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Performance evaluation of cement mortar produced with manufactured sand and offshore sand as alternatives for river sand

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HIGHLIGHTS

- Cement-sand mortars with manufactured sand and offshore sand were evaluated.
- Selected alternatives were blended for a complete replacement of river sand.
- Effects of particle characteristics and properties of fine aggregates were studied.
- Some mortar properties were significantly influenced by the angularity and roughness of particles.
- The proposed mortars were suggested for masonry, plastering and rendering works.

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ABSTRACT

This study investigates the fresh and hardened state properties of cement-sand mortar comprising manufactured sand and offshore sand as alternatives for a complete replacement of river sand. Two types of manufactured sand were selected based on different rock types such as Hornblende-Gneiss and Charnockite. Offshore sand was collected from an open stock pile after required period of washing. Mortars were manufactured with a binder of Portland Limestone Cement. Binder-to-aggregate ratios of 1:3, 1:4 and 1:6 were considered in this study and manufactured sand was replaced at 0%, 25%, 50% and 75% with offshore sand. To check the influence of sand alternatives and blending ratios, fresh and hardened state properties of alternative mortars were analyzed and compared with reference mortars which were made with river sand alone. Wet and dry bulk densities of mortars were increased with lower replacement levels with offshore sand. Most mortars with blended sand improved the workability while consistency and initial setting time of mortars were not significantly affected. Inflated bleeding of mortars was noticed with the alternatives and replacement levels. Workable life was decreased at small replacements. When manufactured sand in mortar content was 25% and 50%, the water retentivity was significantly improved than other replacements and control mixes. Mortars at lower replacements greatly advanced the flexural strength, compressive strength and capillary water absorption. Linear shrinkage and thermal expansion of mortars were also affected with the selected replacement levels. Based on the overall performance of mortars, blended sand at 25% replacement of manufactured sand with offshore sand was deduced as the feasible solution for completely replacing river sand and to produce economical mortars.

1. Introduction

Mortar is the highest consumed cement-based composite material next to concrete in construction activities, which enables the substantial requirement of sand than concrete [1–2]. The research problem was identified with the construction industries who face difficulties in obtaining good quality fine aggregate not only for mortar but also for the entire construction works as a result of the surged problems with river sand mining [3]. This issue has become apparent among most of the construction industries around the world specially in developing countries. A recent survey carried out by Branavan & Konthesingha [4] in 2019 among the local construction industries in Sri Lanka proved that considerable number of large-scale construction industries started utilizing

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manufactured sand and offshore sand alone for producing mortar by partially replacing river sand. Therefore, it is clear that still there is a continuous usage of river sand in construction works. Hence the aim of this study was set to find alternative approaches to completely replace river sand in mortar.

Many studies have been executed so far on finding various sand alternatives for river sand in concrete and mortar to overcome the above issue. Considerable number of studies proved that manufactured sand and offshore can be individually substituted as the partial replacements for river sand in concrete and mortar [5–10]. Authors found both merits and demerits with the mortar mixes when manufactured sand and offshore sand were used as substitutions. When river sand was replaced with manufactured sand, the fresh properties of mortar were significantly reduced than mortar with river sand [11–13]. However, it can be understood that mortar made with offshore sand showed improved fresh characteristics than river sand mortar, which however lowered the mechanical properties [14,15]. Therefore, this research mainly focuses on blending manufactured sand with offshore sand at various replacement levels which is expected to resolve the above problems. Also, this study can be a practicable solution to the issues that arose with the escalated demand for fine aggregates in construction works and for the increased environmental threats.

2. Related studies

Researchers have already executed some studies and are in continuous findings to implement a sustainable mortar using alternative materials to overcome the immediate problems. Some of the most relevant referred literatures with manufactured sand and offshore sand are reported in this section. As a key study, authors' previous publication [16] elucidated the physical and mechanical characteristics of the selected materials used in this study.

The investigation of physical properties of manufactured sand and offshore sand is required in this study to identify the correlation between the properties of mortar and fine aggregate characteristics. An et al. [17] studied the effect of particle shape of manufactured sand on strength properties and thermal expansion of concrete. Authors analyzed particle characteristics through Scanning Electron Microscopy (SEM) and compared with river sand. Results revealed more angularity of manufactured sand particles than river sand which improved the properties of concrete. The study carried out by Ali et al. [18] revealed the rougher surface texture of manufactured sand than river sand from the 25 × magnified SEM images. Also, the work executed by Branavan et al. [16] numerically proved the increased angularity and rougher surface of manufactured sand than river sand. Above study also manifested the smoothness of offshore sand particles. Therefore, based on the previous literatures, it is clear that angularity and surface roughness is increased in the order of offshore sand < river sand < manufactured sand. When angular/cubical shape and rough texture fine aggregate particles are included in mortar, they can advance the mechanical properties while lower the fresh properties [14–16].

Gonçalves et al. [19] studied the mortar properties with river sand and manufactured sand produced from cone and impact crushers. Authors fully replaced river sand with the above two manufactured sand types in mortar. Consistency, total porosity and absorptivity of mortars considering 0.4 and 0.5 water to cement (w/c) ratios were analyzed. Manufactured sand produced from impact crusher lowered the porosity and absorptivity while increased the unconfined compressive strength of mortar. Mortar with manufactured sand collected from cone crusher was come up with the highest porosity, absorptivity and lowest unconfined compressive strength than other mortar types. Bederina et al. [9] reported a study on the durability of mortar replacing river sand with limestone crushed sand. Mass and strength losses of mortar samples were observed against acid, lime solutions and open air. Replacement levels of 0%, 25%, 50%, 75% and 100% of river sand by crushed sand were used for the analysis. Test results proved that the durability of mortars with 0%, 50% and 100% replacement levels in lime solution revealed positive effects while the durability of mortars were reduced in acid solution irrespective to the substitution level.

Jeyaprabha et al. [20] analyzed the effects of elevated temperature and water quenching on strength and microstructure of mortars. Authors prepared two alternative mixes contained manufactured sand and river sand alone with an inclusion of 15% granite powder. All mortars were exposed to the elevated temperatures of 200 °C, 500 °C, 700 °C and 900 °C for 3 h. From the results it was noted that mortar incorporating manufactured sand alone showed increased compressive, splitting tensile and flexural strengths at all elevated temperatures. Schutter & Pope [2] utilized various types of offshore sand in mortars for completely replacing river sand to examine the water demand of mortar. Authors correlated the rheological properties of sand types with the mechanical performance of mortar. The selected offshore sand particles showed higher fineness modulus and apparent dry density than river sand which resulted higher flow, bending tensile strength and compressive strength of mortar than river sand mortar. Also, offshore sand mortar samples manifested lower water absorptions than river sand mortar.

Based on a brief review study, it was noticed that still there are gaps to be fulfilled on complete replacement of river sand in mortar with suitable alternative fine aggregates. In the present days, river sand extraction is a themed problem due to various environment threats such as river bed degradation, saline water intrusion, depletion of aquatic lives, flora and fauna, etc. Therefore, implementing an innovative solution to cease the escalated river sand mining for the construction works should be done promptly. Since manufactured sand and offshore sand are selected for this study as the river sand alternatives which have already used by several researchers. However, none of the previous studies addressed the concept on blending manufactured sand and offshore sand which is used as an innovative method in this study. The significance of this study is defined as the sources for manufactured sand and offshore sand are high-grade rocks and offshore beds respectively. These sources are naturally and plentifully available and provide less harm to the environment during the extraction. Therefore, the utilization of above materials as alternatives for river sand can produce eco-friendly and inexpensive mortars for a sustainable construction.

3. Materials and experiments

3.1. Materials

As the binding agent for materials, a Portland Limestone Cement (PLC) classified under CEM II/A-LL 42.5 R of EN 197–1 [21] was used for this study. The above cement type was selected as it is the most recognized and highly demanded blended cement among other types available in the country. Technical specifications of the selected cement type are listed in Table 1.

All mortars manufactured for this research only contained cement as the binding medium and did not include any mineral or chemical admixtures. Totally four types of fine aggregates were utilized for this research to prepare the mortar mixes. River sand (RS) was directly collected from a river bed in Mahiyanganaya area (Uva Province) which was used to produce the control mix. Manufactured sand and offshore sand were selected as the alternatives

Table 1
Cement properties conforming to EN 197–1 [21]

Property	Selected cement	EN 197–1 [21] limits
Compressive strength (2 days)	> 27 N/mm^2	≥ 20 N/mm^2
Compressive strength (28 days)	> 50 N/mm^2	42.5 – 62.5 N/mm^2
Setting time	130 – 150 min	≥ 60 min
Fineness	370 – 390 m^2/kg	-Not defined-
Soundness	< 1 mm	≤ 10 mm
Relative density	~ 3.08	-Not defined-
Sulfate content (SO_3)	< 3.0%	≤ 4.5%
Chloride content	< 0.08%	≤ 0.1%
Loss of ignition (LOI)	< 8.0%	-Not defined-

for RS. Two types of manufactured sand produced from different parent rocks such as manufactured sand from Hornblende-Gneiss rock (MS(HG)) and manufactured sand from Charnockite rock (MS(CH)) were collected from the crushing plants located in Hokandara (Western Province) and Unawatuna (Southern Province) areas respectively. Offshore sand (OS) was collected from a fresh stockpile located in Muthurajawela (Western Province) after exposure to a considerable period of rain. Particle size distribution of the sand types selected and considered in this study conforming to ASTM C144 [22] are shown in Fig. 1.

RS revealed the best particle distribution when it is in the natural state. However, the gradation curves of alternatives MS(HG), MS(CH) and OS lied out of the limits proposed by ASTM C144 [22]. Regarding the blended sand types as provided in Fig. 1(b), when MS(HG) was replaced with 50% and 75% of OS, the gradation was controlled which lied within the limits. Anyhow, 25% replacement did not improve the gradation where content of larger particles in blended sand was revealed out of the region. Similar trends can be observed with the blended sand types with MS(CH) and OS. Here, all the replacement levels manifested acceptable gradation curves (refer Fig. 1(c)). The rationale behind this is as represented by Fig. 1(a), gradation of MS(HG) and MS(CH) lied out of the upper limit for the particles >2.36 mm. However, OS particles in the range of 1.18 mm to 0.65 mm lies beyond the lower limit. Therefore, blending of these resolved this problem which are presented in Fig. 1(b) and Fig. 1(c). It was also observed that particles <0.15 mm of MS(HG) and MS(CH) lied out of the lower limit and this was not resolved even after the blending due to the limited amount of OS particles <0.15 mm.Table 2 shows the chemical properties of each collected fine aggregates which were analyzed through X-Ray Fluorescence (XRF) technique using 'Spectro-XEPOS XRF Spectrometer' and the mineralogical compositions of the rock types selected as manufactured sand sources from X-Ray Diffraction (XRD) method. All the collected sand types were siliceous materials with >70% of silica. Few amount of Al_2O_3, Fe_2O_3 and CaO were also noticed. It was also identified that the parent rocks were abundant with affable minerals such as quartz, albite and k-feldspar for cement based mixes which shows the positive aspects of using the selected manufactured sand types in this study.

Table 3 lists down the most determining physical and mechanical properties of the sand types and the standards referred for each test. Fineness modulus, loose density, packing density and water absorption of OS and RS were seemed lower than MS(HG) and MS(CH). Deleterious substances such as fines (<0.075 mm) and silt were identified higher in both manufactured sand types than RS and OS. However, higher amounts of clay and friable particles were observed with RS and OS than MS(HG) and MS(CH). Particle characteristics such as shape and surface texture of the selected fine aggregates were determined from the index values. Angularity index (the index

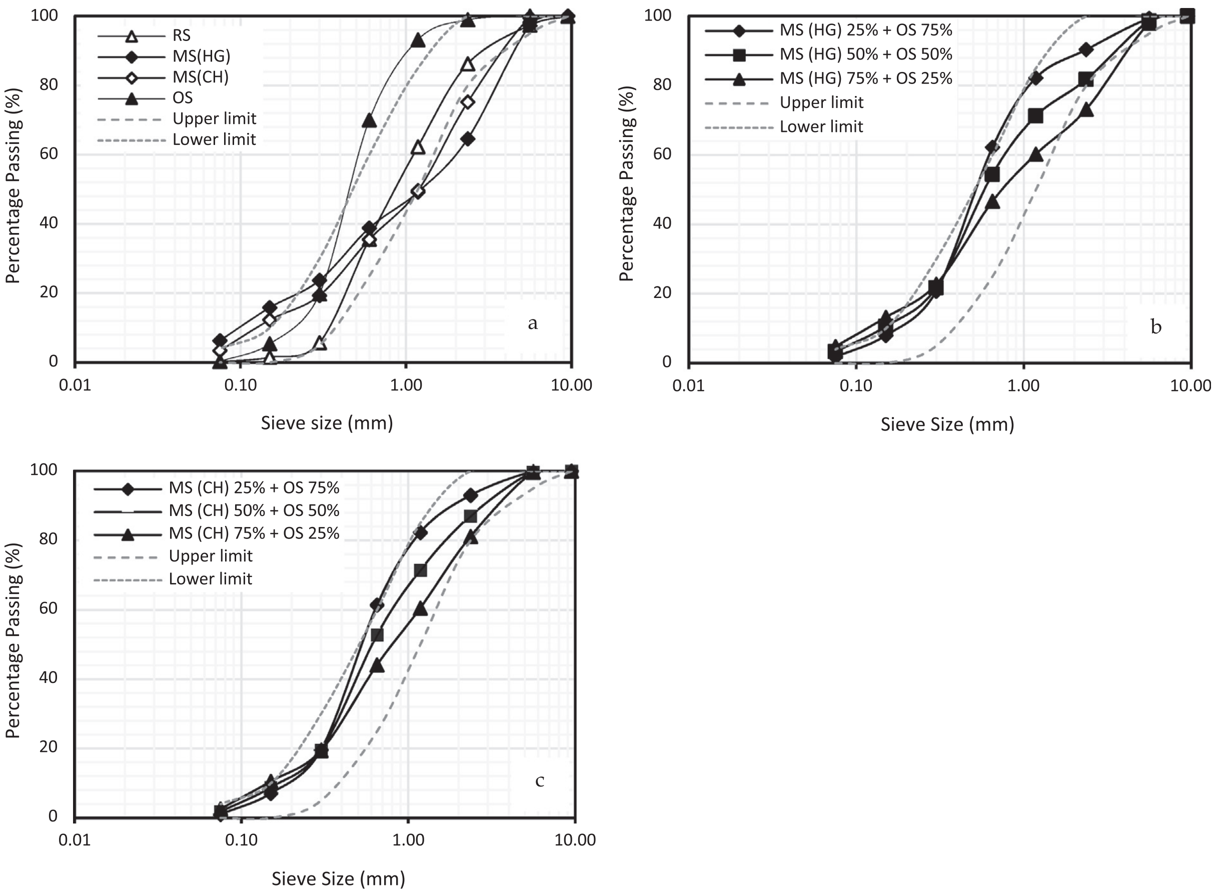

Fig. 1. Gradation curves conforming to ASTM C144 [22]: main fine aggregates [a]; blended fine aggregates of MS(HG) & OS [b]; blended fine aggregates of MS(CH) & OS [c]

Table 2
Chemical properties of fine aggregates and rocks minerals.

Chemical composition %									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	CO_2
RS	97.53	2.84	0.19	0.00	0.00	0.00	0.00	0.76	–
MS(HG)	73.59	7.59	4.83	3.07	1.02	0.00	1.75	1.33	–
MS(CH)	72.01	7.83	2.09	3.95	0.25	0.00	2.08	2.54	–
OS	65.84	15.24	4.78	2.55	2.09	0.00	0.00	0.00	–
PLC	C_3S	C_2S	C_3A	C_4AF	MgO	SO_3	LOI	CaO	
	51.34	23.68	6.41	11.82	2.90	2.50	0.76	1.07	
Mineralogical composition %									
		Calcite	Quartz	Albite	K-Feldspar	Anorthite	Dolomite	Illite	Biotite
Hornblende-Gneiss		0.62	49.48	10.44	10.68	20.30	0.22	6.23	0.02
Charnockite		18.97	27.95	18.03	27.15	4.36	0.23	1.66	0.00

Table 3
Physical and mechanical characteristics of selected sand types.

Characteristic	RS	MS(HG)	MS(CH)	OS	Standard
Fineness modulus	3.113	3.107	3.086	2.128	ASTM C144 [22]
Specific gravity	2.64	2.71	2.70	2.67	ASTM C128 [23]
Total specific surface index	1.106	1.197	1.154	1.113	ASTM D3398 [24]
Angularity index	1.753	1.884	1.915	1.739	ASTM D3398 [24]
Weighted particle index (surface texture)	1.772	2.246	2.259	1.736	ASTM D3398 [24]
Fine content < 0.075 mm (%)	0.18	6.28	3.37	0.24	ASTM C117 [25]
Void content (%)	38.143	38.942	39.167	38.256	ASTM C29 [26]
Loose density (kg/m^3)	1643.15	1783.94	1739.93	1580.32	ASTM C1252 [27]
Packing density (kg/m^3)	1709.81	1915.16	1823.87	1658.28	ASTM C29 [26]
Water absorption (%)	0.95	1.2	1.1	0.75	ASTM C70 [28]
Surface moisture (%)	1.675	4.968	2.371	2.427	ASTM C70 [28]
Clay and friable content (%)	1.59	0.77	0.39	1.18	ASTM C142 [29]
Silt content (%)	0.29	2.88	1.92	0.95	
Bulking (%)	32	40	50	38	
Chloride content (%) *	–	–	–	0.086	
Salt content (%) *	0.0039	–	–	0.016	
Shell content (%) *	–	–	–	7.45	

Note: * Provided by the supplier

for shape characterization) and weighted particle index (the index for identifying surface texture) were increased in the order of OS < RS < MS(CH) ≈ MS(HG). This trend can be correlated with the conclusions driven by the literatures [14–18]. Therefore, it was concluded that particles of the selected manufactured sand types MS(HG) and MS(CH) were more angular/cubical with rougher/uneven surface textures than RS and OS particles. These characteristics of sand particles can enhance various impacts on both fresh and hardened properties of mortar.The microfine content (particles <75 μm) in manufactured sand and chloride, salt and shell content levels in OS may adversely affect the durability of concrete. According to Table 3, the microfine contents were identified as 6.28% for MS(HG) and 3.37% for MS(CH). Standard BS 882 [30] defines that the maximum permissible microfine content in manufactured sand can be up to 16%. Therefore, the determined microfine contents were tolerable and directly used in the mortars. Concerning the shell content, no limitations are provided in BS 882 [30] for particles finer than 5 mm. However, the above standard does not provide any information regarding the allowable salt content in OS for cement-based mixes.Since, the OS selected for this study was directly collected from the treatment plants. During the treatment, OS was exposed to a considerable period of washing and stored in open stock piles. This process enhanced to bring the chloride level in OS to an acceptable value of 0.086%. The level of acceptance of chloride content in OS for cement-based mixes can be followed from the limitations provided in BS 5328 [31] and BS EN 998–2 [32]. BS 5328 [31] permits a range of 0.1 to 0.4% for special concrete such as pre-stressed concrete and concrete with embedded steel and no limits for other concrete. BS EN 998–2 [32] defines a limit of 0.1% Cl of the mortar by dry mass. Because of the actual value was less than the maximum permissible limits, no any additional laboratory test was carried out for OS to limit the chloride level. Also, the study made by Dias et al. [8] highlighted this concept and recommended the risk-free usage of OS after the required washing.Because of the difference of gradation curves of fine aggregates as illustrated in Fig. 1 (a), (b) and (c) due to the blending of manufactured sand and offshore sand at varying replacement levels, both loose and packing densities also varied significantly. Table 3 provides the loose and packing densities of main fine aggregates considered in this study and Fig. 2 illustrates the variation of both densities with respect to the blending percentages.Among the main fine aggregates, both manufactured sand types revealed increased loose and packing densities than RS and OS. As discussed above, comparing with RS and OS, manufactured sand contained more micro fines which can fill up the voids present. This improves well particle packing of fine aggregate. Also, both densities of blended sand types were evolved when manufactured sand was replaced at 75%, 50% and 25% by OS. This can be easily correlated with the gradation curves of blended sand types reported above. The reason for higher densities of BHO75/25 and BCO75/25 was due to the increased micro fine content with increased contribution of manufactured sand (75%). The gradation curves of these blended sand types slightly did not conform to the required limits (refer Fig. 1(b) and (c)). In addition, both loose and packing densities were also used for analyzing the variations in properties of mortars in this study.

3.2. Mix design

Conventional mix design was followed up in this study for designing the mortar mixes. The consumption of fine aggregates

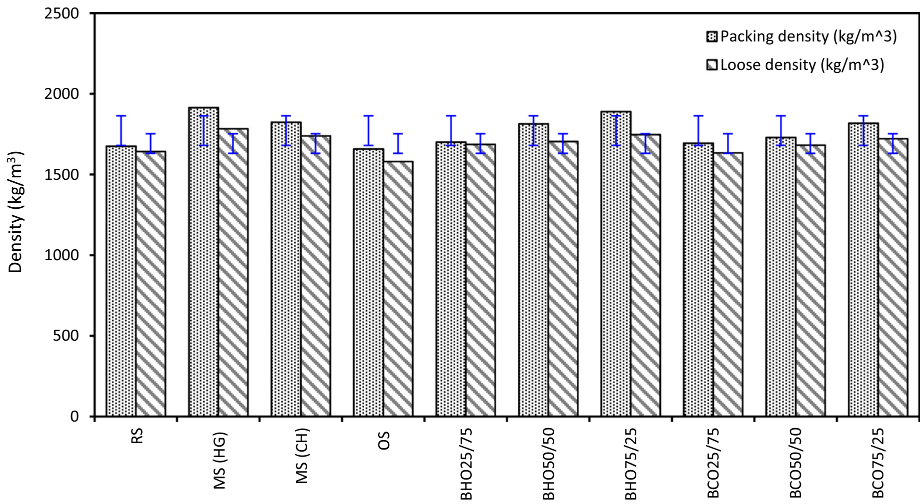

Fig. 2. Loose and packing densities (provided with standard error).

Table 4
Equations for quantifying mortar constituents.

Design parameter	Equation	Equation parameters
Weight of cement	$W_{cem} = \frac{V.1.G_{s,cem}.\rho_w}{1+x}\,(a)$	$G_{s,cem}$: cement specific gravity
Weight of fine aggregate	$W_{FA} = \frac{V.x.G_{s,FA}.\rho_w}{1+x}\,(\mathrm{b})$	$G_{s,FA}$: fine aggregate specific gravity
Weight of water	$W_w = \ (\mathrm{w/c})\ .\ W_{cem} - M_{sand} - W_{ab,sand}(\mathrm{c})$	w/c : water to cement ratio, M_{sand} : moisture content of sand $W_{ab,sand}$: water absorption of sand
Manufactured sand content (%)	$\mathrm{R} \ = \frac{W_{MS}.100}{W_{MS}+W_{OS}}\,(\mathrm{d})$	W_{MS}: manufactured sand weight, W_{OS} : offshore sand weight

Note: V- Total volume of mortar mix; ρ_{w}- Density of water; x - Sand content in cement to sand ratio.

in mortar mixes were done based on saturated surface dry (SSD) condition. Before casting the mortar mixes, all moisture corrections were adjusted. Cement to sand ratios (c/s) of 1:3, 1:4 and 1:6 were considered in this study which are suggested by ASTM C270 [33] and the local specification ICTAD [34] for common industrial applications. For all mortar designs, the w/c ratio was kept constant as 0.5. The mix design equations (a) – (d) listed in Table 4 were used for quantifying the materials for each mix on SSD volume basis. Material requirements were calculated per 1 m^3 of mortar. 'R' represents the manufactured sand content out of the total sand content in the mix. In this study, four replacement levels were considered: 0%, 25%, 50% and 75% of manufactured sand with offshore sand. Table 5 lists down the quantities of materials calculated using the design equations listed in Table 4 for each mortar designation. For each c/s ratio, a control mix was also prepared with river sand alone.

3.3. Experiments

All the tests carried out on mortar were based on ASTM and EN standards. Table 6 lists down the test methods, specimen preparations, climatic conditions maintained for curing of samples and during testing, curing period for each test and the standards followed. To determine the overall performance of mortars and the effects of replacement with alternatives, tests were categorized into two main parts: fresh properties and hardened properties. Seven fresh properties of mortar were analyzed: wet bulk density, workability, consistency, bleeding, initial setting time, workable life and water retentivity. All the mortar prepared in this study contained mineral binder and dense aggregates which satisfied the requirements mentioned in the standards for testing fresh properties.

Just after the mixing of mortar by a mechanical mortar mixer, workability test was performed according to EN 1015–3 [35] to identify the flow of mortar. A mechanical mortorized flow table was used to perform this experiment. Mixed mortar was kept on the disc of flow table and allowed to flow during 15 numbers of vertical impacts. Finally the flow of mortar was determined by mean of two individual diameter readings. Three different types of mortar such as stiff mortar, plastic mortar and soft mortar were identified as represented by Fig. 3. It was observed that when c/s ratio was changed from 1:3 to 1:6, the flow of mortar was reduced due to the low lubricating effect between cement paste and sand particles. Soft mortars were achieved with 1:3 c/s while stiff mortars were come up with 1:6 c/s ratio.

Wet bulk density of mortar was tested according to the standard procedures mentioned in EN 1015–6 [36]. A standard measuring vessel was used to introduce and compact the fresh mortar before applying manual shocks or mechanical vibration (with a frequency of 50 Hz). Consistency of mortar was determined based on standard plunger penetration method described in EN 1015–4 [37]. The freshly mixed mortar was introduced in a standard container and the defined penetration rod was allowed to fall freely through a given height into the fresh mortar. The vertical penetration of plunger into the mortar was directly read from the scale provided in the apparatus. A simple laboratory experiment was performed on mortars for determining the bleeding based on ASTM C940 [38]. A 1000 mL graduated transparent measuring cylinder was used to introduce the fresh mortar upto a level of 800 mL and a medical syringe was used to collect the accumulated bleed water at the surface of mortar at prescribed intervals. A cumulative bleed

Table 5
Mix design of mortars (fixed w/c of 0.5).

Mix ID	Mix Designation	R (%)	c/s	Constituent (kg/m^3)					
				W_{cem}	W_{RS}	$W_{MS(HG)}$	$W_{MS(CH)}$	W_{OS}	W_w
1	M1/RS100	–	1:3	788	1976				394
2	M2/MH100	100		788		2028			394
3	M3/MC100	100		788			2021		394
4	M4/BHO25/75	25		788		507		1499	394
5	M5/BHO50/50	50		788		1014		999	394
6	M6/BHO75/25	75		788		1521		500	394
7	M7/BCO25/75	25		788			505	1499	394
8	M8/BCO50/50	50		788			1010	999	394
9	M9/BCO75/25	75		788			1516	500	394
10	M10/RS100	–	1:4	630	2108				315
11	M11/MH100	100		630		2164			315
12	M12/MC100	100		630			2156		315
13	M13/BHO25/75	25		630		541		1599	315
14	M14/BHO50/50	50		630		1082		1066	315
15	M15/BHO75/25	75		630		1623		533	315
16	M16/BCO25/75	25		630			539	1599	315
17	M17/BCO50/50	50		630			1078	1066	315
18	M18/BCO75/25	75		630			1617	533	315
19	M19/RS100	–	1:6	450	2258				225
20	M20/MH100	100		450		2318			225
21	M21/MC100	100		450			2310		225
22	M22/BHO25/75	25		450		580		1713	225
23	M23/BHO50/50	50		450		1159		1142	225
24	M24/BHO75/25	75		450		1739		571	225
25	M25/BCO25/75	25		450			577	1713	225
26	M26/BCO50/50	50		450			1155	1142	225
27	M27/BCO75/25	75		450			1732	571	225

Table 6
Experimental program.

Property		Standard	Specimen dimensions (No of trials/samples)	Working environment	Curing days
Fresh	Workability	EN 1015–3 [35]	(3)		
	Wet bulk density	EN 1015–6 [36]	(2)		
	Consistency	EN 1015–4 [37]	(2)		
	Bleeding	ASTM C940 [38]	(2)	T: 23 ± 2 °C, RH: 95%	
	Initial setting time	ASTM C403 [39]	(2)	T: 20 ± 2 °C, RH: 95%	
	Workable life	EN 1015–9 [40]	(2)	T: 20 ± 2 °C, RH: 95%	
	Water retentivity	ASTM C1506 [41]	(2)	T: 23 ± 2 °C, RH: 95%	
Hardened	Dry bulk density	EN 1015–10 [42]	Prism 40 mm × 40 mm × 160 mm (3)	T: 105 ± 5 °C	1
	Compressive strength	EN 1015–11 [43]	Broken pieces from flexural strength test (6)	T: 20 ± 2 °C, RH: 65 ± 5%	3, 7, 28
	Flexural strength	EN 1015–11 [43]	Prism 40 mm × 40 mm × 160 mm (3)	T: 20 ± 2 °C, RH: 65 ± 5%	3, 7, 28
	Linear shrinkage	ASTM C531 [44]	Prism 25 mm × 25 mm × 250 mm (4)	T: 23 ± 2 °C, RH: 62 ± 5%	7
	Thermal expansion	ASTM C531 [44]	Prism 25 mm × 25 mm × 250 mm (4)	T: 100 °C	28
	Capillary water absorption	ASTM C1403 [45]	Cube 50 mm × 50 mm × 50 mm (3)	T: 24 ± 8 °C, RH: 60 ± 5%	28

Note: T-Temperature of environment; RH- Relative humidity.

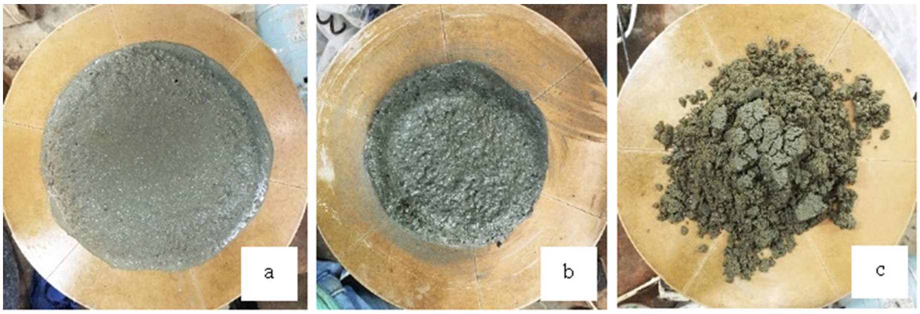

Fig. 3. Flow of soft mortar [a], plastic mortar [b], stiff mortar [c]

water of mortars upto one hour from surface strike-off was calculated for the analysis. Equation (1) was used to calculate the cumulative bleeding of mortar (B) with respect to volume of decanted bleed water (V_w) and volume of sample at beginning of the test (V).

$$B\% = (V_w/V) \times 100 \qquad (1)$$

To study the setting time of mortar, initial setting time was calculated using a standard penetration method according to ASTM C403 [39]. For the industrial applications, determination of initial setting time of mortar is not mandatory, but here this test was executed to study the long-term hardening of fresh mortar with the selected alternatives. Standard penetration needles with different bearing areas were used to penetrate fresh mortar samples. Fig. 4 exhibits the penetration of a standard needle and the penetrated mortar samples with different standard needles. From the graph plotted with time and pressure applied, the initial setting time of mortar was determined when the penetration resistance was 3.5 MPa. Workable life of mortar was also performed using a standard penetration method with a defined rod complying with EN 1015–9 [40]. Fresh mortar was introduced in a standard container and stored inside a polyethelene cover throughout the experiment. Workable life was found out when the mortar reached a defined limit of stiffness (i.e., a penetration resistance of 0.5 N/mm^2).

A simple test setup as shown in Fig. 5 conforming to ASTM C1506 [41] was used to investigate the water retentivity of mortar. This test was involved with the declination of flow after mortar subjected to a controlled 60 s vacuum suction. Equation (2) was referred for the determination of water retentivity (r) with respect to the flow of mortar immediately after the mixing (f_1) and the flow determined after mortar exposed a vacuum suction (f_2). During this test flow of mortar was determined according to the standard method described in the beginning of this section. The pump regulator was adjusted to 6.5 kPa and maintained throughout the experiment for each mortar test. All the other procedures regarding the filling of mortar into the funnel were followed as per the relevant standard.

$$r = (f_2/f_1) \times 100 \tag{2}$$

For hardened properties analysis, fresh mortars were moulded and vibrated using a jolting apparatus with 120 numbers of vertical impacts. After the suffient vibrations, mortar samples were covered with polyethylene sheetings and stored at a temperature of 23 ± 5 °C. After the required period, samples were demoulded and stored for corresponding curing method based on the type of test listed in Table 6.

Dry bulk density of mortar was investigated based on EN 1015–10 [42] after mortar prisms were kept in an oven for 24 h. Oven-dried mass of specimens were measured using an electronic balance sensitive to 0.001 kg after samples were cooled down for atleast 2 h. Flexural and compressive strengths were identified according to EN 1015–11 [43] after mortar prisms were cured for 3, 7 and 28 days. A three-point loading mechanism was arranged for testing the flexural strength of mortar and compressive strength test was performed using the two parts resulted from flexural strength test. Mortar specimens were stressed using an universal testing machine and the tests were performed inside a cabinet with a temperature range of 23 ± 5 °C. Fig. 6 displays the flexural and compressive strength test arrangements in the universal testing machine.

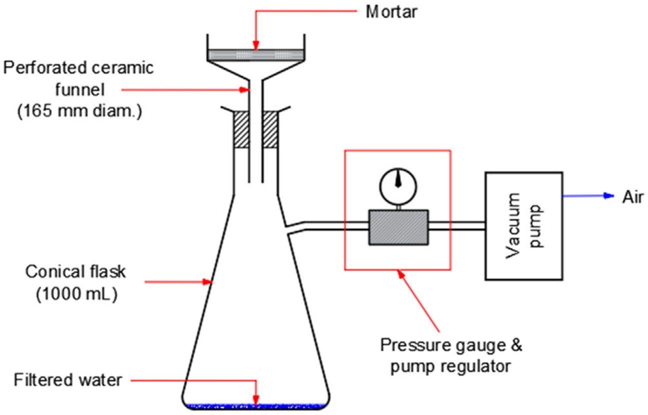

Fig. 5. Test setup for determining water retentivity.

For identifying the dimensional stability of mortar, linear shrinkage test was carried out on mortar auto-clave bars based on ASTM C531 [44]. Specimens were cast along with studs provided at both ends to measure the length change using a length comparator with an accuracy of 0.0001 mm. The same standard was used to examine the thermal expansion of mortar after completing the linear shrinkage test. Before initiating thermal expansion test, mortar bars were undergone for repeat heating and cooling cycles until the bars achieved a constant length to eliminate the effect of shrinkage. The coefficient of thermal expansion of mortar was determined at an elevated temperature of 100°C. Linear coefficient of thermal expansion (C_{exp}) was calculated based on Equation (3) with respect to length of bar and studs at elevated temperature (L_t), length of stud expansion (l_t), length of bar and studs at lower temperature (L_o), temperature change (T) and length of stud at lower temperature (l_o).

$$C_{exp} = (L_t - l_t - L_o)/[T(L_o - l_o)] \tag{3}$$

A standardized procedure was followed up for investigating the water absorption of mortar according to ASTM C1403 [45]. This test was performed to study the water absorption behavior against time through the capillary pores created in mortar cubes after 28 days of curing in a moisture bag. Before starting the test, cube specimens were stored inside an ventilated oven maintained at a

Fig. 4. Penetration of code 1. needle (bearing area of 645 mm^2) and specimens for initial setting time test.

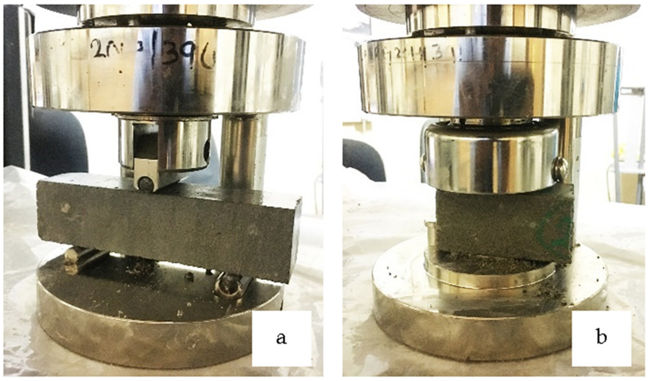

Fig. 6. Flexural strength test [a]; compressive strength test [b]

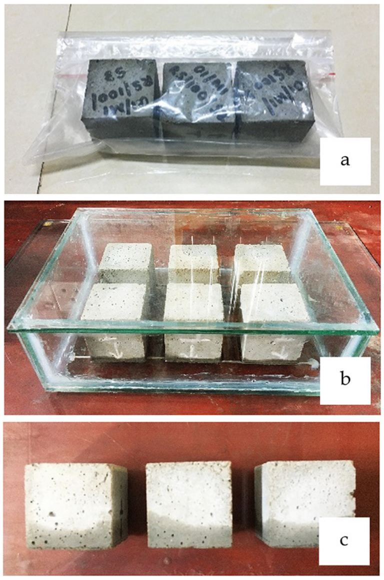

Fig. 7. Curing with moisture bag [a]; container for absorption test [b]; absorption of specimens after 1 h [c]

temperature range of 110 ± 5 °C for 24 h and then cooled down. Mass increment of mortar specimens was recorded at prescribed intervals after specimens were partially submerged in water. Anyhow, this article only deals with the optimum absorption capacity of mortars. Fig. 7 shows the water and air tight container prepared for this analysis and the curing method used prior to the experiment. Water absorption rate (W_{ab}) was calculated in g/100 cm^2 based on Equation (4) incorporating mass of specimen at time T (M_T), initial mass of specimen (M_o), average length of specimen (L_1) and average width of specimen (L_2).

$$W_{ab} = (M_T - M_o) \times 10000/(L_1 \times L_2) \tag{4}$$

3.4. Method of analysis

Simple graphical methods were used in this article for the analyzing purposes. Preferably, line graphs were practiced to show the clear trends when necessary. In some cases, bar graphs were also used. Each graph is provided with reference lines which indicates the property of control mixes. Single and multiple regression analysis were investigated for deriving linear relationships and polynomial models between properties of mortars and sand characteristics.

4. Results and discussion

The test outcomes are described in the following sections with respect to each property of mortar. Graphs were plotted with the effects on property of mortar against 'R' (i.e., the manufactured sand content as mentioned in Section 3.2) for each mortar designation and c/s ratio. Nomenclatures used in the figures are: 'RS': mortar with river sand alone; 'MS(HG) + OS': mortars with manufactured sand made from Hornblende-Gneiss rock and offshore sand; 'MS(CH) + OS': mortars with manufactured sand made from Charnockite rock and offshore sand. The mortar designations listed in Table 5 were applied wherever required.

4.1. Fresh properties of mortar

4.1.1. Wet bulk density

Sand content directly influenced the wet bulk density of mortar where the cement content was constant for each c/s mortar. Wet bulk densities mentioned in Fig. 8 were mean of two individual readings. Considering 1:3 c/s ratio mortars, M1/RS100 mortar showed an approximate wet bulk density of 2400 kg/m^3 which was higher than MS(HG) + OS and MS(CH) + OS mortars up to R-75%. M2/MH100 and M3/MC100 mortars were arrived with the highest bulk densities among other 1:3 c/s mortars. Regarding 1:4 c/s mortars, fresh bulk density of M10/RS100 mortar resulted around 2340 kg/m^3 which was greater than MS(HG) + OS and MS (CH) + OS mortars at R-25%. M15/BHO75/25 and M18/BCO75/25 mortars manifested optimum wet bulk densities than other 1:4 c/s mortars. M19/RS100 mortar showed a wet bulk density of around 2180 kg/m^3. When comparing with blended sand mortars, MS(HG) + OS mortars with 1:6 c/s ratio showed lower wet bulk density at R-25% and 50%, which was increased than reference mortar at R-75% and 100%. However, MS(CH) + OS mortars with same c/s ratio revealed higher wet bulk density at each R level than M19/RS100 mortar.

It can be clearly observed that wet bulk density was reduced when the sand content in the mortar was increased. Small deviations can be noticed between 1:3 and 1:4 c/s mortars, but 1:6 c/s mortars showed greater deviations. This is obvious because higher sand inclusion lowered the cement content in the mortars which thus increased the void content due to the poor micro-pore filling capacity with the available cement paste. With 1:3 and 1:4 c/s mortars, the curves of MS(HG) + OS lied above MS(CH) + OS irrespective to R, which was due to the increased specific gravity and micro-fines content of MS(HG) than MS(CH) as mentioned in Table 3. However, a defined trend was not noted with 1:6 c/s mortars due to the conflicting particle characteristics and the void con-

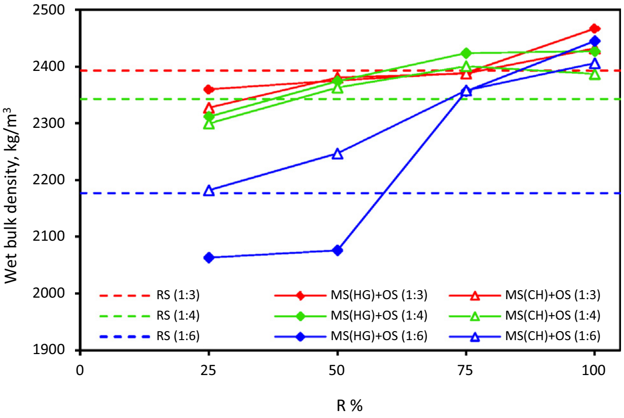

Fig. 8. Wet bulk density of mortars against R.

tent of manufactured sands. When correlating the effect of particle packing and gradation, it was observed that, wet bulk density of mortars was increased with the R levels. This behavior is similar to the advancing packing density values from R-25% to 75% provided in Fig. 2 and the uniform gradation of blended sand types (see Fig. 1(b) and (c)). Therefore, packing density and gradation of sand significantly affected the wet bulk density of mortars.

4.1.2. Workability

Fig. 9 explains the trends of workability of mortars with selected R values. Workability can be defined as the degree of deformability of mortar when subjected to external forces. Workability of fresh mortar was directly influenced by the fine aggregate characteristics (i.e., particle physical properties) and fine aggregate content in the mix. The measured mean diameter of M1/RS100 mortar after defined number of vertical impacts was observed as 185 mm. Each R level of MS(HG) + OS and MS(CH) + OS mortars with 1:3 c/s ratio showed improved workability than M1/RS100 where the curves rested above the reference line. However, both mortar types proceeded towards M1/RS100 when R-100%. The workability of M10/RS100 was arrived with around 125 mm and MS(HG) + OS and MS(CH) + OS mortars with 1:4 c/s ratio manifested a gradual decrease up to R-75%. Mortars M11/MH100 and M12/MC100 showed better workability than or similar to M10/RS100. Increased R values gradually decreased the workability of MS(HG) + OS and MS(CH) + OS mortars when the c/s ratio was 1:6. It was observed that the workability of M19/RS100 mortar showed slightly higher workability than the mortars blended sand.

A significant decline can be noticed with the workability of mortars when c/s ratio was changed from 1:3 to 1:4. So, the higher sand content in the mix reduced the cement amount which thus lowered the lubricating effect between sand particles and cement paste. MS(CH) + OS mortars always manifested improved work abilities than MS(HG) + OS mortars irrespective to R. From Fig. 9, the blending of manufactured sand with offshore sand improved the workability of mortars to an extent than mortars with river sand and manufactured sand alone. So, it is clear that the rationale behind this was purely due to the replacement of manufactured sand particles with offshore sand particles.

When particles are more cubical and rougher surface, they can greatly lessen the workability of fresh mortar by advancing the slip-resistance between the particles [16]. This can be demonstrated from Fig. 10 which illustrates the relationships between particle physical characteristics such as particle shape index (f_A) and surface texture index (f_i) and workability of mortars. Considering the nine mortar types from each c/s ratio, it can be noticed that most of the linear trendlines revealed declining behavior of workability of mortars with the increasing index properties. Here, higher index defines more cubical and rougher surface texture particles.

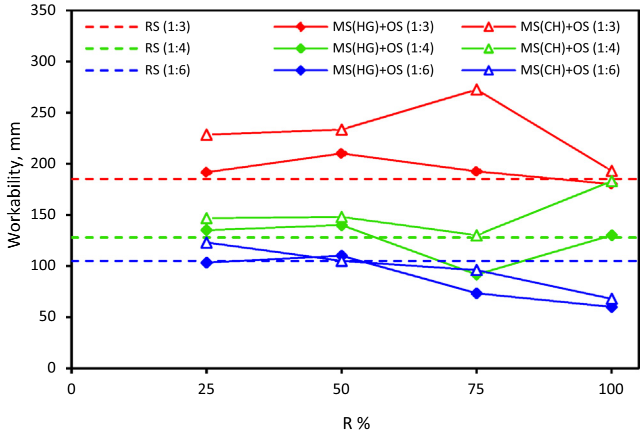

Fig. 9. Workability of mortars against R.

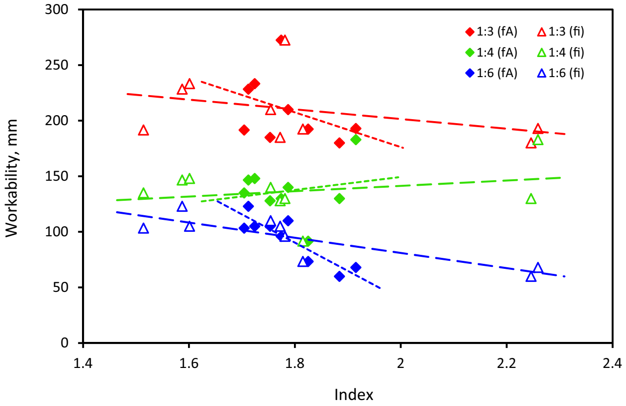

Fig. 10. Relationship between workability of mortars and particle physical characteristics.

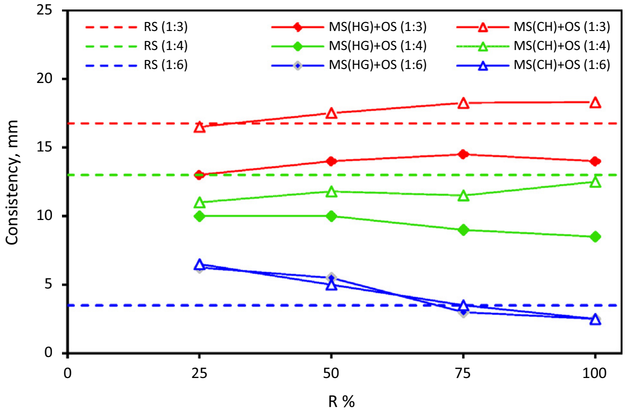

Fig. 11. Consistency of mortars against R.

4.1.3. Consistency

Consistency is also a measure of wetness of fresh mortar similar to flow table test. Consistency of mortar was measured by the vertical penetration of a defined rod. Fig. 11 represents the trends of consistency of mortars made with different R levels. From the curves, it was identified that MS(HG) + OS and MS(CH) + OS mortars with 1:3 and 1:4 c/s ratios did not show a significant difference with R where the curves lied marginally parallel to control mortars. Therefore, an optimum R level cannot be achieved with the above mortars. The penetration values of M1/RS100 and M10/RS100 were around 17 mm and 13 mm respectively. The consistencies of MS (HG) + OS mortars with 1:3 and 1:4 c/s ratios at each R level were lower than the corresponding control mixes. Consistency of M19/RS100 mortar was arrived with 3.5 mm which was much lower than other reference mortars. This was simply due to the greater sand content in the mixes. Up to R-75% the consistencies of both MS(HG) + OS and MS(CH) + OS mortars with 1:6 c/s ratio were advanced than M19/RS100.

As similar to the trends with workability, here also the consistency of mortar was lessened with increased sand content in the mix. It can be observed that most trends of mortars with manufactured sand and offshore sand were come up with lower consistencies than corresponding control mixes. This can be as a result of the higher resistance to vertical penetration of plunger provided by manufactured sand which are more cubical and rougher than other fine aggregates. Also, offshore sand addition did not improve the consistencies of mortars in most cases.

4.1.4. Bleeding

In this study the accumulation of bleed water was measured at the surface of freshly mixed mortar at prescribed intervals. Anyhow, the line graphs included in Fig. 12 represents the bleeding when mortars showed a constant or no further bleeding.

Not similar to above properties, here the bleeding of each reference mix showed considerable decrease than the mortars with manufactured sand and offshore sand. M1/RS100 revealed an optimum bleeding of 4.5% while MS(HG) + OS and MS(CH) + OS mortars with 1:3 c/s ratio manifested a moderate rise up to R-75%. M2/MH100 and M3/MC100 mortars revealed similar bleeding rates while MS(HG) + OS and MS(CH) + OS mortars with 1:4 and 1:6 c/s ratios showed matching trends. Bleeding of control mixes such as M10/RS100 and M19/RS100 with above c/s ratios were come up with nearly 4.3% and 3.6% respectively. Considering each R and c/s ratio, MS(HG) + OS and MS(CH) + OS mortars at R-75% revealed the maximum bleeding rates than the other replacements.

In most replacement levels, mortars contained MS(HG) displayed higher bleeding rates than mortars made with MS(CH). The rationale for the declination of curves after R-75% was the absence of offshore sand and presence voids in the mixes where bleed water filled up the voids. As discussed above, because of the uniform gradation, the packing density of blended sand types were considerably increased which thus resulted in lower porosity. Among all the replacement levels, R-75% blended sand revealed optimum packing density which can be related to the higher bleeding as in Fig. 12. Therefore, it can be concluded that the inclusion of selected alternatives and the blending levels highly increased the bleeding than reference mortars which is a negative aspect of a mortar.

4.1.5. Initial setting time

Fig. 13 conveys the variations of initial setting time of mortars against replacement levels. The approximate mean initial setting time of control mixes was reduced in the order of M1/RS100 > M10/RS100 > M19/RS100. Regarding the alternative mortars, when mortar contained 100% manufactured sand except 1:3, all other c/s ratios revealed increased initial setting times than reference mortars. Manufactured sand types selected for this study contained higher micro-fines than RS and OS. These micro-fines had the ability to keep the mortar fresh for longer time by acting as a coating between cement paste and sand particles. When considering blended sand mortars, optimum setting time was achieved at R-50% and R-75% for MS(HG) + OS and MS(CH) + OS mortars with 1:3 c/s ratio. However, 1:4 c/s ratio blended sand mortars manifested a marginally increasing trend with growing R levels. 1:6 c/s ratio mortars showed contradictory behaviors with R levels. Therefore, it was noticed that the optimum mean initial setting time was achieved at different R levels by the mortars with each c/s ratio.

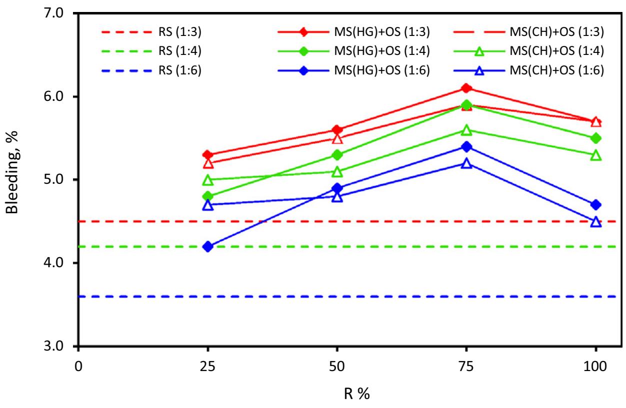

Fig. 12. Bleeding of mortars against R.

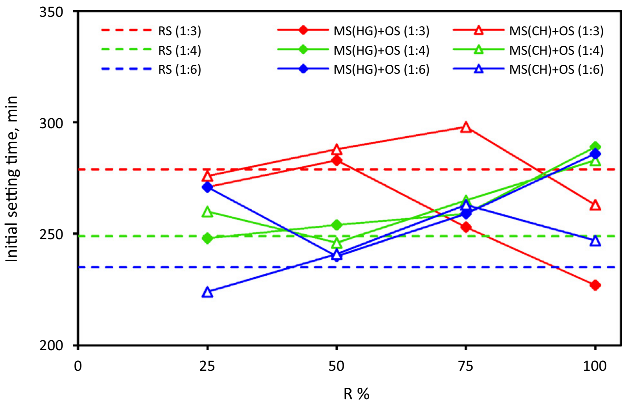

Fig. 13. Initial setting time of mortars against R.

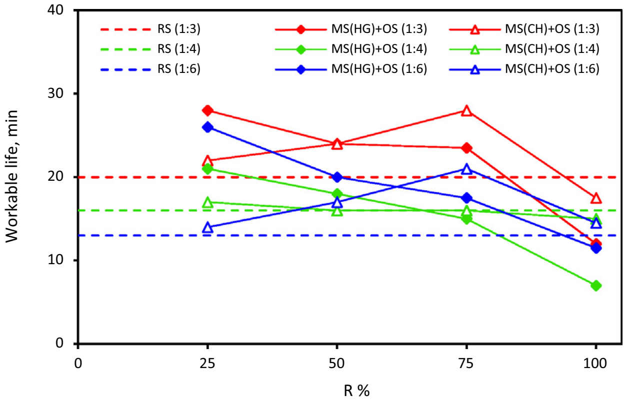

Fig. 14. Workable life of mortars against R.

The replacements of manufactured sand with offshore sand did not show a uniform trend for each c/s ratio. Also, a clear optimum mean initial setting time cannot be obtained for the mortars at selected R levels. Therefore, comparison of mortars contained selected alternatives and blending levels with respect to mean initial setting time cannot be attained.

4.1.6. Workable life

Fig. 14 illustrates the workable life of mortars with varying R values. It was clearly observed that when R was changed from 25% to 100%, the workable life of mortars was reduced gradually except MS(CH) + OS mortars with 1:3 and 1:6 c/s ratios. M1/RS100 was arrived with a workable life of around 20 min while other control mixes such as M10/RS100 and M19/RS100 were come up with around 16 min and 13 min respectively. At a particular R level, blended sand with manufactured sand and offshore sand greatly improved the workable life than the control mixes. MS(HG) + OS and MS(CH) + OS mortars showed better workable life than river sand mix for each c/s ratio up to R-75%. Among the selected replacement levels, optimum workable life was identified at R-25% for MS(HG) + OS mortars and R-75% for MS(CH) + OS mortars irrespective to c/s ratios. Optimum workable mixes were identified for each c/s ratios as: M4/BHO25/75 and M9/BCO75/25 with 1:3, M13/BHO25/75 and M16/BCO25/75 with 1:4 and M22/BHO25/75 and M27/BCO75/25 with 1:6.

Workable life is one of the most influencing properties of mortar which ensures the freshness of mix during the application. Water content in mortar mix highly influence the workability, however in this study to investigate the role of fine aggregates water requirement was maintained constant for each mortar. Therefore, the variation of workability of mortars plotted in Fig. 14 was purely due to the characteristics of fine aggregates in the mix. Based on the observations, it can be concluded that each replacement improved the workable life of mortars than control mix and this was mainly due to the substitution of OS particles for manufactured sand particles. As provided in Table 3, OS particles are more rounded than manufactured sand particles (i.e., around 7% more than MS(HG) and 9% more than MS(CH)). This concept enhanced the slipping effect of OS particles and cement between manufactured sand particles which thus improved the workable life.

4.1.7. Water retentivity

The ability of mortars to retain water under suction was discerned based on a simplified laboratory water retentivity test method. Fig. 15 reveals the trends of water retentivity of 1:3, 1:4 and 1:6 mortars with respect R. As similar to bleeding and consistency, here also a decreasing behavior can be observed when the fine aggregate content was increased. This can be proved from the variation of control mixes where the water retentivity was decreased as 88% for M1/RS100, 76% for M10/RS100 and 69% for M19/RS100. Regarding the mortars with manufactured sand alone manifested lower water retentivity than control mortar for each c/s ratio. Considering the mortars with blended sand, when R was 25% and 50%, most of the 1:3 and 1:4 mortars showed higher water retentivity than control mortars and mortars with manufactured sand alone. Anyhow, this trend was not noticed with 1:6 mortars. Mortars with R-75% revealed marginally similar behavior to R-100% mortars. When comparing the influence of manufactured sand types, a specific conclusion cannot be derived as the variations in Fig. 15 are not unique.

From a relation between the observations and particle characteristics, the particle size distribution of fine aggregates acted a primary role on water retentivity of mortar. The rationale behind the relation is when mortars contained well packed fine aggregate content (uniform particle size distribution), the packing density of fine aggregate was increased which also improved the density of mortar. This reduced the porosity of fresh mortar to an extent. Therefore, the percolation of water added to mortar was decreased through the pores present when suction pressure was applied. This can be further proved from the variations provided in Fig. 1 and Fig. 2. Due to the well packing of blended sand at R-25% and 50%, the water retention ability of mortars was advanced than other R levels. The reason for lowest water retentivity of MH100 and MC100 mortars was as a result of the nonconformity of manufactured sand with limitation provided by the standard.

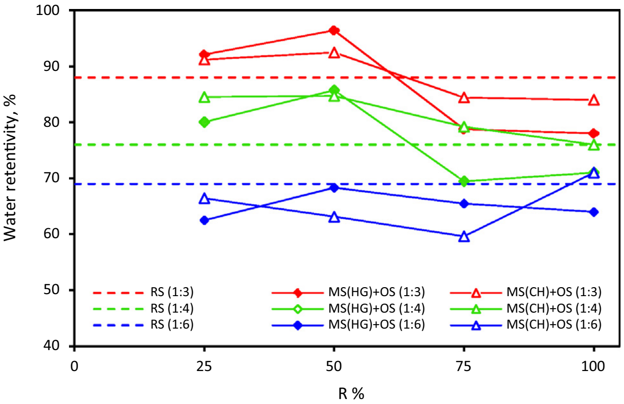

Fig. 15. Water retentivity of mortars against R.

4.2. Hardened properties of mortar

4.2.1. Dry bulk density

Bulk density of hardened mortar was investigated after the complete evaporation of entrapped moisture particles at an elevated temperature. A clear observation can be made from Fig. 16 that when mortars were introduced with manufactured sand alone, highest dry bulk densities were discerned. This was mainly due to the higher specific gravity of selected manufactured sand types than RS and OS as mentioned in Table 3. MS(HG) + OS and MS(CH) + OS mortars with R-75% revealed higher dry bulk densities than other replacement levels. Mortars with 1:3 and 1:6 c/s ratios manifested the outcomes as expected. Mortars with 1:4c/s ratio showed an unusual trend with dry bulk densities. From the above results, it was concluded that higher manufactured sand content in mortar increased dry bulk density than when mortar made with river sand alone.

Also, the reason behind variation of wet bulk density of mortars can be brought here to discuss the variation of dry bulk densities of mortars. Therefore, a well correlation can be observed between the dry bulk densities of mortars and packing densities of fine aggregates. A gradual increase can be noted for both blended sand types when the replacement level was changed from R-25% to 75%, which is similar to the trends reported in Fig. 2.

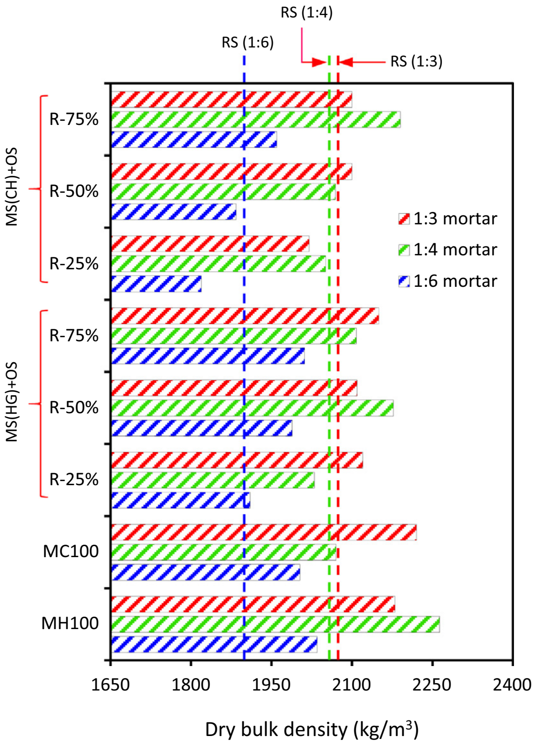

Fig. 16. Dry bulk density of mortars against R.

4.2.2. Flexural and compressive strengths

Mortar prisms after curing were undergone for flexural strength analysis under three-point loading arrangement as illustrated in Fig. 17. Table 7 lists down the mean flexural strength of each mortar with 1:3, 1:4 and 1:5 c/s ratios. Mortars with 100% manufactured sand with each c/s ratio manifested the highest mean flexural strength than reference mortars and other blended sand mortars. The bending strength of mortar prism (flexural bending) solely depends on the porosity/void content created inside the specimens. Fig. 17 exhibits the action and reaction forces created when a line load is applied for bending. Action forces (red arrows) are created from the surface of the specimen and passed through the cement paste and to the sand particles. To resist these actions, reaction forces (blue arrows) are formed from the sand particles. Therefore, when the void content of the specimen is increased the amount of reaction forces created from the sand particles to resist the action forces will be lowered which thus expose to higher bending.

When c/s ratio was changed from 1:3 to 1:6, the flexural strengths were lowered due to the following justifications. Higher flexural strength of 1:3 c/s mortars were because of the micro-filling ability of fresh cement paste by reducing the porosity. 1:6 c/s mortars were arrived with lowest mean flexural strength which can be as a result of reduced cement content. M20/MH100 and M21/MC100 mortars revealed slightly improved flexural strengths than reference mortars. As mentioned in Table 3, the voids created by manufactured sand particles were lessened with micro-fine content which was the reason for reduced porosity of mortar prisms. All the blended sand types with 1:3 and 1:4 c/s ratios revealed higher flexural strengths than reference mixes. MS (HG) + OS and MS(CH) + OS with R-75% were identified as the optimum mortars where in most circumstances they manifested greater mean flexural strengths than reference mortars. However, the inclusion of blended sand in 1:6c/s mortars slightly declined the performance against bending. Fig. 18 represents the relationship between 28 days flexural strength of mortars with c/s 1:3 and the packing density (ρ_c) of fine aggregates. Here, the packing density can be inversely correlated to the void content (V) presented in mortar specimens.

A good correlation can be observed between flexural strength of mortars and packing density of fine aggregates with $R^2 = 0.9449$. From the single linear regression analysis, a linear model can also be developed in terms of the above factors as given in Equation (5).

$$f_l \propto \rho_c \propto 1/V$$

$$\rho_c = 231.75 f_l + 121.89 \tag{5}$$

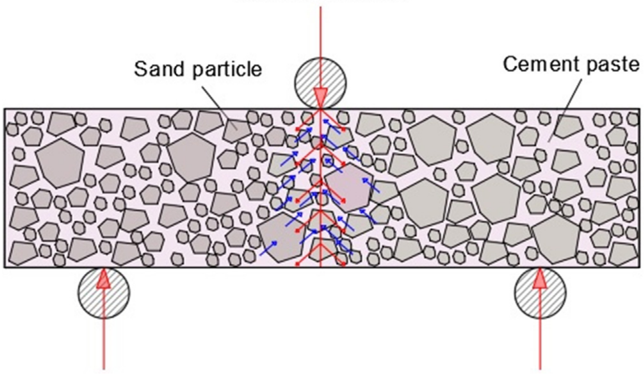

Fig. 17. Action and reaction forces during specimen bending.

After the completion of flexural strength test, compressive strength test was executed on the half-prism specimens resulted from the flexural test. Therefore, for a mortar designation and a curing age, six numbers of samples were tested mean compressive strength. Table 7 also mentions the mean compressive strength of mortars determined in this study. The mean compressive strengths were declined with increasing c/s ratios and this was due to the reduced binding capacity of cement paste with sand particles as a result of lower cement content. It was clearly noticed that at each curing age, M2/MH100 and M3/MC100 showed better compressive strengths than reference mortars. When considering 1:3 mortars with blended sands, M4/BHO25/75 and M9/BCO75/25 manifested greater mean compressive strengths than or similar to the reference mix. M11/MH100 mortar showed a lower mean compressive strength while M12/MC100 mortar marginally advanced the compressive strength than reference mortar. According to 1:4 c/s ratio, MS(HG) + OS mortar at R-75% showed an improved mean compressive strength than reference mortar. MS(CH) + OS mortars at R-50%, 75% revealed better performance than the control mortar M10/RS100.

Regarding 1:6 c/s ratio, mortars comprised manufactured sand alone such as M19/MH100 and M20/MC100 reported higher mean compressive strength at 28 days than M19/RS100 mortar. It was also noted that, the blending ratios up to R-50% did not improve the mean compressive strength. Anyhow, R-75% manifested slightly improved 28 days mean compressive strength than reference mortar. Offshore sand in mortar did not give major impacts to the mean compressive strength, as manufactured sand played the major role. This can be well identified from the optimum compressive strengths which were achieved when the manufactured sand content was high in the mortar. Based on the results of mortars with blended sand, optimum mean compressive strengths can be achieved with MS(HG) + OS and MS(CH) + OS mortars at R-75%.

Manufactured sand alone in mortar created high particle interlocking which enabled higher resistance to the applied stress. As from the observations, physical properties of sand particles mainly influenced the compressive strength. Cubical shape and unsmooth texture particles can increase the friction between the particles which can advance the resistance to external loads [15–18]. Fig. 19 represents the effects of angularity index (f_A) and weighted particle index (f_i) which are the indicators of particle shape and surface characteristics (same as the parameters used in Section 4.1.2) on the 28 days compressive strength (f_c) of 1:3 c/s mortars. As listed in Table 3, higher angularity and weighted particle indexes correspond to the cubical shape and rough texture of sand particles respectively. Because of the compressive strength of mortars linearly varied with angularity indexes ($R^2 = 0.8727$) and weighted particle indexes ($R^2 = 0.7694$), a linear relationship between the above parameters can be derived using multiple linear regression analysis with an adjusted $R^2 = 0.8450$ as shown in Equation (6).

$$f_c \propto f_A, f_i$$

$$f_c = 70.46 f_A - 6.12 f_i - 72.46 \tag{6}$$

4.2.3. Linear shrinkage

Fig. 20 exhibits the variations of length change of mortars at each R levels and c/s ratio up to 7 days from casting. Shrinkage values discussed here were the mean of four mortar bars represented in millimeters. Mortars with all c/s ratios manifested similar trends, but deviated slightly from each other. For the investigation, positive shrinkage and negative shrinkage values were considered as the shrinking and expanding of mortar respectively. From

Table 7
Mean flexural strength and compressive strength of mortars.

Mortar designation	Mean flexural strength (f_l), MPa			Mean compressive strength (f_c), MPa		
	3 days	7 days	28 days	3 days	7 days	28 days
M1/RS100	4.5	5.8	6.9	21.2	30.3	41.3
M2/MH100	5.5	6.7	7.6	23.9	32.9	44.8
M3/MC100	5.1	5.7	7.4	22.8	37.7	50.4
M4/BHO25/75	6.6	5.7	6.8	28.4	29.4	45.7
M5/BHO50/50	5.4	6.0	7.9	26.5	34.9	40.6
M6/BHO75/25	4.9	5.5	6.6	20.9	27.5	37.5
M7/BCO25/75	4.7	5.9	7.2	21.9	26.6	39.5
M8/BCO50/50	4.9	6.0	7.3	24.2	27.9	39.9
M9/BCO75/25	5.3	6.5	7.6	29.0	30.8	41.3
M10/RS100	3.8	4.3	5.5	20.4	22.9	31.9
M11/MH100	4.5	5.7	6.9	21.0	22.9	28.2
M12/MC100	4.3	5.2	6.6	20.6	23.2	32.6
M13/BHO25/75	4.7	4.0	6.2	23.1	23.8	27.0
M14/BHO50/50	4.4	4.5	6.2	21.3	22.9	30.6
M15/BHO75/25	4.5	5.7	6.9	21.2	21.7	37.1
M16/BCO25/75	4.5	4.2	5.8	22.5	23.6	27.1
M17/BCO50/50	4.6	5.6	6.3	20.0	22.7	35.6
M18/BCO75/25	5.7	5.7	6.7	23.1	25.7	38.9
M19/RS100	2.2	2.7	3.8	9.3	12.1	18.9
M20/MH100	2.8	3.1	4.1	11.0	14.4	21.6
M21/MC100	4.8	5.4	6.8	23.7	28.4	32.4
M22/BHO25/75	1.5	1.6	2.2	4.0	4.7	9.7
M23/BHO50/50	1.2	1.5	2.4	2.8	3.8	12.4
M24/BHO75/25	2.6	2.8	3.6	10.5	14.2	22.5
M25/BCO25/75	1.4	1.9	2.6	4.3	9.8	14.9
M26/BCO50/50	2.2	2.5	3.4	6.7	10.6	16.7
M27/BCO75/25	2.4	3.1	4.5	10.8	14.8	19.4

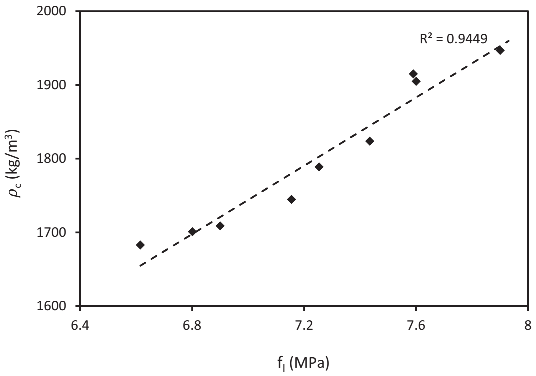

Fig. 18. Relationship between flexural strength and packing density.

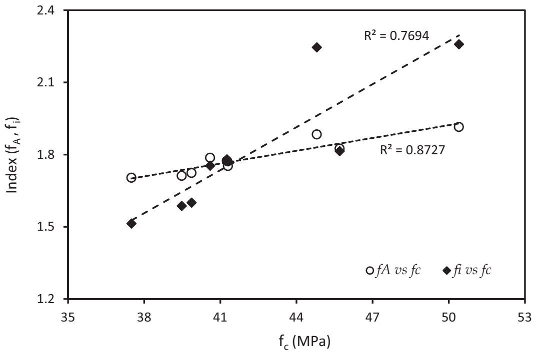

Fig. 19. Effects of angularity and surface indexes on compressive strength.

Fig. 20, it can be identified that each mortar revealed decreasing behavior against the curing time.

The effect of the variation of c/s ratios from 1:3 to 1:6 resulted in decreasing shrinkage. Shrinkage in mortar is mainly influenced by the water content. This defines higher shrinkage can take place when mortar contained higher amount of water. Anyhow, because of the constant water and cement contents in each mortar considered in this research, the comparison of shrinkage of mortars can only be done based on the characteristics of fine aggregates comprised. Therefore, it should be ascertained that when the bond between cement paste and sand particles are strong enough, the shrinkage could take place through binding agent and sand particles. The lower shrinkage of mortars with 1:6 c/s ratio owing to the increased voids created inside the samples because of the reduced micro-filling effect by lower cement content. This created a low bonding capacity of cement between fine aggregates which thus declined the linear shrinkage of mortars. The linear shrinkage of mortars with 100% manufactured sand showed similar trend to the reference mortars or higher.

However, MS(HG) + OS and MS(CH) + OS mortars except 1:6 c/s ratio manifested a considerably increased shrinkage than control mortars which were due to the increased bonding characteristics due to the well packing density of mortars. Among the blending ratios, it was observed that R-75% mortars revealed higher linear shrinkage. Therefore, these outcomes can be directly related to the packing density of blended sand types illustrated in Fig. 2. According to the Fig. 2, the packing density of blended sand types were increased in the order of R-25% < R-50% < R-75%. Therefore, blended sand with higher packing density significantly reduced the porosity of mortar which thus ended up with higher shrinkage.

4.2.4. Thermal expansion

The main aim of investigating the response to elevated temperature was to determine the coefficient of thermal expansion of mortars with alternatives and to compare with the reference mortars. Fig. 21 shows the variations of coefficient of thermal expansion of mortars with selected c/s ratios and sand replacements. MS(HG) + OS and MS(CH) + OS mortars with each sand content revealed approximately similar trends and mortars with all c/s ratios manifested lower thermal coefficients than reference mortars.

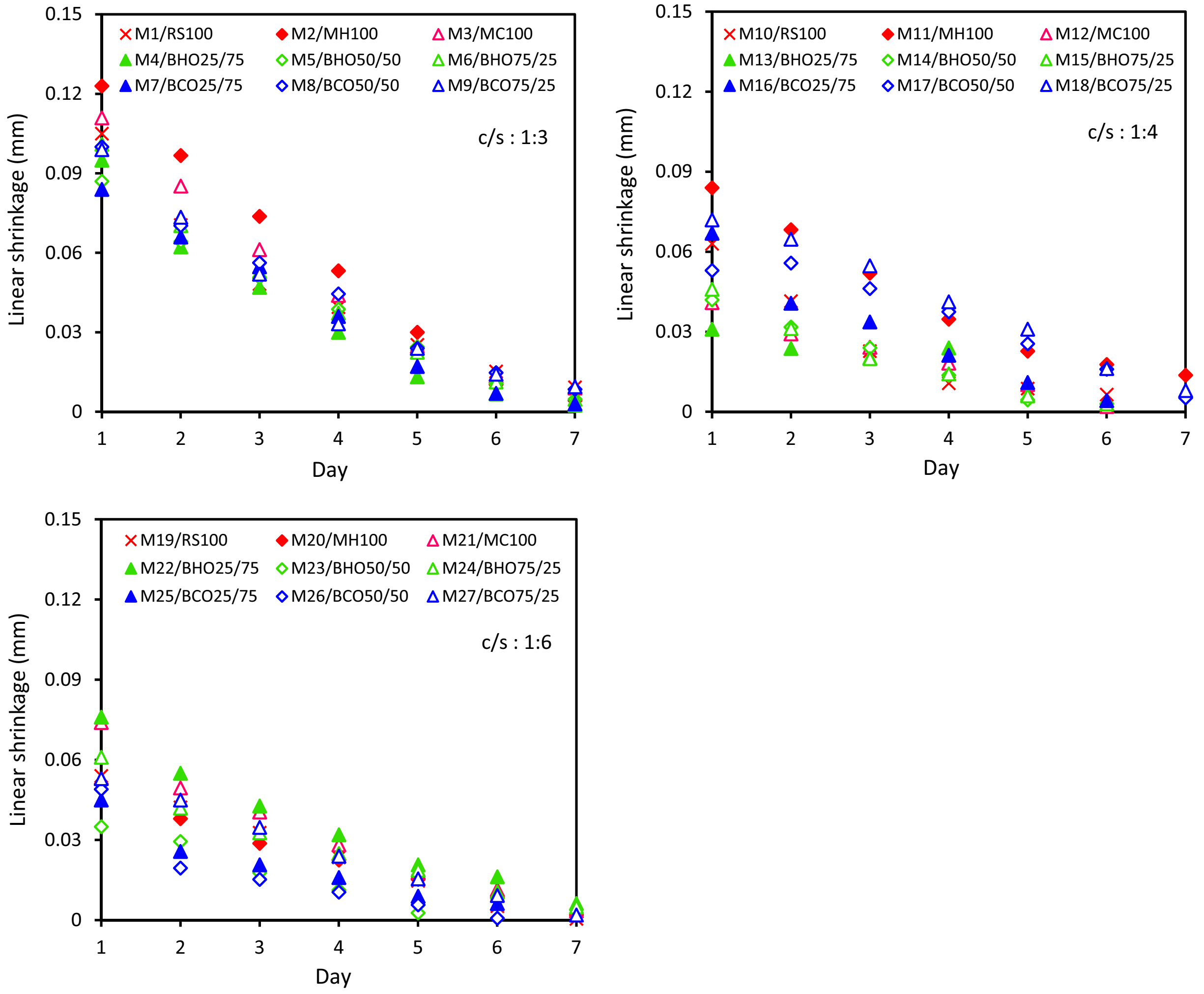

Fig. 20. Linear shrinkage of mortars against time.

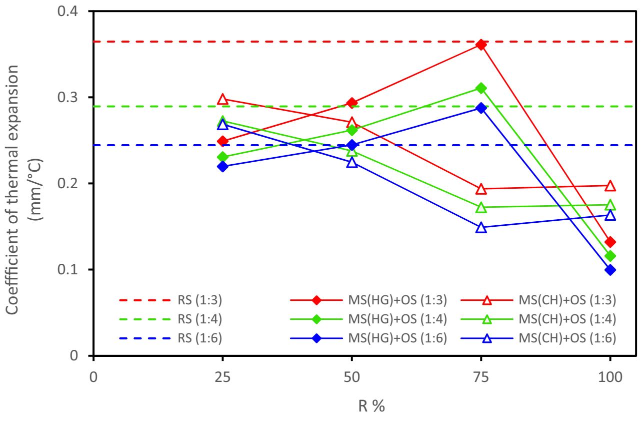

Fig. 21. Coefficient of thermal expansion of mortars.

Thermal expansion coefficients of MS(HG) + OS mortars with each c/s ratio gradually increased up to R-75% and then suddenly declined. MS(CH) + OS mortars with each c/s ratio manifested gradual decreasing trend with increasing R values. In most cases, it was noticed that when mortars comprised both manufactured sand and offshore sand, the coefficient of thermal expansion was lowered to an extent than river sand mortar. The reason behind this scenario may be due to the varying thermal properties of manufactured sand and offshore sand at elevated temperature. Also, thermal expansion was reduced in the order of 1:3 mortar > 1:4 mortar > 1:6 mortar, irrespective to the fine aggregate contents. This varying behavior was purely due to the amount of cement added to the mortars. As discussed in Section 4.2.3, the stability of mortars also depended on the bonding characteristics between cement and fine aggregates, which can be clearly identified from Fig. 21. Therefore, the selected alternatives improved the stability of mortars against the elevated temperature comparing to the reference mortars.

4.2.5. Capillary water absorption

Mortar cube specimens were cast to study the water absorption capacities through capillary pores. Fig. 22 describes the pore structures of river sand, manufactured sand and blended sand with respect to the particle physical characteristics. It was identified that the voids generated by manufactured sand were relatively higher than river sand in consequence of higher angularity. However, the increased voids in manufactured sand were declined to an extent when round and tiny offshore sand particles were blended. This process reduced the capillary water absorption of blended sand mortars than mortars with manufactured sand and river sand alone. Water absorption rate (W_{ab}) was determined based on the Equation (7) with respect to the mass of specimen at time T (M_T), initial mass of specimen, (M_o), average length of specimen (L_1) and average width of specimen (L_2).

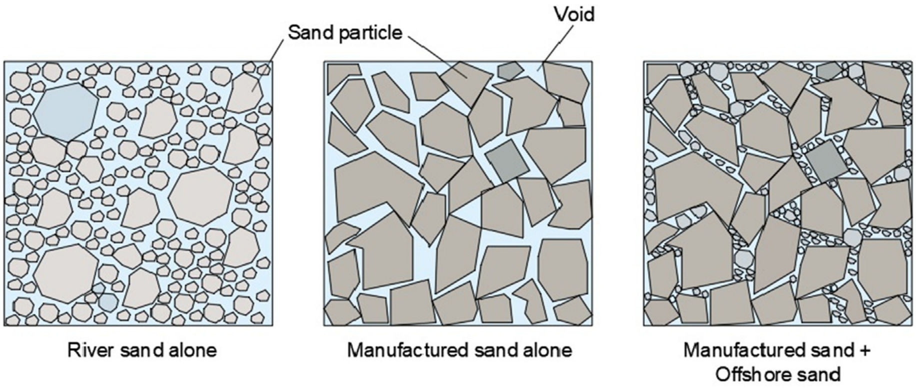

Fig. 22. Pore structure of fine aggregates: river sand [left], manufactured sand [middle], manufactured and offshore sand [right]

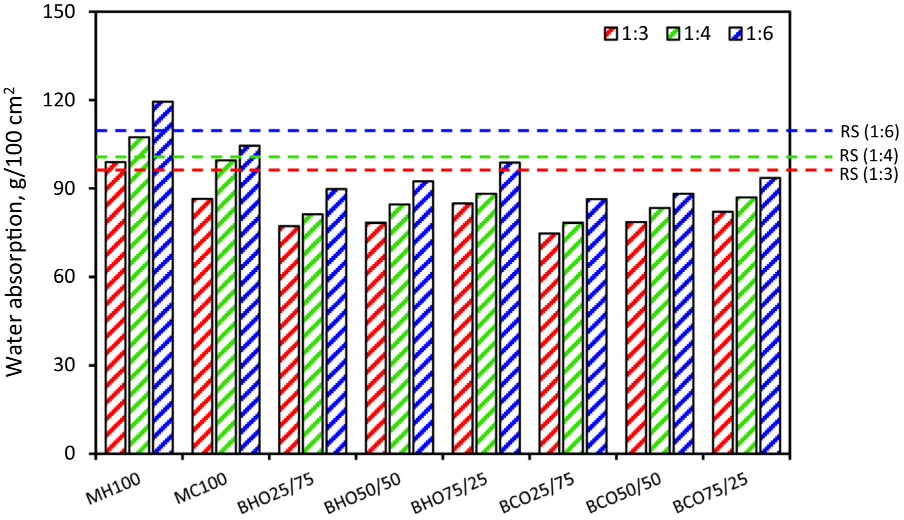

Fig. 23. Capillary water absorption of mortars.

$$W_{ab} = (M_T - M_o) \times 10000/(L_1 \times L_2) \tag{7}$$

Fig. 23 shows the capillary water absorption of mortar at 24 h from partial soaking into water. The water absorption values discussed here were the mean absorption values of three individual samples. When 1:3, 1:4 and 1:6 mortars were fully replaced with manufactured sand, a drastic increase was noticed by wicking. This was due to the influence of capillary pores created inside the samples (refer Fig. 22). Anyhow, the above issue with manufactured sand was solved when offshore sand was partially introduced as the manufactured sand replacement. Among both manufactured sand types, MH100 mortars revealed greater absorptions than MC100 mortars.

The absorption capacities of mortars were increased when R was changed from 25% to 75% for both MS(HG) + OS and MS (CH) + OS mortars. Comparing with other mortar types, mortars with blended sand decreased the capillary water absorption. It was also noted that the water absorption of mortars was increased when c/s was changed from 1:3 to 1:6. Throughout the experiment, each mortar attained a rapid suction at initial stages (up to 4 h) and the absorption was remained marginally unchanged thereafter.

The capillary water absorption of mortars depends on various parameters such as porosity, total specific surface, environmental conditions, etc. Anyhow, as mentioned above, the rationale behind the rapid water absorption of mortars (at initial stage) was mainly relied on the total specific surface of mortar specimens. The total specific surface of fine aggregate played a vital role on the surface of mortar specimens. The results provided in Fig. 23 can be correlated with the total specific surface indexes (f_x) of fine aggregates which were determined through the material properties analysis. A polynomial relationship with R^2 = 0.8842 can be modelled between the capillary water absorption of mortars (W_{ab}) and the total specific surface index of sand (f_x) as shown in Equation (8) and Fig. 24.

$$W_{ab} = 160.73{f_x}^2 - 272.7f_x - 191.56 \tag{8}$$

4.3. Expenditure analysis

To understand the effect of selected alternatives on cost of mortar, a simple cost analysis was carried out and reported in this study. Cost comparisons of mortars were done considering a particular c/s ratio to consider the unique requirement of cement and water for the mixes. Therefore, the comparisons of mortars were investigated based on the price indexes of fine aggregates. To validate the results, the current market prices of the selected sand types were obtained and converted into price indexes as showed in Table 8. The table also provides the information regarding percentage of cost deviations of each alternative mortar from reference mortar and the current market price of fine aggregates.

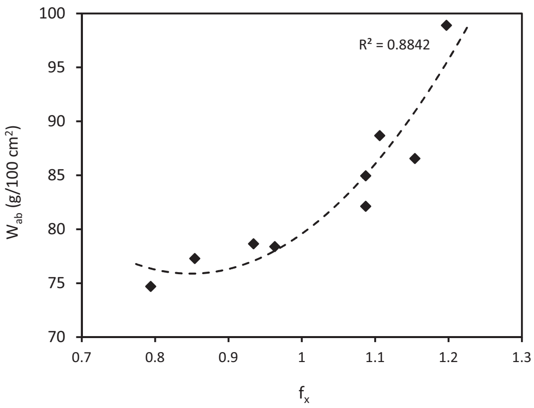

Fig. 24. Relationship between capillary water absorption and total specific surface index.

River sand revealed the inflated market price for 1 cube than other alternatives which highlights the present escalated demand for river sand. Price of offshore sand was between the prices of manufactured sand and river sand. It was clearly noticed that when mortars included manufactured sand alone, cost was drastically reduced than reference mix (around <47–50%). This was due to the lowest market prices of manufactured sands. Mortars with blended sands also proved declined costs when compared to control mortar. Price of mortar was reduced in the range of 32–44% than river sand mortar when it included MS(HG) and OS. Mortars with MS(CH) and OS also manifested similar cost reductions (around 31–42%) than reference mortar. When R was changed from 25% to 75%, cost of mortars was gradually decreased and each replacement declined the cost than reference mortar.

Table 8
Price indexes of mortars and market price of fine aggregates.

Mortar	Price index of mortar	Cost less than reference mix
RS100	X	–
MH100	0.50 X	50%
MC100	0.53 X	47%
MS(HG) + OS, R-25%	0.68 X	32%
MS(HG) + OS, R-50%	0.62 X	38%
MS(HG) + OS, R-75%	0.56 X	44%
MS(CH) + OS, R-25%	0.69 X	31%
MS(CH) + OS, R-50%	0.64 X	36%
MS(CH) + OS, R-75%	0.58 X	42%
	Market price (LKR) for 1 cube	Price index of sand
RS	17,000	X
MS(HG)	8,500	0.50 X
MS(CH)	9,000	0.53 X
OS	12,500	0.74 X

4.4. Applicability of mortars and innovation of the study

Various codes of practices are available now for selecting mortar types based on end applications such as rendering, plastering and masonry works. BS 5628–3 [46] briefly recommends some cement-sand mortar types which are applicable for masonry works. The code classifies above mortars into four designations based on severity conditions that the masonry exposes. Furthermore, BS EN 998–1 [47] and BS EN 998–2 [32] define some declarations for properties of plastering mortar and masonry mortar respectively. Also, ASTM C270 [33] includes some required limitations for masonry mortar. The local standard ICTAD [34] partly set proportions for plastering and masonry mortars without defining limitations on the properties. Based on a brief review of existing standards, most of them suggests 1:3 to 1:4 mortars for plastering works, 1:3 to 1:6 for masonry works and 1:6 for rendering works. Therefore, when comparing the selected mortar grades (1:3, 1:4 and 1:6) in this study, this complies the above ranges.

However, it is also important to check the end application of each mortar prepared in this research, as the mortars contained different fine aggregates which were used for complete replacement of river sand. For the comparison purposes all the mortars were considered as general-purpose mortars. Table 9 consists the required limitations of mortar properties defined by standards and conformity of selected mortars for the intended purpose. The observed ranges provided in Table 9, are selected based on minimum and maximum values of properties obtained with mortars incorporated river sand alternatives. The properties except listed in Table 9 such as wet bulk density, dry bulk density, bleeding and flexural strength are not defined with a range in any of the above standards. Anyhow, ASTM C270 [33] states that fresh properties such as consistency, initial setting time and workable life should be in an acceptable range based on the satisfaction level by mason practitioner. Therefore, the applicability of mortars were

Table 9
Applicability of selected mortars complying with standards.

Property	Provision by standard		Present study outcome		Applicability
	Limitation	Standard	Grade	Observed range	
Workability (mm)	≥ 200	EN 1015–6 [36]	1:3	193–273	✓ (M)
	140–200		1:4	128–148	✓ (P)
	< 140		1:6	60–123	✓ (R)
Water retentivity (%)	≥ 75	ASTM C270 [33]	1:3	78–96	✓ (M)
			1:4	69–86	✓ (M)
			1:6	60–71	×
Compressive strength (MPa) [a]	≥ 6	BS EN 998–1 [47]	1:3	37.5 – 50.4	✔ (P, R)
			1:4	27.0 – 38.9	✔ (P, R)
			1:6	9.7 – 32.4	✔ (P, R)
Linear shrinkage (%)	0.04 – 0.1[b]	BS 5628–3 [46]	1:3	0.026 – 0.096	✔ (M)
			1:4	0.014 – 0.084	✔ (M)
			1:6	0.009 – 0.061	✔ (M)
Thermal expansion ($\times10^{-6}$/K)	11–13	BS 5628–3 [46]	1:3	3.79 – 10.47	×
			1:4	3.33 – 8.93	×
			1:6	3.14 – 7.84	×
Capillary water absorption (kg/m^{2}min$^{0.5}$)	≤ 0.4	BS EN 998–1 [47]	1:3	0.23 – 0.41	✔ (P, R)
			1:4	0.51 – 0.78	×
			1:6	0.59 – 0.96	×

Note: M – masonry mortar; P – plastering mortar; R – rendering mortar; [a] strength at 28 days; [b] shrinkage at initial drying stage not evaluated based on these properties due to the unavailability of specific required limitations.

According to Table 9, it can be identified that the workability of mortars incorporated the selected river sand alternatives were complied with the required limitations which are intended to use as masonry mortar (1:3), plastering mortar (1:4) and rendering mortar (1:6). Among the c/s ratios, 1:3 and 1:4 mortars with manufactured sand and blending of manufactured sand and OS at selected R levels, can be used as masonry mortars, where the observed water retentivity values were satisfied with the requirements. Therefore, it can be concluded that the mortars with selected alternatives and replacements can be used for industrial purposes with respect to fresh properties.

Regarding the hardened properties, each alternative c/s ratio mortar considered in this study can be utilized for plastering and rendering works which fulfils the minimum requirement of compressive strength at 28 days. Also, the above mortars meet the requirements for linear shrinkage for masonry works. However, none of the alternative mortars with selected c/s ratios complied the minimum requirement for the thermal expansion. Therefore, the mortars with selected alternatives and replacement levels cannot be applied for the masonry works that exposed to high temperatures. 1:3 mortars with the alternatives and R levels revealed less capillary water absorptions than the maximum values defined, which can be applied for plastering and rendering works.

Since none of previous studies was successful in applying manufactured sand as a complete replacement for river sand. The blending of fine aggregates concept executed in this study is original where even the existing standards are not providing information regarding this. Based on the brief investigation of mortars with the selected alternatives and blending ratios, positive effects were resulted with respective to both fresh and hardened properties. Moreover, the expense of alternative mortars was identified much lower than the mortars with river sand. Therefore, variables of this study can be applied for the industrial purposes which are effective in producing economical mortars and reducing escalated environmental drawbacks.

5. Conclusions

The aim of this research is to understand the behavior of cement sand mortar when manufactured sand and offshore sand were used as the complete replacements for river sand. To study this behavior, fresh and hardened properties of mortars were investigated when river sand was completely replaced with the selected alternatives and different replacement levels such as 0%, 25%, 50% and 75% of manufactured sand with offshore sand. Two manufactured sand types were considered in this study based on the sources used for production of manufactured sand: manufactured sands produced from Hornblende-Gneiss rock and Charnockite rock. Binder to sand ratios of 1:3, 1:4 and 1:6 were used reflecting the most common ratios considered for real engineering applications. As expected, the inclusions of alternatives in mortar improved most of the fresh as well as hardened state properties and the main findings of this experimental work are reported here:

Wet bulk densities of MS(HG) + OS and MS(CH) + OS mortars were increased with larger R levels. Mortars with R-100% showed extreme wet bulk densities among all mortars. 1:3 c/s mortars with each blended level improved the workability than reference mortar, but few 1:4 and 1:6 c/s mortars showed lower workability than river sand mortar. MS(CH) + OS mortars manifested better work abilities than MS(HG) + OS mortars irrespective to the c/s ratios. Replacement levels did not reveal significant effects on the consistency of mortar.

Mortars with alternatives revealed drastic bleeding rates than the reference mortars. Among them MS(HG) + OS and MS (CH) + OS mortars at R-75% manifested maximum bleeding. Alternatives did not significantly affect the initial setting time of mortars. Mortars at R-50%, 75% showed slightly lesser initial setting times comparing with other R levels. Workable life of mortars was gradually reduced with increasing R levels. Similar to wet bulk density, the dry bulk density of mortars was advanced when c/s ratio was changed from 1:3 to 1:6 and R from 25% to 100%. Flexural and compressive strengths were narrowed when c/s varied from 1:3 to 1:6. Mortars with R-100% reported highest flexural and compressive strengths for each c/s ratio. MS(HG) + OS and MS(CH) + OS mortars at R-75% manifested higher flexural and compressive strengths than other R levels.

In most cases, mortars with manufactured sand evinced higher shrinkage than reference mortars. Anyhow, blended sand mortars lowered the shrinkage to an extent than river sand mortar. The stability of mortars against elevated temperature was improved with each R level. The highest capillary water absorption of mortars was observed at R-100%. Blended sand mortars manifested lower water absorptions than river sand mortars. A marginal increase of the water absorptions was observed when R changed from 25% to 75%.

Therefore, an assertion can be made that among the blending ratios, R-75% can be the optimum solution for completely replacing river sand in terms of each mortar property and for producing inexpensive mortars.

CRediT authorship contribution statement

Branavan Arulmoly: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **Chaminda Konthesingha:** Conceptualization, Validation, Resources, Writing - review & editing, Supervision, Data curation. **Anura Nanayakkara:** Validation, Resources, Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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