on tectonic setting and the age of rocks: Wanni Complex (WC), Vijayan Complex (VC) and Highland Complex (HC) [12,15,16]. The age of each above rock complex is also given in the figure as 'Ma', which defines the mega annum or millions of years. Sedimentary limestone with Miocene age (22.5 to 5 million years ago) can be identified in the North-Western area (coastal belt from Madurankuli to Killinochi). Northern province areas contain limestone facies and the North-Eastern area (coastal belt from Paranthan to Mullaithivu) is underlain by sandstone [17]. Small clusters of mudstone and sandstone of Jurassic age (201 million years) rocks were identified in Tabbowa, Andigama, and Pallama areas having hard sandstone and clay interbedded with limestone and mudstone [18]. Precambrian rocks such as quartzite, charnockite, granulite grade pelitic gneisses, limestone, biotite gneisses are found in HC. Similarly, granitic-gneiss, biotite gneiss, and calc-gneiss rocks are identified in VC while WC is with prominent rock types [15-17]. It is identified that mainly high-grade metamorphic rocks are distributed within this island, which is very strong and hard shows the possibility for manufacturing good quality concrete and mortar aggregates. Some parts of this country are covered with weathered rocks which are not deemed for aggregate production [19].

Some studies proved the linkage between Sri Lankan geology with the global geology, which leads to the depth of this research work to an extent. Prame [20] has explained the lithological similarity of HC with the Trivandrum block of the South Indian granulite belt. Kroner [21] and Pinna et al. [22] proposed that HC geology highly coincides Madagascar-Tanzania and Mozambique while VC rocks have similarities with East and West Gondwana. Sandiford (1986, cited in [20]) compared the lithological affinity with the Rayner Complex of Enderby Land, Antarctica. Yoshida et al. (1992, cited in [20]) correlated Ongul/Skallen groups, Yamato-Belgica Complex, and Prince Olav Complex of Antarctica with HC, VC, and WC respectively.

Limited studies have been carried out so far on the effect of mineral and chemical compositions on the quality of fine aggregates for concrete and mortar production and some of them are included in this section. Dahanayake and Jayasena [23] carried out a study on some of the mineral compounds, texture, and grain direction of gneiss, amphibolite, and some intrusive rocks in VC. A microscopical mineralogical backscattered electron analysis was done by Malaviarachchi and Takasu [24] on some pelitic and intermediate to mafic granulites from HC to check the metamorphic grade based on the mineral assemblages. A key investigation was carried out by Jayawardena & Dissanayake [25] on the selection of suitable rock types for quarry dust production where the sample collections were done only in the Central and Northwestern provinces of Sri Lanka.

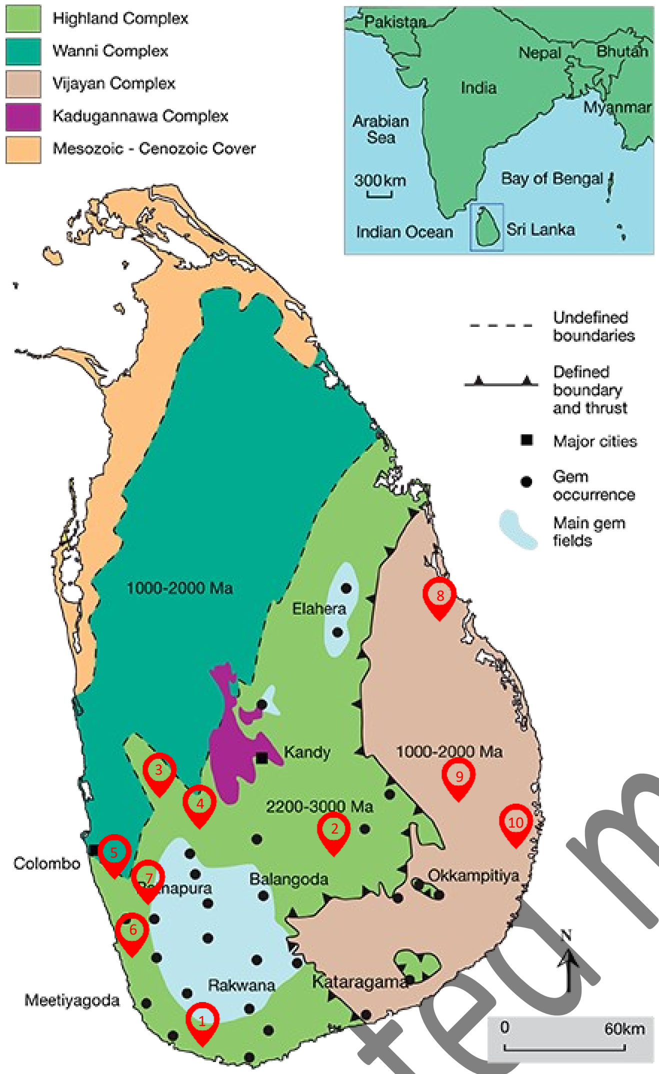

Figure 1. Simplified geological map of Sri Lanka [17]

Petrographic studies were followed for the collected samples and some important conclusions were derived: quartz, feldspar, hornblende, hypersthene, and a few biotite mica contents were identified in charnockite, hornblende-gneiss, and granitic-gneiss rocks from the collection areas which were mainly used for quarry dust production in the country. A recommendation of using quartzite for manufacturing quarry dust was also suggested by the authors as it is usually free from mica content. Mica and clay are considered the most harmful minerals in the rocks. Mica drastically lowers the workability of mixes due to flaky particles and clay significantly reduces the strength of concrete and mortar due to its fine form. Tugrul et al. [26] investigated the effects of feldspar, mica, and clay minerals on compressive strength of mortar where replacement of river sand with 20% of mica and 4% of clay minerals such as illite and montmorillonite reduced 50-60% compressive strength at 28 days. A detailed study was accomplished by Leemann and Holzer [27] on various grain size inclusions of mica minerals such as muscovite, biotite, and chlorite in the mortar and muscovite in concrete. Diminished workability, compressive and flexural strengths, and increased void content were observed with higher larger grain-sized mica inclusions in mortar and concrete. From the investigation executed by Norvell et al. [28], greater water demand and drying shrinkage and dwindled compressive strength of concrete was noticed when the aggregates had higher contents of montmorillonite than illite and kaolinite.

Coarse aggregate is also a manufactured primary aggregate that is obtained from several industrial processes. The quality of rock-derived coarse aggregates mainly depends on the properties of the original rock which are used for manufacturing [29]. Therefore, coarse aggregates should have high strength, better particle shape and gradation, good wear resistance and resistance to climatic changes, etc. [30]. van Wyk and Croucamp [13] checked the suitability of quartzite, tillite, sandstone, and shale rocks for concrete based on strength and durability parameters. Authors found that required concrete compressive strength was achieved with each rock aggregates but tillite and shale showed unsatisfactory performance with durability. Quartzite revealed the best durability among the selected rocks from slake durability test. Loorents and Johansson [31] studied the quality of granitoid rock aggregate based on free mica grains. Authors identified that the finer particles were abundant with free mica at each fraction while medium and coarse rocks showed high mica content at the fraction of 125-250 μm. Ugolini et al. [32] analyzed mineralogical, physical, and chemical properties of sandstone and siltstone fragments in the soil. The authors noticed that there was a distinct mineralogical difference between sandstone and siltstone while the physical and chemical properties were marginally similar. Scott and Rollinson [33] investigated the mineralogy and surface textures of granite, granodiorite, lava, pyroclastic, gabbro, dolerite, limestone, dolostone, gritstone, greywackes, anorthosite rocks. Johansson et al. [34] researched the quality of mica-schist rock by conducting the micro-Deval test, Los-Angeles abrasion test, and Nordic test on drilled samples. Because the results were within the required limits, the authors suggested the selected rock to produce good quality aggregate.

To achieve the aim of this study, a number of tasks were solved:

a) investigation on identifying the high-grade metamorphic rocks available based on the geology and linkage with global geology based on the literature review;

b) research of the mineralogical and chemical compositions of high-grade metamorphic rocks and identifying the most suitable rock types for concrete and mortar;

c) study of the availability of selected rock types based on the geology;

d) analyzation of the most determining physical, mechanical, and durability properties of the suitable and abundantly available rocks and compliance with standards.

2. Methods

2.1 Materials

Concerning the geology of Sri Lanka [17], for the preliminary investigation on chemical and mineralogical composition identifications, ten rock types were selected considering the metamorphic class. Figure 1 shows the locations of sample collection for the first stage of this research. Here the weathered rocks such as alluvial, fluvial, and residual deposits which are covering the Northern and North-Western parts of the country were not selected as those are not usually suitable for aggregate. 'ExpertGPS 7.03 Map' software was used to locate the quarries with the global North (N)-East (E) coordinate system as mentioned in Table 1.

Table 1. Locations of sample collection for Stage 1

Location code	Rock type	Complex	Quarry	Province	Coordinates	
					North (N)	East (E)
1	Charnockite	HC	Unawatuna	Southern	6.01913°	80.25134°
2	Calc-Gneiss	HC	Walapane	Central	7.09548°	80.85943°
3	Hornblende-Gneiss	HC	Pahala-Bomiriya	Western	6.93210°	80.00483°
4	Cordierite-Garnet-Gneiss	HC	Batawala	Western	6.88119°	80.05676°
5	Quartzite	HC	Mabima	Western	6.96388°	79.97711°
6	Schist	HC	Magala	Western	6.29783°	80.12590°
7	Marble	HC	Kosgoda	Western	6.33665°	80.03380°
8	Intrusive Charnockite	VC	Unnichai	Eastern	7.63300°	81.53725°
9	Granitic-Gneiss	VC	Damana	Eastern	7.20869°	81.61647°
10	Biotite-Gneiss	VC	Komari	Eastern	6.99742°	81.86762°

Approximately 12" × 12" rubble sample was collected from each quarry as a representative of the corresponding rock type. Sample collection was done in two complexes as represented by Figure 1: Highland Complex (HC) (covering the Central, Sabaragamuwa, and Western provinces and some parts of Eastern province) and Vijayan Complex (VC) (covering Eastern, Uva, and Southern provinces). Figure 2 illustrates the digital images of the collected ten rock rubble samples for the identification of the mineralogical and chemical composition.

To investigate the physical parameters of the rock types which were filtered from the first and second stages of this research, various sizes of rock samples were collected from the corresponding quarries as mentioned here. For the determination of relative density (specific gravity) of rocks, a nominal maximum size of 19 mm rock samples was used. A nominal maximum size of 12.5 mm rock samples was utilized for identifying the loose and packing densities of rocks. The absorbed water and surface moisture of rocks were tested using the maximum size of 9.5 mm samples. Uniaxial compressive strength and tensile strength were determined based on the representative rock samples within the range of 55 mm to 70 mm. The aggregate impact value test was conducted using the rock specimens passing 12.5 mm sieve and retained on 9.5 mm sieve according to gradation criteria provided in ASTM C136. The same quantities of rock specimens retained on 9.5 mm and 6.3 mm sieves were collected for investigating the abrasion. For testing the crushing strength, rock specimens passing 12.5 mm sieve and retained on 9.5 mm sieve were utilized. The response of rocks to wetting and drying conditions was checked using representative rock specimens within the range of 50 mm to 65 mm.

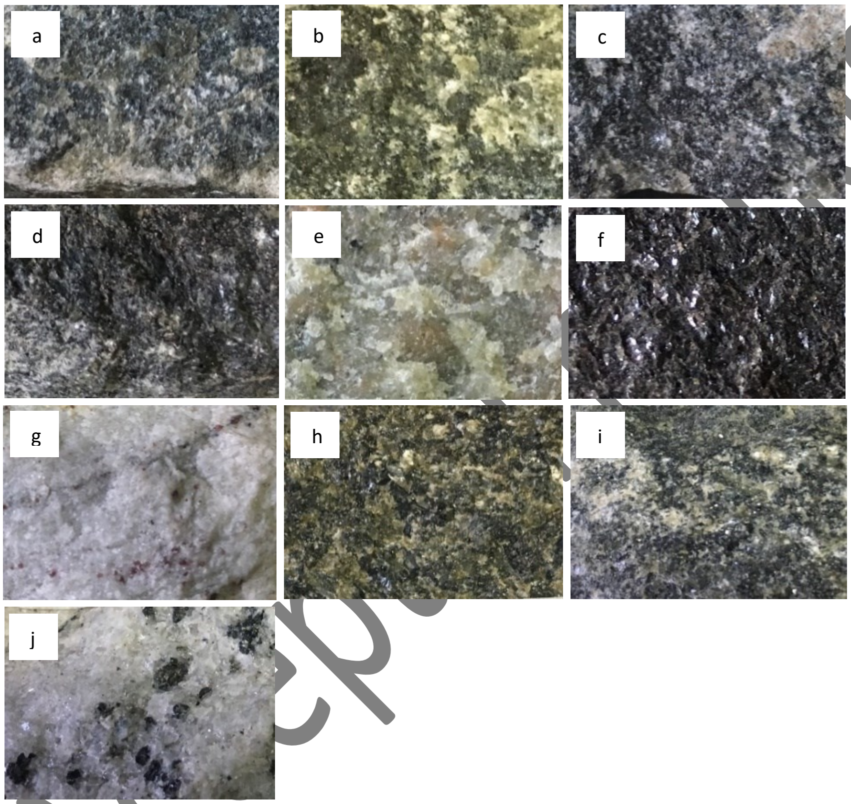

Figure 2. Digital images of rocks listed in Table 1 (a-Charnockite; b-Calc-Gneiss; c-Hornblende-Gneiss; d-Cordierite-Garnet-Gneiss; e-Quartzite; f-Schist; g-Marble; h-Intrusive-Charnockite; i-Granitic-Gneiss; j-Biotite-Gneiss)

2.2 Experiments and test methods

This study was carried out to suggest the most applicable metamorphic rock types for producing construction aggregates under three stages: Stage 1 (filtering the selected ten rock types based on the constitution of potentially harmful minerals), Stage 2 (determining the most suitable rock types among the filtered rocks from Stage 1, according to the availability) and finally Stage 3 (checking the physical, mechanical and durability characteristics of the selected rocks from Stage 2). Figure 3 illustrates a flowchart for the methodology of this study and Table 2 lists down the experiments, standards referred to, the number of trials used for the experiments, and equations used for calculating the parameters in this study.

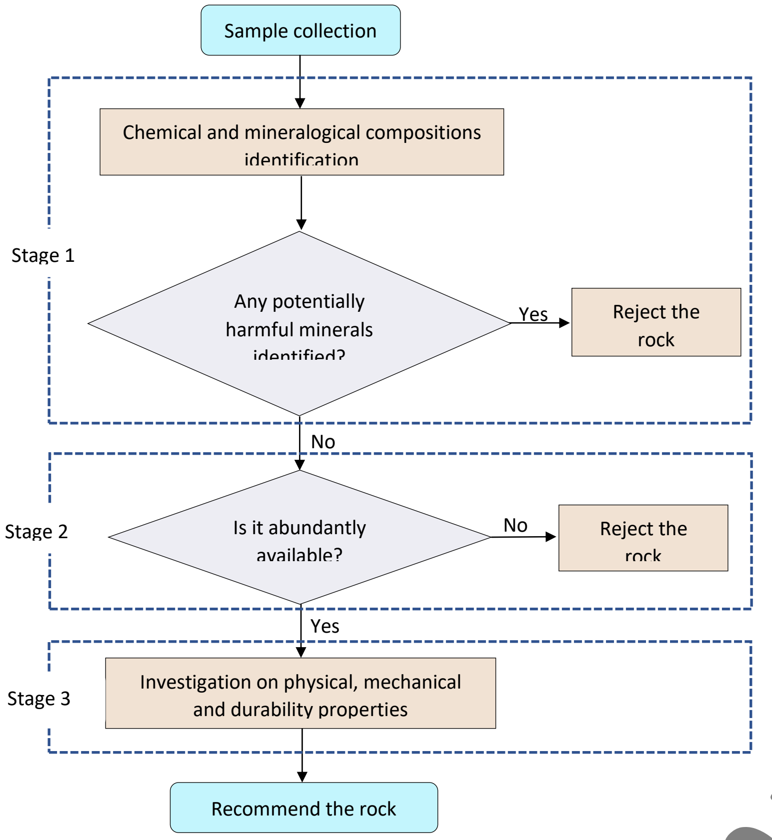

Figure 3. Methodology flowchart

Table 2. Experiments, standards referred and equations used in this study

Property (Stage No)	Experiment	Standard referred	Trials	Equations for determining numerical values	
Chemical (1)	X-Ray diffraction (XRD)	-	1	-	
	X-Ray fluorescence (XRF)	-	1	-	
Physical (3)	Bulk SSD specific gravity (G_{SSD})	ASTM C127	2	$G_{SSD} = M_{SSD} / (M_{SSD} - M_{SSD,W})$	[i]
	Apparent specific gravity (G_{AP})		2	$G_{AP} = M_D / (M_D - M_{SSD,W})$	[ii]
	Water absorption (W %)		2	$W = (M_{SSD} - M_D) / M_D \times 100$	[iii]
	Loose (ρ_l) & packing density (ρ_k)	ASTM C29	2	ρ_k , $\rho_l = M_{SSD} / V$	[iv]
	Water content (w %)	ASTM D2216	3	$w = (M_w / M_D) \times 100$	[v]
Mechanical (3)	Uniaxial compressive strength f_c)	ASTM D5731	10	$f_c = I_s(50) \times$ factor C	[vi]
	Tensile strength (f_t)			$f_t = 80\% \times I_s(50)$	[vii]
	Aggregate impact value (AIV)	EN 1097-2	2	$AIV \% = (M_D / M_{2.36}) \times 100$	[viii]
	Los-Angeles abrasion (LAA)	ASTM C131	2	$LAA \% = (M_{2.36} / M_D) \times 100$	[ix]
	Aggregate Crushing Value (ACV)	EN 1097-2	2	$ACV \% = (M_D / M_{2.36}) \times 100$	[x]
Durability (3)	Slake durability index ($I_d(2)$)	ASTM D4644	2	$I_d(2) \% = (M_{D,2} / M_{D,1}) \times 100$	[xi]
Note:	M_{SSD}: mass of SSD sample	M_w: mass of moist sample (soaked in water for 24 hours)			
	M_D: mass of oven-dried sample	$M_{2.36}$: mass of sample passing 2.36 mm sieve after the test			
	$M_{SSD,W}$: mass of SSD sample in water	$M_{D,1}$: mass of oven-dried sample after 1st cycle of rotation			
	V: volume of measure	$M_{D,2}$: mass of oven-dried sample after 2nd cycle of rotation			

2.2.1 Chemical properties

Firstly, a quantitative analysis was carried out to determine the chemical properties of the selected ten rock types. Initially, each collected rubble sample was crushed using a laboratory-scale 'Barmac' crusher to get a powdered form (particle size < 30 µm) and oven-dried at 105 ± 5^0C for 48 h. XRD test was executed for investigating the mineralogical compositions of rocks using 'Rigaku Ultima IV X-ray Diffractometer'. Crushed powdered granular samples were tested from 2-theta (2θ) as small as 2^o to 90^o diffraction angle. XRF test was conducted to analyze the chemical compositions of the collected rock types. 'Spectro – XEPOS XRF Spectrometer' was used for this analysis using the pellet samples prepared from the rubble specimens. Output results such as spectral data and intensity of minerals present in the rocks and quantitative contents of chemical compositions were received.

2.2.2 Physical properties

Surface characteristics were visually observed using 10X magnification digital image process. The composed behavior of various minerals and chemicals in rocks influence the surface textures and porosity. The uniform composition of rocks (made up of uniform-sized minerals) enables higher porosity than rocks with different-sized minerals. The total porosity of a rock (n) was calculated theoretically using Equation 1 suggested by the studies [35,36] based on bulk density (P_b) and particle density (P_d).

$$n = (1 - P_b / P_d) \times 100 \quad [1]$$

Bulk saturated surface dry (SSD) specific gravity (G_{SSD}), apparent specific gravity (G_{AP}) and water absorption ($W\,\%$) of rocks were analyzed using buoyancy balance with wire mesh basket conforming to ASTM C127. The corresponding equations for calculating the above parameters are mentioned in Table 2 [i-iii]. For the above tests, rock specimens were soaked in water for 24 hours to essentially fill the pores before the testing. Rock usually contains permeable and impermeable voids which determine the rate of water absorption. This influences the quality of rocks for construction works or is suitable for aggregate production. The density of rocks was determined in both loose and compacted form, which are also some of the important properties of rocks, determine the degree of compaction and self-weight of the structures that resulted from it. After the required calibration of measure, the loose density (ρ_l) and compacted or packing density (ρ_k) were investigated using 'shoveling' and 'rodding' procedures respectively as described in ASTM C29. Both absorbed water and surface moisture in rock-derived aggregates influence the drying shrinkage of concrete and mortar. Here, the water content of rocks ($w\,\%$) was determined by mass using 'Method B' as stated in ASTM D2216 and based on the equation provided in Table 2 [v].

2.2.3 Mechanical properties

Determination of uniaxial compressive strength (f_c), tensile strength (f_t) and failure patterns of rocks were investigated using the 'Point Load Index' test method according to ASTM D5731. Strengths were obtained by performing an irregular lump test to identify the point load strength index ($I_s(50)$) of the irregular rock samples. Ten rock specimens were selected from each rock type and initially, the preliminary specimen size requirements were checked as per the above standard. The load was applied to the specimens using platen-to-platen end condition attached to the point load tester and the strengths were calculated using the standard charts and the equations provided in Table 2 [vi-vii]. Additionally, the common failure patterns were also observed with the fractured rock specimens, and finally, the water content of the fractured specimens was determined individually. Figure 4 shows the point load tester used for this analysis with the support conditions.

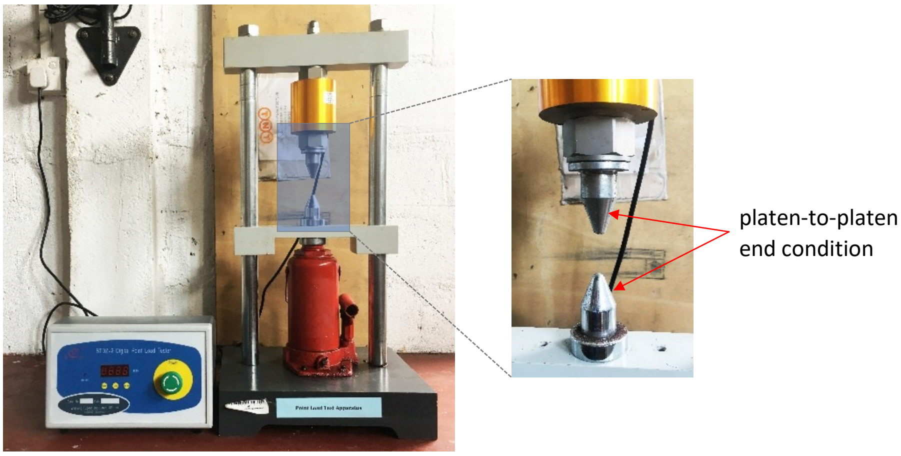

Figure 4. Point load tester

Rock-derived aggregates should have enough toughness to withstand sudden shocks or impacts. Therefore, the rock sources for aggregates must have sufficient toughness to resist the impacts. The rock impact resistance capacity (AIV) was tested using an aggregate impact tester conforming to EN 1097-2. After enough impacts, mass losses were calculated using the weight of the specimen retained on a 2.36 mm sieve. The equation provided in Table 2 [viii] was used to calculate the AIV of each selected rock in percentage.

When rock aggregates are used in heavy-duty structures, there is a possibility of failure of particles due to the higher abrasion. Therefore, investigating the abrasion resistance of parent rocks may also give additional support to the selection of materials. Los Angeles abrasion (LAA) test was performed here for investigating the abrasion resistance of rocks according to ASTM C131. After the test, mass losses were determined based on the number of fines passing 2.36 mm sieve, and LAA % was determined according to the equation mentioned in Table 2 [ix]. Under the standardized conditions as per EN 1097-2, the crushing test was performed on rock specimens by applying a gradual compressive load using a universal testing machine. The crushing strength of aggregates (ACV) also partially determines the strength of constructions when the aggregates are only exposed to higher stresses. Once the test was carried out, the ACV was calculated in percentage using the weight of crushed particles passing through a 2.36 mm sieve based on the formulae given in Table 2 [x].

2.2.4 Durability properties

The durability of rock is affected mainly due to climatic changes. The cyclic process of wetting and drying can develop permanent strain in rocks, which may result in a volume increase. Due to the changes in temperature and moisture content, the expansion and contraction coefficients of rocks are varied. In this study, the durability of rocks was investigated quantitatively using slake durability test according to ASTM D4644. Rock specimens were undergone for two cycles of wetting and drying, and the mass losses were obtained after the specimens were oven-dried at 105 ± 5^0C for 48 hours. The equation given in Table 2 [xi] was used for determining the slake durability index ($I_d(2)$) after the two complete cycles of wetting and drying.

3. Results and Discussion

3.1 Stage 1: Identification of chemical and mineralogical compositions

Initially, complete mineralogical testing was carried out for each collected ten rock types. Table 3 represents the quantities (%) of the most common minerals present in the rock types. Based on the results, it was identified that except Calc-Gneiss, Intrusive Charnockite, and Granitic-Gneiss rocks, all others were abundant with quartz. Also, considerable intensities of feldspar minerals such as albite (plagioclase feldspar - $NaAlSi_3O_8$), anorthite (plagioclase feldspar - $CaAlSi_3O_8$, k-feldspar (orthoclase feldspar - $KAlSi_3O_8$) were noticed in the collected samples. The constitutions of calcite ($CaCO_3$), dolomite

($CaMg(CO_3)_2$), pyrite (FeS_2), and biotite minerals were very low compared to other available minerals. Here, special attention should be given to illite and biotite minerals, which are from non-expanding clay and mica mineral groups respectively may significantly give adverse effects on the performance of concrete and mortar.

Table 3. Mineral constituents of rocks (%)

Rock type	Calcite	Dolomite	Quartz *	Illite *	Pyrite *	Albite *	K-feldspar *	Anorthite	Biotite *
Charnockite *	1.97	0.23	27.95	1.66	0.01	18.03	27.15	4.36	0.00
Calc-Gneiss	0.00	0.46	2.51	13.43	1.06	10.63	9.39	50.33	0.09
Hornblende-Gneiss *	0.62	0.22	49.48	4.23	0.11	10.44	10.68	20.30	0.00
Cordierite-Garnet-Gneiss	0.00	0.18	68.33	9.50	0.15	4.92	3.08	12.53	0.05
Quartzite	1.64	0.26	32.59	4.77	0.08	16.48	10.35	20.32	0.12
Schist	0.44	0.60	30.44	4.73	0.46	14.35	12.41	30.37	0.00
Marble	2.45	1.43	40.11	2.85	0.15	15.99	24.07	8.33	0.00
Intrusive Charnockite *	0.35	0.09	18.06	1.57	0.12	27.90	28.63	19.02	0.00
Granitic-Gneiss *	2.06	0.82	21.49	3.07	0.06	36.66	31.13	2.86	0.00
Biotite-Gneiss	0.76	1.11	31.67	3.39	0.06	34.77	12.03	9.27	0.35
1st richest rock	🟥				* Most harmful minerals identified				
2nd richest rock	🟩				* Minerals give positive effects				
3rd richest rock	🟦				* Filtered rocks for Stage 2				

A quick chemical/elemental analysis was carried out on the ten rock types and the chemical constituents are listed in Table 4. Rocks selected for this study can be categorized as silicate rocks, which are mainly composed of SiO_2 (more than 50% of total mineral content). Oxides of Al (Al_2O_3) and Fe (Fe_2O_3) were also identified as abundant compositions in the samples, where the maximum values were noticed in Quartzite, Calc-Gneiss, and Schist rocks. It was noted that the constituents of sulfur trioxide (SO_3) and chloride (Cl^-) can be negligible in each sample which is the main source, give adverse effects to the function of concrete and mortar. Higher contents of SO_3 may affect the dimensional stability, where Zayed et al. [37] found that aggregates contained SO_3 beyond 3%, significantly increased the drying shrinkage of cement. More Cl^- content in aggregates gives harmful effects to the corrosion of reinforcements.

Alkali metal oxides such as Na_2O and K_2O and alkaline-earth metal oxides like CaO and MgO were also identified in the rocks with smaller quantities. Figure 5 exhibits the diffraction patterns of the ten rock types resulted from the XRD test. The graphs were plotted with the counts against diffracted angle 2-theta (2θ). The peak intensities mentioned in Table 3 are also marked with the abbreviations of minerals. Various minerals present in the rock-derived aggregates can influence the strength, workability, and durability properties of concrete and mortar. When parent rocks are extracted and crushed for manufactured sand and coarse aggregate production, it enables the reactive form of minerals present in the outputs.

Table 4. Chemical compositions of rocks (%)

Rock type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl^-
Charnockite	72.01	7.83	2.09	3.95	0.25	0.00	2.08	2.54	0.00
Calc-Gneiss	54.17	12.10	12.38	8.75	2.76	0.00	1.51	0.67	0.02
Hornblende-Gneiss	73.59	7.59	4.83	3.07	1.02	0.00	1.75	1.33	0.00
Cordierite-Garnet-Gneiss	79.14	5.70	7.05	0.00	0.73	0.00	1.03	1.09	0.00
Quartzite	68.38	10.60	7.01	3.83	0.85	0.00	2.26	1.32	0.00
Schist	66.30	10.56	8.41	4.29	0.83	0.00	2.77	1.18	0.00
Marble	70.51	8.09	1.34	4.43	0.22	0.00	2.05	2.34	0.00
Intrusive Charnockite	70.55	9.23	5.42	3.20	0.24	0.00	2.81	2.43	0.00
Granitic-Gneiss	68.86	9.55	6.89	3.21	0.38	0.00	3.02	2.52	0.00
Biotite-Gneiss	69.61	8.12	2.56	5.49	0.35	0.00	2.28	2.32	0.00

As discussed above, most of the selected rocks revealed higher content of quartz which is a crucial mineral for aggregates as it is always inert. At normal conditions quartz is a less reactive and more controllable tool for concrete and mortar and even at high temperatures, it is more stable with a very strong Si-O bond. In some cases, there is a possibility of the formation of silica gels (which attract water, swells, and form cracks) in concrete as the result of the reaction between very fine crystalline quartz and alkaline substances (typically $Ca(OH)_2$) [38]. Feldspar minerals were the second richest minerals identified in the rocks. Albite can fuse and act as a cementing medium at high temperatures which helps to bind the materials. K-feldspar mineral usually has a greater hardness, which results in higher strength of cement-based mixes [35]. Anorthite is the least stable feldspar mineral but can encourage less hydration rate during the acceleratory period of cement [40]. Therefore, considering the durability, rocks such as Calc-Gneiss, Quartzite, and Schist should be neglected as the sources for aggregate production.

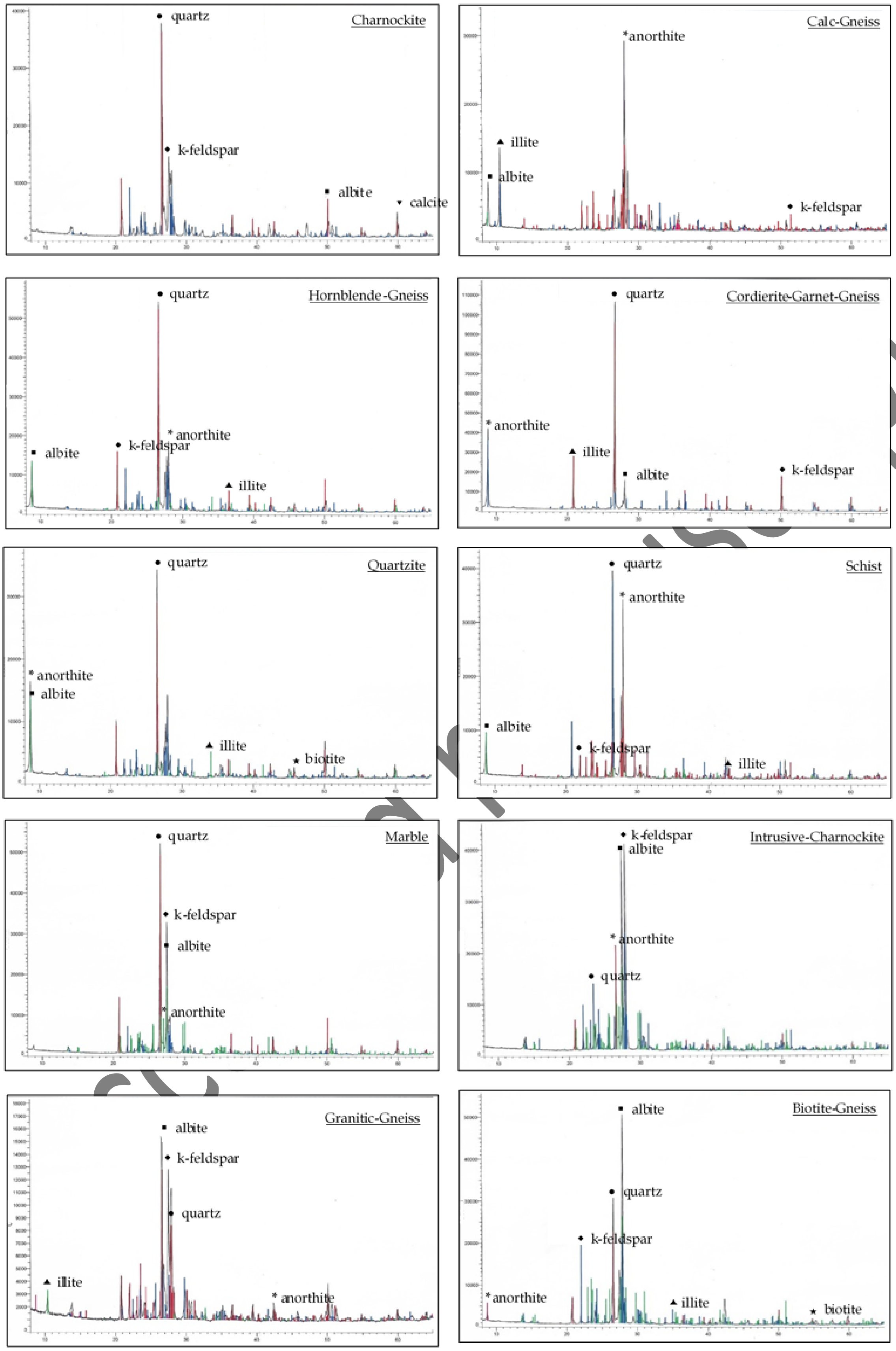

Figure 5. X-Ray diffraction patterns of rocks

The availability of carbonate minerals is restricted in the collected samples. Two minerals of the carbonate mineral class were discerned: calcite and dolomite. Increased calcite demands the water requirement for the mixes and decreases free calcium hydroxide and bindings of aluminate phases, which help form stable hydration products [41,42]. It is better to avoid marble for aggregate production as it showed a considerable percentage of calcite minerals. Dolomite mineral aggregates contribute high compressive strength and resistance against abrasion; however, dolomite contents are seemed identical in each rock type. Pyrite (FeS_2) is a sulfide mineral, gives harmful effects to concrete when manufactured sand or aggregates contained it. Pyrite starts to break down and forms sulfuric acid (from the oxidation process) when water and air get into the concrete through small cracks and pores. This enables the expansion of concrete by cracking and allowing more water and air into it [43,44]. Based on Table 3, Calc-Gneiss rock revealed considerable pyrite content and should be avoided for aggregate production.

Calc-Gneiss and Cordierite-Garnet-Gneiss rocks were identified as the two main sources of illite, which is a clay toxic mineral that directly influences the compressive strength and workability of concrete and mortar. Illite is an intermediate level between smectite (clay mineral**)** and muscovite (mica mineral), which significantly increases the water requirement in the mixes. It also reduces the strength of concrete and mortar by diminishing the binding capacity between cement paste and aggregates when it acts as a coating [28].

Determination of mica minerals should be highlighted here as they are the most damaging minerals in the aggregates. According to ASTM C294, the mica class contains muscovite, biotite, and chlorite minerals, but based on the XRD patterns, biotite was the only mica mineral identified in the selected rocks. Increased mica minerals in the mixes lead to low workability and considerably lessen the strength and durability with the growth of voids. Among the ten rock types, Calc-Gneiss, Cordierite-Garnet-Gneiss, Quartzite, and Biotite-Gneiss rocks were sparsely detected with biotite; hence, the quarry operators should be vigilant in selecting these rocks for manufacturing aggregates.

Consequently, Charnockite, Hornblende-Gneiss, Intrusive Charnockite, and Granitic-Gneiss were deemed as the most suitable rock types for manufactured sand and coarse aggregate production as they were not highly detected with the potentially harmful minerals for concrete and mortar.

3.2 Stage 2: Filtering the rocks based on availability

Due to the rapid development of infrastructures, the construction activities have been escalated in most of the developing countries including Sri Lanka. It was also identified that; Sri Lanka is now running with the lack of availability of natural resources to fulfill the increased demand for aggregates in construction works. Therefore, proposing alternatives for natural aggregates should also comply with the possibility of continuous usage in the construction works.

As discussed in the previous section, Charnockite, Hornblende-Gneiss, Intrusive Charnockite, and Granitic-Gneiss were concluded as the acceptable rocks for producing aggregates among the ten rock types. To satisfy the persistent construction activities with rock-derived aggregates, this section focuses on the availability of the above four applicable rocks based on a detailed geological map of Sri Lanka. Figure 6 elucidates the approximate area covered by each rock type mentioned in km^2.

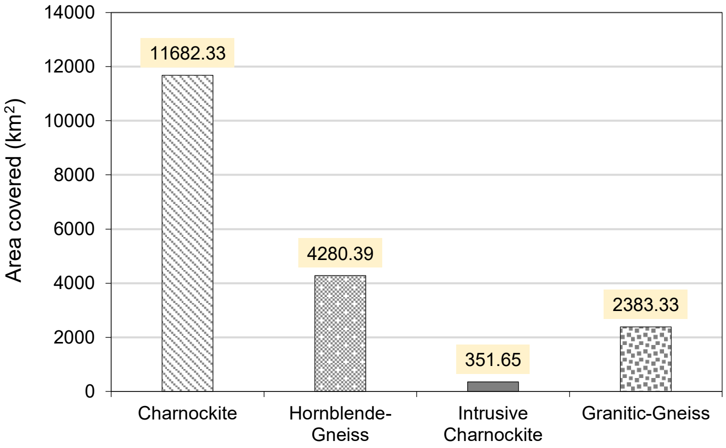

Figure 6. Area covered by the rocks selected from Stage 1

Charnockite and Hornblende-Gneiss rocks are available in HC of the country. It was identified that Charnockite rock covers the most part, which is around more than 60% of the total area of HC. This contributes around 40% of the area of Sri Lanka. Around 15% area of HC is contributed by Hornblende-Gneiss rock which is around 9.5% of the country. Intrusive Charnockite rock was observed in few areas of VC, wherefrom Figure 6, it was noticed that the rock covers only 351.65 km^2. Granitic-Gneiss rock contributes around 25% of the area of VC, which is around 6% of the country's terra. Accordingly, Charnockite and Hornblende-Gneiss rocks were designated as the long-term available sources for construction aggregates production and selected for further investigation under Stage 3.

3.3 Stage 3: Checking the properties of most applicable and available rocks

Sections from here describe the analysis of physical, mechanical, and durability properties of the selected rocks from Stage 1 and Stage 2: Charnockite and Hornblende-Gneiss.

3.3.1 Surface texture, porosity, and other physical properties

Figures 7(a) and 7(c) show the rubble samples of Hornblende-Gneiss and Charnockite collected to study the surface characteristics such as surface texture, crystallization, and surface pores which may influence the properties of concrete and mortar. Figures 7(b) and 7(d) are the digital images of the representative surface of the above rock types used for this analysis. The surface texture of metamorphic rocks depends on the size, shape, and arrangement of the crystals, uniformity of composition, and degree of isotropy.

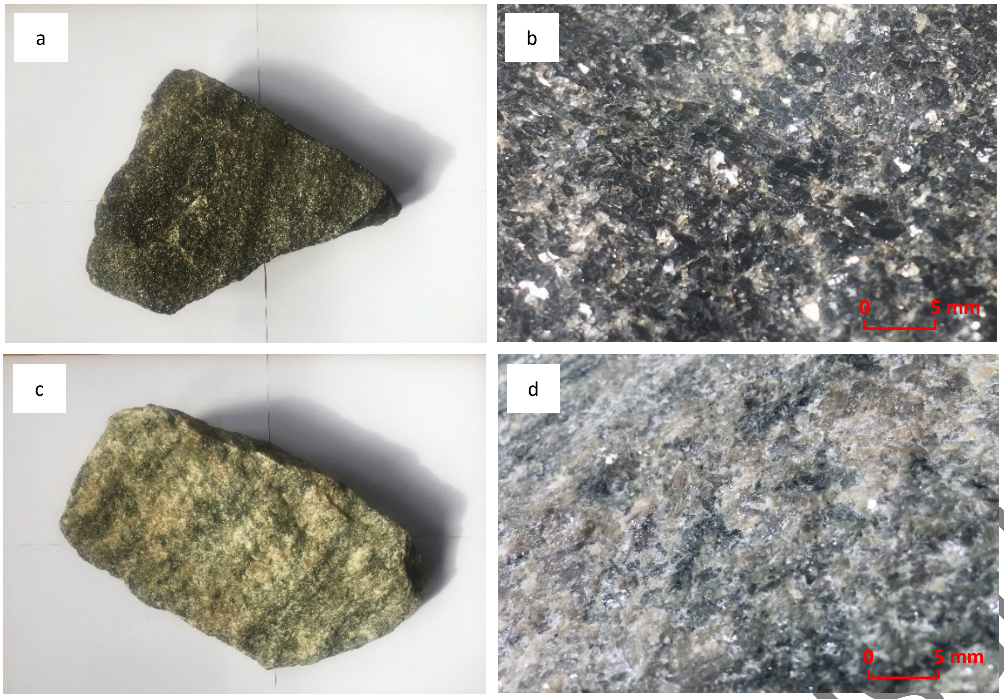

Figure 7. (a) Hornblende-Gneiss rubble sample; (b) digital surface image of Hornblende-Gneiss; (c) Charnockite rubble sample; (d) digital surface image of Charnockite

From the observations, it was found that Hornblende-Gneiss was configured with medium-sized (0.75 - 1 mm) grains and 'isometric' crystals which are euhedral cube-shaped with sharp angles, edges, and smooth flat facets. Charnockite was deposited with very coarse-sized (> 2 mm) grains and 'enantiomorphic' shaped crystals which are having optical characteristics. Charnockite crystals, grains, and matrices showed the continuity and non-fabric (uniform arrangement of grains) behavior while Hornblende-Gneiss crystals were formed as fabric (non-uniform arrangement). Minerals were formed as layers (uniform distribution) in Charnockite, but a non-uniform (random) composition of minerals was observed with Hornblende-Gneiss. The above characteristics enhanced Hornblende-Gneiss with rougher surface texture than Charnockite.

The porosity of rocks also depends on the arrangement of grains, composition, and rock type. The calculated porosity values using Equation 1 were 0.25% for Hornblende-Gneiss and 0.26% for Charnockite. Both rocks were formed by metamorphism and the slight difference of porosity was due to the variation in grain size, shape, and composition of crystals. Figure 8 can be referred to for a better understanding of the distribution of surface pores in the above rock types. It was observed that the pores are created at the intersections of grains of the rock. As described above, because of the larger grans in Charnockite, increased pore spaces were noticed than Hornblende-Gneiss.

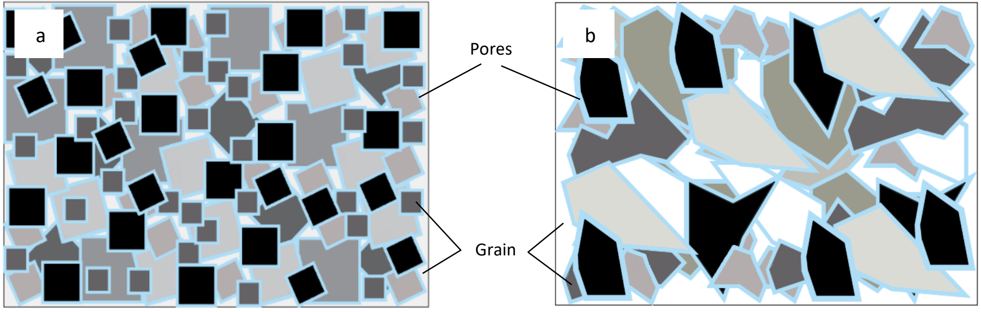

Figure 8. Surface pore space structure (a) Hornblende-Gneiss; (b) Charnockite

Some basic physical properties of the above rock types were determined and the average values of the properties are listed in Table 5. It was identified that Hornblende-Gneiss was slightly denser than Charnockite. Specific gravity at saturated surface dry (SSD) condition, apparent specific gravity, and bulk specific gravity were noticed higher for Hornblende-Gneiss than Charnockite. This can be directly correlated with the porosity values mentioned above where Hornblende-Gneiss revealed lower porosity than Charnockite which resulted in higher specific gravity. Charnockite manifested greater water absorption than Hornblende-Gneiss which was due to the increased pores. Because of the higher unit weight and lower porosity of Hornblende-Gneiss, greater packing density was observed than Charnockite. Hornblende-Gneiss proved an inflated moisture content than Charnockite. Because of the rougher surface texture of Hornblende-Gneiss, there is always a possibility for trapping the moisture particles between the euhedral cube-shaped crystals.

Table 5. Average physical properties of rocks

Properties	Hornblende-Gneiss	Charnockite
P_d (kg/m^3)	2797	2697
G_{SSD}	2.804	2.704
G_{AP}	2.816	2.716
$W\,\%$	0.246	0.261
ρ_l (kg/m^3)	1359	1258
ρ_k (kg/m^3)	1553	1397
$w\,\%$	0.305	0.267

3.3.2 Strength and other mechanical properties

Strength properties of Hornblende-Gneiss and Charnockite were tested at SSD conditions. An irregular lump test was performed on the non-uniform sized rock specimens used for this investigation by calculating the equivalent core diameter (D_e) for all specimens to attain a common behavior against the applied point loads. Hornblende-Gneiss performed well against the applied point loads where increased uniaxial compressive strength (f_c) and tensile strength (f_t) were noticed than Charnockite. It was also noted that both rocks were weak against the tensile loads as they are brittle in nature. Table 6 tabulates the dimension, failure load, calculated equivalent core diameter, point load index, and the strengths of irregular rock specimens.

Table 6 mentions the failure type of all selected rock specimens where most of the Hornblende-Gneiss specimens manifested axial failure (AF) while a considerable number of Charnockite samples were fractured due to the shear failure (SF). Figure 9 represents few samples from both rock types and their failure planes. In both cases at the start of load applying, cracks were propagated perpendicular to the stress applied which ultimately left flat surfaces at the breakpoint. The failure behavior of rocks can be directly influenced by the grain direction and crystallization where layer arrangement of minerals in Charnockite gave the possibility of breaking along the weaker mineral layer which formed a failure shear plane. However, the absence of the above feature in Hornblende-Gneiss ended up in axial failure. The rock specimens were considered at SSD condition for determining uniaxial compressive strength and tensile strength. Impermeable and permeable pores in rock specimens usually contain water when they are in SSD condition. Therefore, the water content of rock specimens played a major role in the uniaxial compressive strength and tensile strength. To investigate this behavior, the relationship between water content and uniaxial compressive strength was analyzed and represented by Figure 10(a). Linear relationships were observed between water content ($w\,\%$) and uniaxial compressive strength of both rock types (Hornblende-Gneiss: $R^2 = 0.9594$ and Charnockite: $R^2 = 0.9151$).

Table 6. Uniaxial compressive strength, tensile strength, and failure type of rocks

Rock type		*w* (mm)	*d* (mm)	*P (N)*	D_e (mm)	*F*	$I_s(50)$ (MPa)	f_c (MPa)	f_t (MPa)	Failure type
Hornblende-Gneiss	1	37	17.5	13300	57.414	1.064	4.294	94.463	3.435	SF
	2	35.5	23	17800	64.473	1.121	4.801	105.627	3.841	AF
	3	36	25	18500	67.689	1.146	4.627	101.801	3.702	AF
	4	39	25	19600	70.453	1.167	4.608	101.367	3.686	SF
	5	37	17.5	14800	57.414	1.064	4.778	105.116	3.822	AF
	6	38	22.5	16700	62.406	1.105	4.738	104.231	3.790	AF
	7	45	27.5	18500	70.000	1.163	4.393	96.940	3.514	SF
	8	37.5	27.5	17700	42.457	1.182	4.389	96.560	3.511	AF
	9	42.5	26	19400	71.848	1.177	4.424	97.329	3.539	AF
	10	40	25	18500	66.742	1.139	4.729	104.048	3.784	AF
Charnockite	1	52	42	21300	105.445	1.399	2.680	64.323	2.144	SF
	2	44	36	22500	89.800	1.301	3.631	87.153	2.905	AF
	3	60	52.5	33400	126.635	1.519	3.164	75.939	2.531	SF
	4	62.5	53	39900	129.860	1.536	3.635	87.249	2.908	SF
	5	53	37	22500	99.916	1.366	3.078	73.862	2.462	SF
	6	45	32.5	25000	103.544	1.388	3.236	77.655	2.588	SF
	7	64	56.5	26500	135.679	1.567	2.256	54.141	1.805	AF
	8	55	51.5	26800	120.083	1.483	2.757	66.162	2.205	SF
	9	48	36	23500	93.793	1.327	3.545	85.090	2.836	SF
	10	57	32.5	21000	97.113	1.348	3.002	72.047	2.402	AF

w: Sample width; *d*: Sample depth; *P*: Failure/fracture load

D_e: Equivalent core diameter [= $4(w \times d)/\pi$]

F: Size correction factor [= $(D_e/50)^{0.45}$]

$I_s(50)$: Corrected point load strength index [= $F \times (P/D_e^2)$]

$f_c = I_s(50) \times$ *factor C (for Hornblende-Gneiss = 22; Charnockite = 24)*

$f_t = 80\% \times I_s(50)$

Sample ID: 1
Failure type: SF

Sample ID: 2
Failure type: AF

Sample ID: 3
Failure type: AF

Sample ID: 4
Failure type: SF

Sample ID: 1
Failure type: SF

Sample ID: 2
Failure type: AF

Sample ID: 3
Failure type: SF

Sample ID: 4
Failure type: SF

Figure 9. Failure planes of typical rock specimens with respect to load applied (SF: Shear failure; AF: Axial failure)

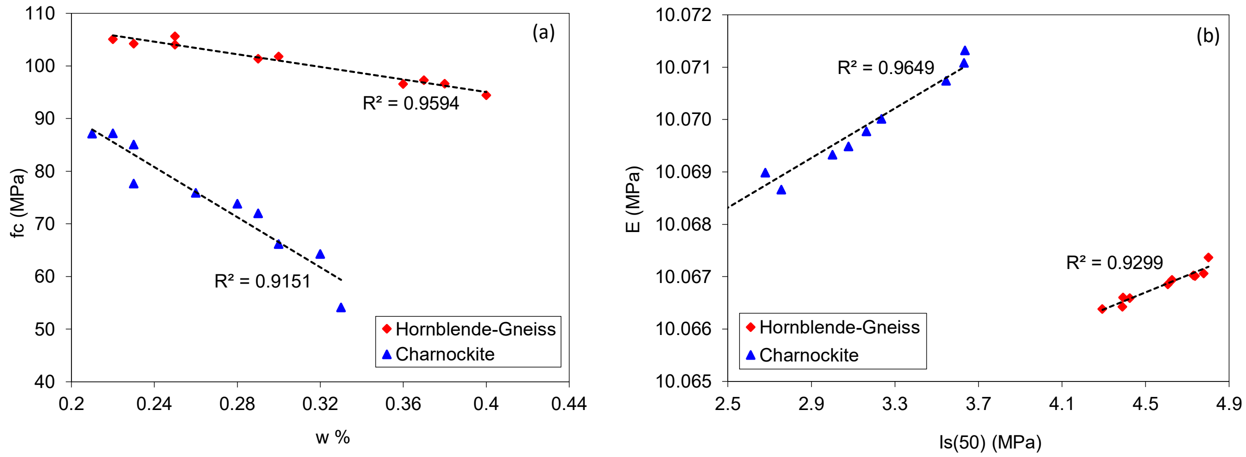

Figure 10. (a): Effect of water content on uniaxial compressive strength; (b): Young's modulus vs Corrected point load strength index

Both relationships showed a decreasing trend from which it can be concluded that uniaxial compressive strength was linearly and negatively affected by water content. Based on the regression equation derived by Leite and Ferland [45] as provided in Equation 2, Young's modulus (E) of rock specimens was calculated based on porosity (n) in this study.

$$E = 10.10 - 0.109 \times n \qquad [2]$$

Furthermore, the above regression was correlated with the corrected point load strength index ($I_s(50)$) which were calculated using equivalent core diameter, size correction factor, and failure load in this study as listed in Table 6. To achieve this, relationships between the E values determined using Equation 2 and $I_s(50)$ were plotted as shown in Figure 10(b). Based on the results, it was observed that Equation 2 and the calculated values in this study were correlated with a high coefficient of determination values. Linear increasing relationships were noticed with E and $I_s(50)$ for Hornblende-Gneiss (with $R^2 = 0.9229$) and for Charnockite (with $R^2 = 0.9649$).

Multiple linear regression analysis was executed (at 95% confidence interval) for uniaxial compressive strength of Hornblende-Gneiss ($f_{c,\ Hbl\text{-}Gn}$) (with adjusted $R^2 = 1.000$) and Charnockite ($f_{c,\ Chkt}$) (with adjusted $R^2 = 1.000$) as given in Equation 3(a) and 3(b) concerning porosity (n), water content (w), corrected point load strength index ($I_s(50)$) and density (ρ).

$$f_{c,\ Hbl\text{-}Gn} = -\,8.969\times10^{-13} + 2.084\times10^{-12}\, n - 3.268\times10^{-14}\, w + 22\, I_s(50) + 5.142\times10^{-17}\, \rho \qquad [3(a)]$$

$$f_{c,\ Chkt} = 3.100\times10^{-13} - 1.100\times10^{-12}\, n - 1.900\times10^{-13}\, w + 24\, I_s(50) + 6.000\times10^{-17}\, \rho \qquad [3(b)]$$

Simple regression was also done (at 95% confidence interval) to determine the relationship between uniaxial compressive strength and young's modulus of rocks as represented by Equations 4(a) and 4(b). Hornblende-Gneiss ($R^2 = 0.9299$) and Charnockite ($R^2 = 0.9649$) revealed linear relationships.

$$E_{Hbl\text{-}Gn} = 7\times10^{-5}\, f_{c,\ Hbl\text{-}Gn} + 10.059$$

[4(a)]

$$E_{Chkt} = 1\times10^{-4}\, f_{c,\ Chkt} + 10.062 \qquad [4(b)]$$

The results of other mechanical properties such as 'Aggregate Impact Value' (AIV), 'Los Angeles abrasion value' (LAA), and 'Aggregate Crushing Value' (ACV) of Hornblende-Gneiss and Charnockite are reported here. AIV, LAA, and ACV are the determinations of toughness, abrasion resistance, and crushing resistance of the rock specimens. Table 7 mentions the average AIV, LAA, and ACV of Hornblende-Gneiss and Charnockite, and the recommended values suggested corresponding standards. Lower AIV indicates the rock specimens are tougher or more resistant to impact loads. Based on the provisions given in BS EN 12620:2002, it was concluded that the aggregates produced from Hornblende-Gneiss and Charnockite are safe to be used for heavy-duty concrete floor constructions.

Table 7. Average AIV, LAA, and ACV of rocks

Properties	Hornblende-Gneiss	Charnockite	Limiting values by standards
AIV (%)	22	23	< 25% for heavy duty concrete floor finishes, BS EN 12620:2002
LAA (%)	60	61	< 30% for stone matrix asphalt, AASHTO T96-02
ACV (%)	42	40	< 45% for wearing surfaces, EN 1097-2

Rock abrasion characteristics are not very important in building constructions. However, in this study, LAA was determined to check the adequacy of rock specimens to degradation and disintegration when impact and abrasion loads are applied on the aggregates. It was found that the LAA of both rocks did not comply with the maximum limitations provided by AASHTO T96-02. ACV was determined under a gradually applied compressive load. Rock specimens with lower crushing values indicate the lower crushed fraction under the applied load and more economical performance. ACV of rocks acts a minor role in the constructions which are subjected to higher stresses. According to the test results, the ACV of the selected rocks satisfied the maximum limits and can be suggested for use in the construction of wearing surfaces.

3.3.3 Durability against wetting and drying

The durability of Hornblende-Gneiss and Charnockite rocks was estimated quantitatively after the two cycles of wetting and drying with abrasion. Slake durability index of both rocks were determined after the second cycle as abbreviated by '$I_d(2)$'. The higher $I_d(2)$ value defines the higher resistance to cyclic wetting and drying conditions. Results concluded that the corresponding average $I_d(2)$ values of Hornblende-Gneiss and Charnockite rocks were 99.285% and 99.445% respectively. Figure 11 illustrates the observations made during and after the experiment.

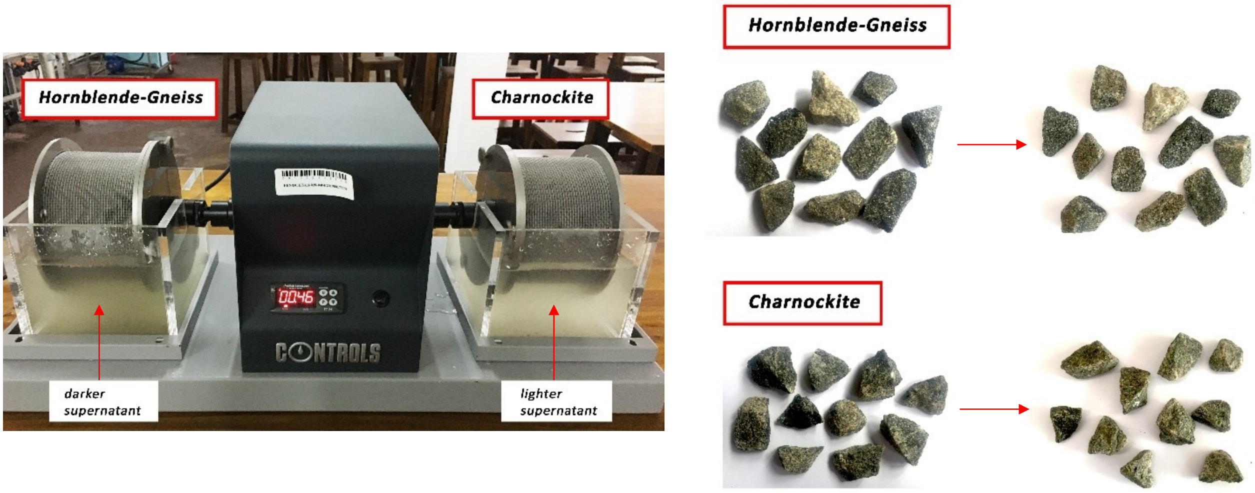

Figure 11. Slake durability test apparatus and transformation of rock specimens

ASTM D4644 suggests three types of rock samples based on the visual observations after two complete cycles of wetting and drying: Type I (retained specimen remain virtually unchanged), Type II (retained specimen consist large and small fragments), and Type III (the retained specimen is exclusively small fragments). Because the retained Hornblende-Gneiss and Charnockite specimens remained virtually unchanged, it was concluded that they conformed to Type I. According to the classifications of $I_d(2)$ values provided by Franklin and Chandra [46], the rocks selected for this analysis were also termed as 'extremely high' durable rocks. Therefore, aggregates produced from Hornblende-Gneiss and Charnockite can be utilized for any building constructions without uncertainty.

According to the Franklin Rating System [47], Hornblende-Gneiss and Charnockite selected for this study were defined with a rating value (R) based on the average $I_d(2)$ and $I_s(50)$ values. The interpolated R-value for Hornblende-Gneiss was observed as 8.26 with $I_d(2)$ of 99.285% and $I_s(50)$ of 4.578 MPa. The R-value for Charnockite was determined as 7.94 with $I_d(2)$ of 99.445% and $I_s(50)$ of 3.098 MPa.

Various factors influence the durability of rocks, but the most dominant factors are the rock's mineral and chemical compositions. As observed in Section 4.1, Charnockite and Hornblende-Gneiss rocks are abundant with friendly minerals and chemicals. Anyhow, it was also noticed that there are few percentages of potentially harmful minerals present in those rocks. Therefore, the influence of those minerals on the durability of rocks was investigated and reported with the outcomes from multiple linear regression analysis and *F*-test. Here, the statistically significant effects of both friendly and harmful minerals on the slake durability indexes of rocks after the 1st cycle $I_d(1)$ and 2nd cycle $I_d(2)$ of wetting and drying were examined using *F*-test results and the relationships were derived with the multiple linear regression analysis as shown in Table 8.

Table 8. Summary of F-test and multiple linear regression analysis for $I_d(1)$ and $I_d(2)$ with durable and harmful minerals

Predictor	*F*-test (at 95% confidence interval)			Multiple regression analysis (Linear model) (at 95% confidence interval)
	df	*f*	* Statically significant?	

$I_d(1)$					
Quartz (*Qz*)	3	0.00015	Yes	$I_d(1) = 98.3 + 0.003\ Qz + 0.17\ Ab - 0.06\ Kf$	adj. $R^2 = 0.8745$
Albite (*Ab*)	3	0.00102	Yes		
K-feldspar (*Kf*)	3	0.00021	Yes		
Illite (*Il*)	3	0.00761	Yes	$I_d(1) = 100.0 - 0.11\ Il + 0.36\ Py$	adj. $R^2 = 0.9403$
Pyrite (*Py*)	3	1.49302	Yes		
$I_d(2)$					
Quartz (*Qz*)	3	0.00013	Yes	$I_d(2) = 92.1 + 0.01\ Qz + 1.17\ Ab - 0.51\ Kf$	adj. $R^2 = 0.8321$
Albite (*Ab*)	3	0.00093	Yes		
K-feldspar (*Kf*)	3	0.00019	Yes		
Illite (*Il*)	3	0.00694	Yes	$I_d(2) = 99.6 - 0.03\ Il - 0.81\ Py$	adj. $R^2 = 0.9911$
Pyrite (*Py*)	3	1.36055	Yes		

* Statistically significant result: "Yes": when *f* value < *F* critical value; "No": when *f* value > *F* critical value
df: Degree of freedom

As expected, from the *F*-test results, the durable and friendly minerals such as quartz, albite, and k-feldspar statistically and significantly affected both slake durability indexes. Also, the detected potentially harmful minerals such as illite and pyrite statistically and significantly affected the durability indexes after the 1st and 2nd cycle of wetting and drying. Here, biotite mineral was not considered as both Charnockite and Hornblende-Gneiss were not detected with considerable quantities. Therefore, based on the above statistical approaches, it was concluded the above five minerals revealed statistically significant effects on the durability of rocks. Consequently, analyzing the above minerals is mandatory when selecting the rock-derived aggregates for high durable applications.

4. Conclusions

This research was executed to implement the most appropriate high-grade metamorphic rocks available in Sri Lanka, for producing rock-derived outputs such as manufactured sand and coarse aggregate. All the rock types were selected from the high-grade metamorphic category having extreme hardness and strength, which is expected as the ideal solution for construction aggregate manufacturing. It was identified that the demand for natural resources to fulfill the aggregate requirements in the construction activities has been escalated now. Therefore, the contractors are now trying to introduce both fine and coarse aggregates made from parent rocks in the construction works. The problem was noticed that the quarry operators who are producing manufactured sand and coarse aggregates are not paying much attention to selecting the suitable parent rocks. The investigation on analysis of the properties of high-grade rocks concludes the followings:

Initially, for sorting out the appropriate high-grade rocks, chemical and mineralogical tests were performed on the selected ten metamorphic rocks. Among the detected minerals, illite, pyrite, and biotite were considered as the most harmful constituents to the performance of concrete and mortar. Calc-Gneiss, Cordierite-Garnet-Gneiss, and Quartzite rocks showed a significant content of illite. Calc-Gneiss, Schist, and Marble rocks arrived with a considerable pyrite content. A noticeable content of biotite was observed in Calc-Gneiss, Quartzite, and Biotite-Gneiss rocks. Consequently, Charnockite, Hornblende-Gneiss, Intrusive Charnockite, and Granitic-Gneiss were concluded as the most suitable metamorphic rocks for producing aggregates for concrete and mortar.

To inspect the perpetuity of sources for aggregates to be used in constructions, the availability of the above selected four rock types was investigated using a detailed geological map of the country. Charnockite was identified as the most abundant rock type while, Hornblende-Gneiss revealed a considerable percentage of the total land area. Intrusive Charnockite and Granitic-Gneiss rocks underlie very small parts of the country's crust.

Physical, mechanical, and durability properties of the most applicable and plentifully available rocks such as Charnockite and Hornblende-Gneiss were examined. Hornblende-Gneiss manifested rougher surface texture than Charnockite. Other physical properties such as particle density, specific gravities, loose and packing densities, and water content were observed slightly higher with Hornblende-Gneiss than Charnockite. However, Charnockite showed higher water absorption than Hornblende-Gneiss due to the increased porosity.

Study on the strength properties resulted in good uniaxial compressive strength and tensile strength of Charnockite and Hornblende-Gneiss rocks. The AIV, LAA, and ACV of both rocks lied within the acceptable limits, which deduces the applicability of Charnockite and Hornblende-Gneiss derived aggregates in high-load bearing structures. Above both rocks manifested extreme performance against continuous wetting and drying cycles, which showed the pertinency of both rock-derived aggregates in high-durable applications.

As a consequence, high-grade metamorphic rocks such as Charnockite and Hornblende-Gneiss are deemed as the most appropriate and available rock types for producing manufactured sand and coarse aggregates to be used in concrete and mortar.

Acknowledgment

The authors are grateful to the INSEE Cement, Sri Lanka for providing supports to conduct the Chemical and Mineralogical analysis of rocks.

Conflict of interest

The authors declare that there is no conflict of interest exists for this study.

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Статья поступила в редакцию 02.01.2021. Одобрена после рецензирования 08.10.2021. Принята 09.10.2021.

Received 02.01.2021. Approved after reviewing 08.10.2021. Accepted 09.10.2021.