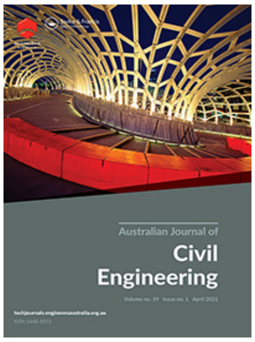

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Branavan Arulmoly & Chaminda Konthesingha

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REVIEW ARTICLE

Pertinence of alternative fine aggregates for concrete and mortar: a brief review on river sand substitutions

Branavan Arulmoly and Chaminda Konthesingha

Department of Civil Engineering, University of Sri Jayewardenepura, Ratmalana, Western Province, Sri Lanka

ABSTRACT
Construction industries around the world are facing many difficulties in obtaining good-quality fine aggregates for concrete and mortar due to a shortage of river sand. This problem leads the researchers to find possible alternatives to replace river sand in construction. A brief review has been carried out to identify the alternatives suggested by researchers, merits and demerits of substitutions, availability of standards, and previous studies on the effects of replacing river sand with alternatives in concrete and mortar. Manufactured sand (M Sand), offshore sand, sea sand, quarry dust, and demolition waste have been identified as the most common substitutions for river sand. M Sand and quarry dust have more angularity, rougher surface, higher total specific surface, and lower presence of deleterious substances than river sand, offshore sand, and sea sand. These characteristics played a vital role in the fresh, hardened, and durability performance of cement-based mixes where studies revealed both positive and negative outcomes when comparing with river sand concrete and mortar. Intensely, the strengths of cement-based mixes were improved with angular and rough particles while the workability was declined. The void content and specific surface of alternatives manifested pivotal effects on water absorption of concrete and mortar.

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River sand; rock-derived aggregates; sea-based aggregates; replacements; concrete; mortar

1. Introduction

Fine aggregate is a granular material, a cementing hydraulic medium used as a constituent of concrete and mortar. Concrete is the largest consumable material after water, with nearly three tons are utilised annually by each person (Sankh et al. 2018; Kosmatka, Kerkhoff, and Panarese 2011). The consumption rate of fine aggregate has become very high due to the excessive usage of concrete and mortar in infrastructure developments (Sankh et al. 2018). The demand for river sand has been increased due to the major developments by building industries around the world (Branavan and Konthesingha 2019; Mudunkotuwa 2003). A recent survey carried out by Branavan & Konthesingha (Branavan and Konthesingha 2019) among the local construction industries, revealed that 80% of the construction industries are still using river sand as the main fine aggregate for concrete and mortar. The authors also identified that the river sand substitutions such as M Sand and offshore are being utilised in some of the large-scale construction activities in Sri Lanka. Rationales behind the continuous usage of river sand in construction work by the industries are elucidated by different researchers.

Most studies showed that the contractors are willing to use river sand due to the higher workability of mixes because of the improved particle characteristics (Kwan 2000; Mia, Salman, and Ahmed 2017; Sun et al. 2020). On the other hand, Kwan (Kwan 2000) explains some negative impacts of the deleterious contents of river sand such as clay and silt. The escalated demand for river sand enhances the over-extraction near riverbeds and improper sand processing which allows considerable silt and clay contents without converging to the limitations (Sing, Love, and Tam 2012). Padmalal & Maya (Padmalal and Maya 2014) concluded that river sand extraction is widespread in most developing and developed countries. The authors also mentioned that the fluvial systems (i.e. with a catchment area of lesser than 10,000 km^2) of developing countries are highly affected due to increased sand mining. Gavriletea (Gavriletea 2017) and Walker et al (Walker et al. 2016) briefly highlighted the environmental impacts from various river sand mining activities such as deforestation, soil erosion, disruptions to the eco-system, and loss of biodiversity. The authors also stated that placer mining leads to the increased pollution of streams, production of toxic wastewater, erosion of seam banks, and the open-pit mining affects complete eco-system destruction. Pereira & Ratnayake (Pereira and Ratnayake 2013) described some more adverse effects such as lowering of groundwater table and deterioration of water quality due to the degradation of riverbeds and erosion of the banks. Therefore, to overcome such environmental impacts, researchers are now

CONTACT Branavan Arulmoly brana14arul@gmail.com Department of Civil Engineering, University of Sri Jayewardenepura, Ratmalana, Western Province 10390, Sri Lanka

suggesting different alternatives to replace river sand fully or partially in construction works through various laboratory studies.

It can be identified that M Sand is better than the most commonly available substitutions such as offshore sand, sea sand, quarry dust, and demolition waste especially for making high-strength concrete and mortar (Branavan and Konthesingha 2019; Manguriu et al. 2013; Lohani et al. 2012). Presently, the view on M Sand for utilising as a river sand alternative has been emerged due to various positive impacts concerning the availability of sources and special particle characteristics (Mibei 2014; Malaviarachchi and Takasu 2011; Jayawardena and Dissanayake 2008). The studies implemented by Malaviarachchi & Takasu (Malaviarachchi and Takasu 2011) and Jayawardena & Dissanayake (Jayawardena and Dissanayake 2008) revealed the possibility of using M Sand produced from parent rocks based on the friendly and detrimental mineral compositions for concrete and mortar performance. Intensely, Cooray (Cooray 1989) and Vithanage (Vitanage 1985) recommended some parent rock types for utilising and neglecting for M Sand manufacturing. Certain studies are also involved with quarry dust which is also a rock-derived aggregate having similar particle characteristics to M Sand. Studies also proved the applicability of sea-based fine aggregates such as offshore sand and sea sand as the river sand substitutions in concrete and mortar through experimental investigations (Walker et al. 2016; Bide and Mankelow 2014; Nanayakkara 1999). Offshore sand and sea sand are naturally available resources, narrowly utilised for river sand in construction activities (Sanjeevan et al. 2006). Furthermore, industrial waste materials such as demolition wastes, furnace slag, and glass wastes have also become interesting options for building industries for partially replacing river sand to overcome the increased cost and problems with sustainable dumping (Sanjeevan et al. 2006; Ingale et al. 2016; He et al. 2016).

As reported above, a considerable number of studies suggested different alternatives for replacing river sand in cement-based mixes. However, to achieve the aim of this work the alternatives were selected based on the number of studies available so far on the alternative. The performance of concrete and mortar is determined by several properties that are achieved throughout the lifetime. The workability, water retentivity, consistency, bleeding, setting time, and workable life are the most important fresh-state properties where the compressive strength, flexural strength, tensile strength, shrinkage, thermal conductivity, and creep can be considered as the basic mechanical properties of cement-based mixes. Anyhow, the present study is limited to some of the above-mentioned properties which were elucidated by most of the previous research. The durability is a primary factor that determines the long-term function of concrete and mortar. Different works investigated the alkali-silica reactivity, resistance to acid and base solutions, capillary water absorption, etc. of concrete and mortar regarding several design parameters. Hence, this work reports some of the literature implemented on the durability of concrete and mortar with the inclusions of river sand replacements.

2. Significance of the study

A solution for river sand in concrete and mortar has become an emerging theme among the construction industries to immediately cease or control the escalated sand mining. It has been identified that a considerable number of review studies are available on scrutinising the applicability of different substitutions for river sand. However, most of the studies are limited in analysing the effectiveness of by-products or waste materials. Also, the influence of the characteristics of substitutions on the properties of cement-based mixes is less or scarcely analysed by the literature. The present study mainly focuses on the previous studies with the most common mineral resources and waste materials for the river sand replacement in concrete and mortar. This work aims to relate the properties of concrete and mortar with the most influencing characteristics of fine aggregate particles which are carried out by none of the review studies available. To achieve this, the optimum replacement levels suggested by the researchers were related to the angularity, surface roughness, and total specific surface of particles. Therefore, this review is expected to convey sufficient information to the researchers and industry regarding the influence of the particle characteristics on the fluid, mechanical, and durability properties of cement-based mixes. This piece of work can also be considered as support when selecting mineral resources for construction activities that require special performance. Furthermore, a review of cost analysis and future demand could enable the industry to check the continuity of the works with the alternatives. A concise review of existing standards is also implemented for supporting this work.

3. Previous studies on river sand substitutions

Many researchers have already carried out and are in progress on studying the applicability of partially and fully replacing river sand with alternatives in concrete and mortar. Researchers are now more intrigued in checking the pertinence of by-products and waste materials for replacing river sand. This section describes the past research studies implemented with the man-made mineral resources such as M Sand and quarry dust, the waste materials like marble powder, demolition waste, furnace slag, recycled glass waste, and plastic waste, and some naturally available minerals such as offshore sand, sea sand, and dune sand. The main aim of this section is to provide a clear intention on the applicability of the above alternatives executed by different researchers in concrete and mortar. Therefore, this part is not including all the studies which are repetitive/similar to the studies mentioned. However, for validating purposes, all the referred studies are used for the analysis part carried out under Section 5.

3.1. Manufactured sand (M Sand)

A considerable number of studies have already been executed using M Sand in concrete. These days, M Sand is considered as one of the mineral resources due to the increased quarry operations. Manguriu et al (Manguriu et al. 2013) experimented on partially replacing river sand with crushed rock sand with 0.55 and 0.59 water to cement ratios. Vijayaraghavan & Wayal (Vijayaraghavan and Wayal 2006) conducted experiments with the replacement levels of 0%, 50%, and 100% river sand by M Sand which showed the increased compressive strength of 5.7% for 50% replacement and 7.03% for 100% replacement than control mix. Shanmugapriya et al. (Shanmugapriya, Uma, and Meiraj 2014) performed a study by replacing river sand at 0%, 20%, 40%, 60%, 80% and 100% with M Sand and replacing the cement with silica fume at 0%, 2.5%, 5%, 7.5% and 10%. Another experimental investigation was carried out by Joe et al. (Joe et al. 2013) on the effects of M Sand in high-performance concrete made by replacing 40%, 50%, 60%, and 70% of river sand with an addition of 1% steel fibres. Mathew et al. (Mathew et al. 2016) presented a study on the strength of concrete by partially replacing river sand with both M Sand and laterite soil with the addition of superplasticizers. Visnu et al. (Visnu, Karthikeyan, and Arulraj 2015) carried out an experimental investigation on high-performance concrete with partial replacements of river sand by M Sand with 40%, 50%, and 60% replacements and cement with fly ash at 10%, 20%, and 30% levels. Vijaya & Selvan (Vijaya et al. 2015) made a comparative study on the strength and durability properties of concrete with M Sand considering different grades M30, M40, and M50. Weight losses under acid and sulphate attack were observed for each sample to check the improvements in the durability of concrete.

Substantial researches have been implemented on the performance of mortar with M Sand. Jadhav & Kulkarni (Jadhav and Kulkarni 2013) studied the effect of replacement of natural sand by M Sand in the mortar with 1:2, 1:3, and 1:6 cement to sand ratios. The authors also studied the effect of water to cement ratios of 0.5 and 0.55. Higher strength was achieved at a 50% replacement level for each cement to sand and water to cement ratio. Manjunath et al. (Manjunath, Mahadeva, and Sunandha 2018) carried out work on mortar cubes with water to cement ratios of 0.4 and 0.5 which were made with M Sand alone. The authors observed a drastic decrease in compressive strength when M Sand was fully included. Bauchkar & Chore (Bauchkar and Chore 2010) scrutinised the effects of 0%, 6%, 12%, 18%, and 24% micro fines content of M Sand on workability and workability retention properties while keeping the water to cement ratio, fly ash, and cement to sand ratio as 0.27, 30% and 1:1.26 respectively. The authors noticed decreased workability and workability retention with increased micro fines in the M Sand. More et al (More et al. 2017) inspected the effects of fully replacement of river sand with crushed sand for 1:4 and 1:6 mortars and 0.5 and 0.7 water to cement ratios. Sharp increases of 21.23% and 65.9% in strength were noticed for 1:4 and 1:6 mortars respectively comparing with control mortar.

Furthermore, He et al. (He et al. 2016), Kozul & Darwin (Kozul and Darwin 1997), Aswath (Aswath 2014), O'Flynn (O'Flynn 2000), and Wigum et al. (Wigum et al. 2009) addressed the influence of particle size and shape of M Sand on the properties of concrete and mortar based on the strength and the durability characteristics. This concept is well elucidated to an extent in the studies made by Branavan et al. (Branavan et al. 2020) and Nataraja & Priyanka (Nataraja and Priyanka 2016) concerning the flow cone tests using river sand and different types of M Sand. The authors also studied the impacts on the packing densities when fine aggregates were blended at varying levels. Mathew et al (Mathew et al. 2016) briefly related the performance of both concrete and mortar with M Sand manufacturing stages concerning the influence of particle shape, surface texture, and micro fines of M Sand. As a basis, a short review on crushing stages of parent rocks for M Sand production was done by Cepurītis (Cepurītis 2013) investigating the two most important parameters such as the number of crushing stages and the crusher types. Few studies have been executed on the functionalities of concrete and mortar contemplating the above parameters. A brief experiment was carried out by Reddy (Reddy 2012) on the suitability of M Sand in concrete and mortar by investigating the shape of M Sand and river sand. Authors identified higher compressive and flexural strengths for both 1:4 and 1:6 mortars with M Sand than river sand. The higher strength achievement was due to the complete resembling of river sand particles with M Sand. However, a marginally increasing range of 12–15% of compressive strength was observed with M Sand concrete when comparing with river sand samples.

Coarse aggregate has more influence on the strength of concrete than the fine aggregate. However, fine aggregate solely provides the strength for mortar. Therefore, replacing fine aggregates with alternatives in mortar may impact more than concrete. Furthermore, O'Flynn (O'Flynn 2000) conducted a brief study on geology, resources available, future demands for fine sand, transport impacts, and types of quarries to exhibit the future demand for M Sand. An experimental study regarding the long-term compressive strength of concrete with M Sand was carried out by Ding et al (Ding et al. 2016) with stone powder replacements of 5%, 9%, and 13% with M Sand. Long-term compressive strength was increased at the higher stone powder substitutions where 9% replacement showed the best performance. Similar research work was performed by Mingkai et al. (Mingkai et al. 2008) using stone dust blended with M Sand which ended up with low elastic modulus at the increased replacement levels of stone dust in M Sand. Another study on the durability parameters of concrete with M Sand was done by Sangoju et al. (Sangoju et al. 2017) by conducting Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), and Accelerated Curing Test (ACT). The study proved a better durability performance of concrete with M Sand when it was exposed to a chloride-induced environment than a carbonation-induced environment.

3.2. Offshore sand

Offshore sand has also become a common river sand substitute that is dredged from deep seabeds. Various studies have been implemented on selecting appropriate offshore sand, the processing after dredging and using it as an alternative fine aggregate for river sand. Nanayakkara (Nanayakkara 1999) and Dolage et al. (Dolage, Dias, and Ariyawansa 2013) have executed some case studies on finding suitable locations for dredging offshore sand and treatment for reducing the chloride levels. Authors identified that the offshore sand dredged from the location of 1 to 7 km from the shoreline at the depth of about 14 m in the Western reaches of the continental shelf close to Sri Lanka showed better performance for both normal and reinforced concrete. A brief experimental study was carried out by Dias et al. (Dias, Seneviratne, and Nanayakkara 2008) on the performance of reinforced concrete against the chloride ions in offshore sand collected between 10 m to 15 m depth lines at 5 km to 10 km off the Western Coast of Sri Lanka. From the above study, it can be identified that offshore sand with reduced chloride content (i.e. from 0.3% to 0.075%), satisfied the performance of concrete against the corrosion of reinforcement. Girish et al. (Girish, Tensing, and Priya 2015) performed a study on offshore sand as a replacement for river sand in concrete regarding the grading of fine aggregate, compressive, flexural strengths of concrete, and water absorption. Positive results with all the above-mentioned properties were achieved at 30% replacement of river sand with offshore sand.

Furthermore, Mahendran et al. (Mahendran et al. 2016) investigated the effects of 50% and 100% replacements of river sand with washed offshore sand in concrete. The selected substitutions did not improve the compressive, splitting tensile and flexural strengths of concrete than river sand. Brief research work was done by Luhur & Khandelwal (Luhar and Khandelwal 2015) on the durability of concrete with dredged sand at 50% and fully replacements by conducting acid resistance, sulphate resistance, and chloride resistance tests. M20 and M40 concrete were cast using both Ordinary Portland Cement (OPC) and Pozzolana Portland Cement (PPC). It was concluded that dredged sand performed well against the acid and sulphate attacks while low performance was noticed against the chloride exposures. Athira & Neethu (Athira and Neethu 2016) carried out a study on completely replacing river sand with combined offshore sand and M Sand. The authors noted that concrete with blended sand of 60% M Sand and 40% offshore sand achieved higher strength than control concrete. Above blended sand also improved the rate of water absorption and sorptivity than other replacement levels. Raju & Johny (Raju and Johny 2016) checked the compressive, flexural, and split tensile strengths of concrete made with dredged sand at 10%, 15%, 20%, and 25% replacement levels. The authors concluded that 15% replacement of natural sand by dredged sand showed overall better performance than other concretes.

3.3. Dune sand

Very few studies have been carried out on investigating the suitability of dune sand as a fine aggregate and some of them are mentioned here. Sanjeevan et al (Sanjeevan et al. 2006) studied the concrete and mortar properties by partially replacing quarry dust with dune sand. Results showed a marginal increase in compressive strength of concrete (i.e. 8% more than control concrete) when dune sand was substituted for quarry dust. However, the strength of mortar with dune sand highly advanced the compressive strength and satisfied the minimum requirements provided by the Sri Lankan standard. Seif (Seif 2013) scrutinised the quality of dune sand collected from Western Egypt areas by conducting an X-Ray Diffraction (XRD) test. The authors observed the dune sand collected from the particular area had abundant quartz and feldspar minerals and negligible silt and clay contents. It was also identified that the minerals presented in dune sand improved the workability of mortar to an extent that lied within an acceptable range.

3.4. Quarry dust

Quarry dust is a waste produced during the crushing of rocks in the quarries. Currently, huge problems are identified on effectively dumping the waste due to increased air pollution. To minimise this effect, researchers have started investigations to utilise this waste material in construction works. Rajapaksha & Sooriyaarachchi (Rajapaksha and Sooriyaarachchi 2009) conducted research using quarry dust to study the compressive strength variations of concrete. The authors successfully achieved a high-strength concrete when river sand was completely replaced by quarry dust. On the other hand, the authors found increased water demand at larger replacement levels. Rajput et al (Rajput et al. 2014) experimented on using quarry dust as a partial replacement for laterite soil. The combination of 40% quarry fine with 60% laterite sand manifested the improved performance of concrete concerning both fresh and hardened properties. A quick study performed by Balamurugan & Perumal (Balamurugan and Perumal 2013a) showed that 50% replacement of river sand with quarry dust improved the compressive, splitting tensile, flexural strengths of both reinforced and unreinforced concrete samples. Dhanalakshmi et al (Dhanalakshmi et al. 2018) and Khan & Chandrakar (Khan and Chandrakar 2017) have also performed studies on the partial replacements of river sand with blended quarry dust and red soil. Both studies concluded that the half-replacement level (50%) manifested the optimum performance of concrete than other substitution levels than control concrete.

3.5. Demolition wastes

The growth of construction activities brings uncertainty to eliminate the demolition wastes that arise at the construction sites. To control the above problem, researchers have started finding alternative techniques to utilise the waste in acceptable ways including using it as a river sand substitution. Considerable studies have already been executed on investigating the suitability of recycled demolition wastes in concrete and mortar. Levy & Helene (Levy and Helene 2004) investigated the water absorption, total pore, and carbonation properties of concrete with 0%, 20%, 50%, and 100% replacements of river sand with demolition wastes. Similar workability and compressive strength were noticed for all concrete grades while minimum water absorption and less total pore volume were observed with 20% replacement. However, carbonation depth was decreased when the replacements were 20% and 50%. Rao et al. (Rao, Jha, and Misra 2007) conducted a case study on introducing demolition wastes in concrete by briefly analysing the construction and demolition waste management in different countries. Chan & Poon (Chan and Poon 2006) checked the applicability of using demolition waste as fine aggregate in concrete paving blocks at 0% to 100% replacements with 25% increments. Compressive strengths of blocks were initially increased up to 50% replacement and then declined beyond that. Low water absorption levels were observed at small replacements (i.e. for 0% and 25% replacement levels) and maximum unpolished slip resistance was noticed with 50% replacement. Neno et al. (Neno, Brito, and Veiga 2014) carried out a brief investigation using fine recycled concrete aggregate for mortar by analysing the cracking susceptibility, water vapour permeability, adhesive strength, modulus of elasticity, water retentivity, and dimensional stability. Positive results were concluded at 20% replacement of river sand regarding each analysed parameter comparing control concrete.

Lima & Leite (Lima and Leite 2012) implemented a study on drying shrinkage of mortar by repacing 50% of natural fine aggregate with construction and demolition waste (which consists of 55% mortar waste, 26% ceramic waste, and 16% concrete waste). Compressive strengths were reduced, while density, absorption, drying shrinkage, and porosity were increased at higher substitution levels. Baali et al. (Baali, Naceri, and Said 2007) studied the properties of mortars made with crushed waste bricks as alternative fine aggregate replacing 25%, 50%, 75%, and 100% of dune sand. Workability and dry density of fresh mortar were analysed from which it was noticed that the inclusion of crushed brick waste considerably decreased the workability and dry density. Ledesma et al. (Ledesma et al. 2014) analysed both fresh and hardened properties of mortar with demolition wastes as river sand alternative. The authors identified the decreased trends with fresh properties such as wet density, workability, workable life, and entrained air with the replacements. Also, hardened properties such as dry density, strengths, shrinkage, water absorption, and vapour permeability were declined with increased replacement levels. Aboutaleb et al (Aboutaleb et al. 2017) executed a study on self-compacting mortar with crushed refractory bricks as a river sand replacement by analysing the fluidity, dry density, compressive strength, and flexural strength. This study also concluded the decreased mortar properties at increased replacement levels. Darshika & Udamulla (Darshika and Udamulla 2016) analysed the strength, water absorption, and slip resistance properties of concrete with replacements of 25%, 50%, 75%, and 100% natural fine aggregate by crushed demolition wastes. Increased slip resistance was reported up to 50% replacement. Concrete strength and water absorption values were increased at higher replacement levels of crushed demolition wastes.

3.6. Marble powder

A huge problem has arisen on efficiently dumping the waste of marble powder by the marble industries. From the several research studies, it can be identified that one of the main solutions undertaken by the industries is to utilise this waste as a construction material. This section describes how the authors effectively used marble powder in the construction activities. Binici (Binici 2007) studied the effects of replacing natural sand with crushed ceramic in concrete. The author found that the addition of crushed ceramic improved the overall workability, compressive strength, and chloride penetration depth of all concrete grades. Minimum and maximum abrasion resistance were observed with control concrete and concrete with 60% crushed ceramic. Ulubeyili & Artir (Ulubeyili and Artir 2015) investigated the applicability of 25%, 50%, 75%, and 100% replacements of natural fine aggregate, coarse aggregate, and both fine and coarse aggregates with waste marble aggregates. Fluctuating trends were noted with fresh density and air content of all concrete grades. Workability was decreased with increased replacement levels and both fine and coarse aggregate replacements increased the overall compressive strength. Raju & Johny (Raju and Johny 2016) completed a study on testing the properties of concrete using marble powder replacing 5%, 10%, and 15% of natural fine sand. A marginal increase in compressive and splitting tensile strengths was observed at 10% replacement where all other replacements did not reveal considerable changes. Hebhoub et al. (Hebhoub et al. 2011) studied the feasibility of crushed marble sand in concrete replacing natural river sand. Samples were soaked in water for 2, 14, 28, and 90 days for the determinations of compressive and flexural strengths. Results revealed that the inclusion of waste marble sand considerably increased the strengths. Concrete with 25%, 50%, and 75% replacement levels showed significant improvements with both compressive and flexural strengths.

3.7. Sea sand

Significant researches have been carried out on the applicability of sea sand in concrete and mortar. Sea sand and offshore sand are sea-based resources that differ according to the place of extraction. Offshore sand is dredged from deep sea beds where sea sand is extracted from inshore areas. These extraction processes could significantly influence the presence of chloride, shell, and salt contents due to the variation of contact time with water.

Huiguang et al (Huiguang et al. 2011) explored the chloride ion penetration in concrete with different sand inclusions such as sea sand alone, sea sand with river sand, desalinated sea sand with river sand with varying water to cement ratios, and curing times. A minimum chloride ion diffusion coefficient of 2.45 was observed with desalination sea sand concrete with a water to cement ratio of 0.5 and a curing time of 180 days. A maximum coefficient of 4.75 was observed with river sand concrete with the water to cement ratio of 0.55 and at 80 days curing. The study made by Bhuvaneswari et al. (Bhuvaneswari et al. 2018) proved the maximum compressive and split tensile strengths at 20% and 30% replacements of river sand with sea sand in concrete. Sidhardhan et al. (Sidhardhan, Sheela, and Meylin 2017) analysed the compressive and bond strengths of mortar with partial replacements of river sand by sea sand. The authors probed an optimum replacement level of 20% which showed 0.5% increased strength. Subashini et al. (Subashini et al. 2016) checked the compressive strength of both concrete and mortar prepared with sea sand free of salt. A special experimental setup was proposed to remove the salt content in sea sand before the application. The authors identified better performances of concrete and mortar when river sand was fully replaced with washed sea sand. Ratnayake et al. (Ratnayake et al. 2014) evaluated the potential of sea sand collected at different levels in stockpiles for use in concrete analysing crushing strength, chloride content, mineralogy, and texture characteristics. The authors concluded that sea sand lowered the compressive strength (around 10% less than river sand concrete) and reduced hardening speed comparing with control concrete.

Mahendran et al. (Mahendran et al. 2016) executed an investigation on substituting sea sand in concrete. The results revealed reduced compressive, split tensile and flexural strengths with sea sand inclusion. Ammari et al. (Ammari et al. 2017) performed research on concrete and mortar made with blended sand (i.e. 1:1 limestone sand to sea sand) with 29%, 14%, and 4% replacements of seashells. Increased compressive strengths for both concrete and mortar were observed at lower replacements with seashells. Flexural strength showed a direct proportionality with increasing sea shell replacements. Moreover, Sun et al. (Sun et al. 2020) implemented a study on the effects of multi-substance film on mechanical and durability properties, thermal curing, and freeze-thaw resistance of mortar made with washed sea sand, unwashed sea sand, and river sand. Higher compressive and flexural strengths of concrete were noticed with washed sea sand than river sand. Samples made with washed and unwashed sea sand attained low mass and strength losses after the freeze-thaw cycles. Benslafa et al. (Benslafa et al. 2015) researched investigating the durability of mortar with sea sand examining compressive strength and acid attacks in HCl and H_2SO_4 solutions. Results manifested that the optimum substitution of 5% with sea sand enhanced higher compressive strength and lower weight losses in both acid solutions, which showed the high durability of mortar. Schutter & Poppe (Schutter and Poppe 2004) quantified the water demand of mortar with river sand, sea sand, quarry sand, and artificially composed sand correlating fineness modulus, relative specific surface, and fictitious weight of sand.

3.8. Blast furnace slag

Granulated blast-furnace slag or blast furnace slag is also a recyclable waste product outcome during furnace operations. Similar to quarry dust, environmentalists face various problems with effectively detach the blast furnace slag from the industries as a result of air pollution observed with open dumping. Few studies were followed up on using blast furnace slag in construction works and some of the referred studies are reported here. Rashad (Rashad 2016) reviewed the previous studies conducted using granulated blast-furnace slag and copper slag as partial or complete replacements for river sand. The above review was carried out analysing various principle parameters of concrete and mortar such as workability, water absorption, chloride ion penetration, shrinkage, compressive strength, bleeding. The author found both positive impacts and contradictory results in different studies when blast furnace slag was used as a substitution for river sand. Manso et al. (Manso et al. 2011) studied the durability parameters such as density, porosity, microstructure, and permeability of masonry mortars constituting ladle furnace slag with plasticisers. All the above durability parameters were advanced when the mixes contained only ladle furnace slag and plasticisers. López et al. (López, Pineda, and Gutiérreza 2015) also evaluated the durability and mechanical properties of cement mortar with blast furnace slag analysing the expansion of mortar bars and strength of mortar cubes. However, the authors noticed some negative durability and strength results when river sand was replaced with blast furnace slag irrespective of the replacement ratio.

Furthermore, Du et al. (Du et al. 2018) proved the applicability of alkali-activated slag in cementing composite for deepwater oil wells. The resin content in composite was replaced with 80%, 90%, 95%, and 100% of slag where the authors found that the increasing slag content considerably increased the compressive strength and improved initial and final setting times. In addition, the study executed by Du et al. (Du et al. 2019) incorporated superfine ground-granulated blast furnace slag into a cementing fluid at a ratio of 0.1:1 with an activator to check the applicability for using in deep-water weakly consolidated oil and gas well. The authors distinctly identified that the proposed cementing fluid was effective for oil well cement as well as a formation curing agent from the compressive strength and thickening time of cementing fluid.

3.9. Recycled glass and plastic wastes

Iucolano et al (Iucolano et al. 2013) investigated the applicability of recycled plastic waste in mortar by checking the physical, mechanical and thermal properties. Higher replacement levels showed increased porosity in the mortar specimens due to the microstructural behaviour. Due to this, both compressive and flexural strengths were reduced than river sand mortar. However, the authors observed the mortar made with plastic waste showed 50% lower thermal conductivity than the control mortar. Hui & Sun (Hui and Sun 2011) implemented a study on the properties of mortar with Cathode Ray Tube (CRT) glass waste, fly ash, and silica fume. Samples with the full inclusion of CRT waste considerably increased the slump flow, drying shrinkage, compressive strength, flexural strength, and resistance to alkali-silica reactivity. Inclusions of CRT waste and fly ash or silica fume effectively reduced the expansion of mortar. Safi et al. (Safi et al. 2013) investigated the porosity, water absorption, bulk density, sound velocity, and mini-slump of self-compacting mortars with plastic waste as a replacement for river sand. Up to 50% replacement showed acceptable fluidity and compressive strengths. On the other hand, the porosity, water absorption, and sound velocity of alternative mortars were reduced than river sand samples regardless of the replacement levels.

4. Merits and demerits of different alternatives

Physical behaviours such as particle shape and surface texture of fine aggregates greatly influence the mechanical and durability properties of concrete and mortar (He et al. 2016). The comparison of physical characteristics of the most used fine aggregate types such as rock-based and sea-based sand types are reported in this section. Rock-based sand includes M Sand/crushed sand and quarry dust where sea-based sand includes offshore sand and sea sand. River sand has round and smooth surface particles that help to make good workable mixes (Kwan 2000; Mia, Salman, and Ahmed 2017; Sun et al. 2020; He et al. 2016). Especially, river sand plays a crucial role in masonry works with its physical characteristics (Sun et al. 2020; He et al. 2016). The cheapest alternative to river sand is M Sand which is produced from high-grade rocks to desired size range and grade through several crushing stages (Manguriu et al. 2013; Jayawardena and Dissanayake 2008; Elavenil and Vijaya 2013). The physical characteristics of rock-based sand types and sea-based sand types can be easily compared with river sand through different methods available. One of the basic sources used to study the above characteristics is the digital images produced through microscopic analysis. Figure 1 manifests the microscopic views of river sand, M Sand, and offshore sand (Nanayakkara 1999). A clear comparison can be made where particle angularity and rougher surface texture are increased in the order of offshore sand < river sand < M Sand.

The second method used by the authors is the scanning electron microscopy (SEM) method. From here, several SEM images of river sand, M Sand, sea sand, and pit sand used by different studies are included to have a clear background on the physical characteristics. Figure 2 covers the SEM images of

Figure 1. Particle images (size range 1.14–2.28 mm) – (a) river sand; (b) M Sand; (c) offshore sand (Nanayakkara 1999).

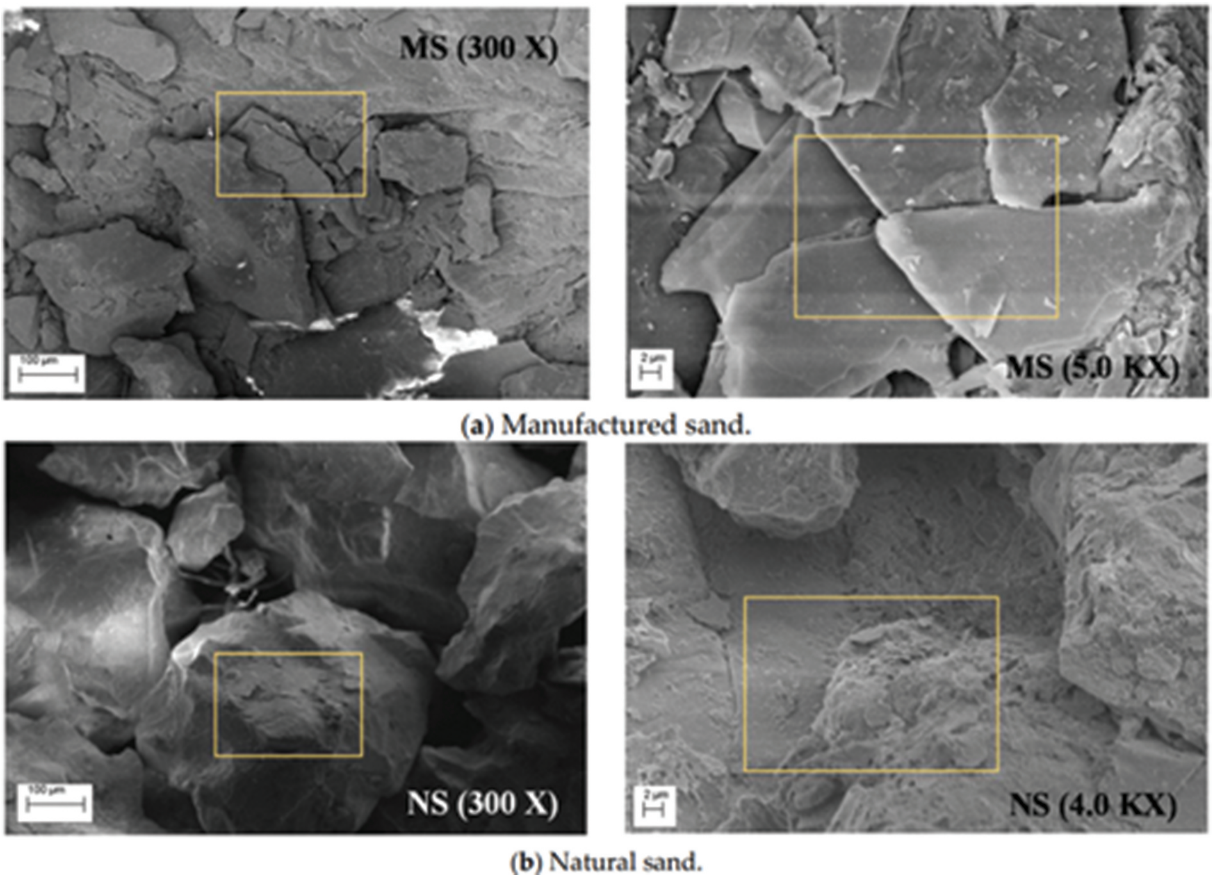


Figure 2. Particle angularity comparison of M Sand and natural sand (An et al. 2017).

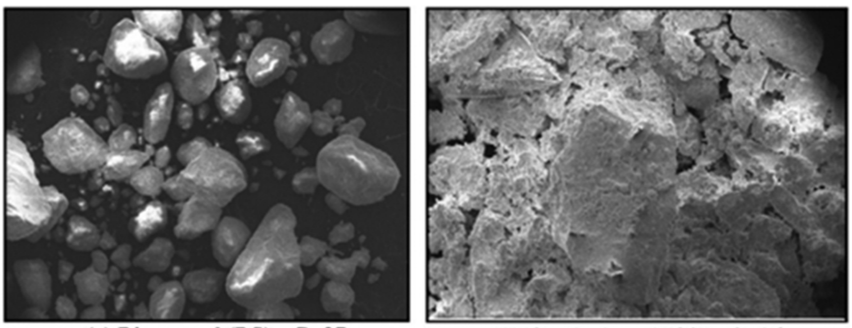
river sand and M Sand adopted from the study (An et al. 2017) for analysing the angularity characteristics. Box references reveal the study areas of M Sand and river sand where the particle edges were distinctly observed. It can also be identified that river sand particles show lower angularity/rounded than M Sand particles. Due to the higher angularity particles, a better particle-interlocking pattern can be achieved with M Sand while less angularity river sand particles can create lower inter-particle shear strength. Chitlange & Pajgade (Chitlange and Pajgade 2010) describes the benefits of M Sand through higher bonding characteristics between cement paste and sand particles based on the above merits and demerits regarding particle angularity characteristics.

A similar study was carried out by Bederina et al. (Bederina et al. 2013) on the effects of roundness of river sand and crushed sand particles on mechanical properties of mortar. Figure 3 includes the SEM images used by the authors showing the variation of roundness of river sand and crushed sand particles. These observations satisfy the conclusions driven by the study (An et al. 2017) where river sand particles showed higher roundness than crushed sand. Angular-edged particles can improve the mechanical properties of both concrete and mortar. Therefore, construction industries have started utilising M Sand/crushed sand to produce high-strength concrete and mortar. However, reduced workability (flowability) of mixes was noticed in the studies due to higher elongated/angular particles (Joe et al. 2013; Bederina et al. 2013).

Shreyas (Shreyas 2017) disclosed that the efficient production process of M Sand ceases any impurities or wastages present which are the primary constituents that influence both mechanical and durability properties of concrete and mortar. Process attrition of M Sand through vertical shaft impactors, washing, and screening systems makes sand particles good enough to fall within the required zone for construction activities (Elavenil and Vijaya 2013; Shreyas 2017). Not only the particle shape but the surface texture of particles also greatly controls the properties of concrete and mortar. Ali et al. (Ali et al., 2015) investigated the surface textures of river sand, pit sand, and two types of M Sand used for their study. Figure 4 shows the collection of SEM images of surface characteristics obtained by the authors. Generally, river sand and pit sand are naturally available and processed through years of attrition. Therefore, a smooth surface texture can be noticed with both naturally available sand types which can be due to the attrition of surfaces. When comparing with river sand and pit sand, harder/rougher surface texture can be observed with both M Sand types. This behaviour can also be discerned in Figure 2. M Sand is purposely made fine sand from parent rocks through several crushing stages. Therefore, the degree of attrition of M Sand is considerably lower than river sand and pit sand which enables the particles with a rougher surface.

The work carried out by Verma (Verma 2015) revealed the correlation between the surface characteristics of river sand and sea sand. The corresponding backscattered images of the above study are mentioned in Figure 5. The author identified that river sand reflected the electrons in only one phase which highlights the increased smoothness of particle surface. The single-phase reflection can be observed with the unique colour formation in the images. The second phase of reflection can be noted with sea sand particle images. This phase concludes a higher roughness of sea sand particles than river sand particles. Therefore, from the past studies mentioned above, river sand, sea sand, and pit sand particles manifest similar behaviours regarding smoother surface texture and increased roundness than M Sand particles. Those contrast characteristics may give both advantages and disadvantages to concrete and mortar when they are used as fine aggregates.

Irrespective of the above visual observations, few researchers numerically investigated and compared the angularity and surface roughness of different particles. For example, a quantitative study was carried out on the effect of blended sand types by Branavan et al. (Branavan et al. 2020) with river sand, offshore sand, and M Sand from two different rock types. The



(a) River sand (RS) - G=37 (b) Crushed sand (CS) - G=36

Figure 3. Comparison of roundness of river sand and crushed sand (Bederina et al. 2013).

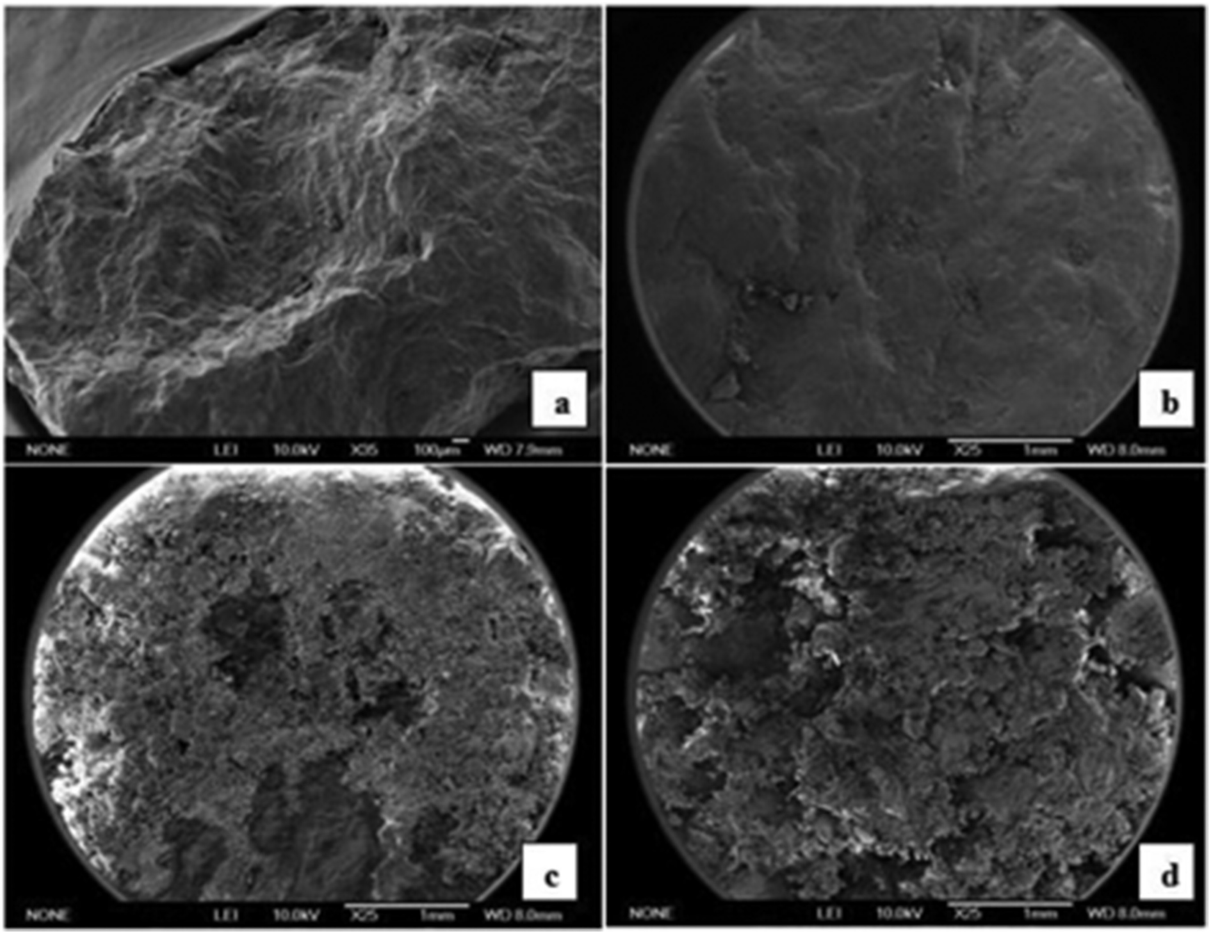


Figure 4. Surface textures at 25× magnification – (a) river sand; (b) pit sand; (c & d) M Sand types (Ali et al. 2015).

study was carried out by comparing the characteristics of river sand and blended sand types with M Sand and offshore sand at 25%, 50%, 75%, and 100% replacement levels. The authors proposed a linear model for determining the total specific surface index (f_X) concerning the surface index (f_I) and shape index (f_A) characteristics as given in Equation 1.

$$f_X = 2.575 - (0.576 \times f_A) - (0.274 \times f_I) \quad (1)$$

The results revealed that river sand and offshore sand showed higher total surface index values of 1.084 and 1.146 respectively. This was due to the roundness of particles which reduced the pores and thus increases the total specific surface. The index values of both M Sand types were concluded as 0.872 and 0.946. All blended sands showed the index values ranged between the maximum and minimum values. These index values highlight the shape and surface texture properties of different river sand alternatives. The identification of the total specific surface of a fine aggregate is mandatory, as it can reflect the total water requirement for concrete and mortar mixes to achieve required workability. Fine aggregate with a higher specific surface requires more water to have a workable mix. Hence, river sand and offshore sand may consume more water than M Sand. A similar test method was followed up by Janoo (Janoo 1998) for investigating the roundness and roughness of crushed gravel and crushed stones. The authors observed that the roundness and roughness of crushed gravel were in the range of 60.9–87.9 and 1.004–1.058 respectively where the ranges observed for crushed stones are 54.6–80.1 and 1.03–1.06 respectively. Similar results were also observed in the work carried out by Beixing et al. (Beixing, Guoju, and Mingkai 2011) where the authors found higher roughness values for the M Sand samples (in the range of 15.8–18.7) than the river sand samples (in the range of 13.1–14.6).

Another most important quantitative analysis identified from the literature is the image processing technique. Here, the researchers incorporated micro-scale images of representative sand samples to determine the angularity and surface roughness. Different authors used different techniques to numerically measure the roundness and roughness of particles as shown in Figure 6. Prudencio et al (Prudencio et al. 2013) observed larger horizontal projection areas with more angularity/cubical particles produced from basalt and granite rocks as provided in Figure 6(a). A different method was followed up by He et al. (He et al. 2016) where the authors measured and compared the roundness of particles between the ordinary method and by introducing convex hull bounding the particle (see Figure 6(b)). However, as shown in

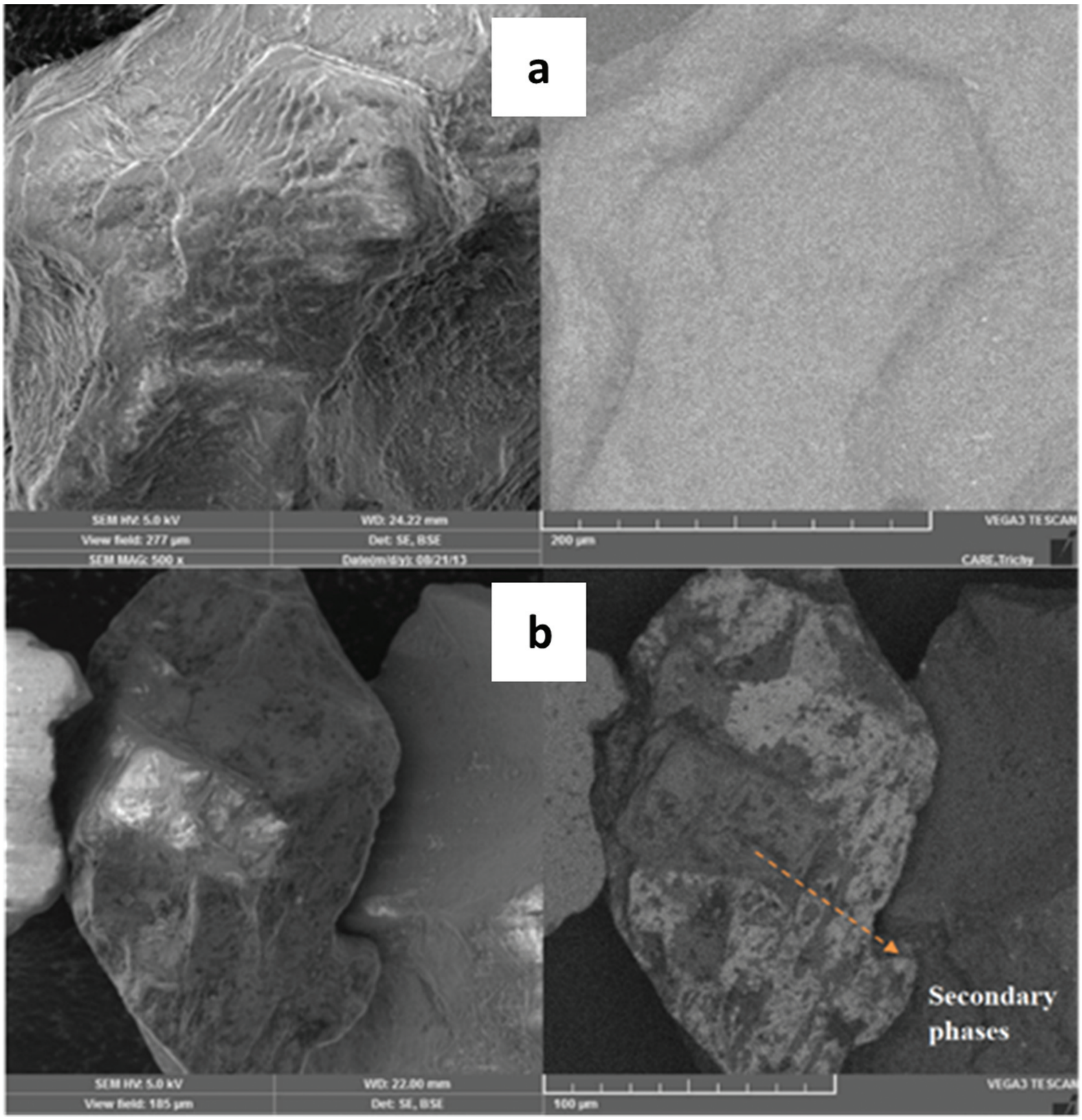


Figure 5. Comparison of surface grains (a) river sand; (b) sea sand (Verma 2015).

Figure 7, contradictory outcomes were observed in the study where both methods revealed more circularity and elongation values for river sand than crushed sand.

Furthermore, few more researchers also reported the advantages and disadvantages of different alternatives. Based on the pilot survey, Dolage et al. (Dolage, Dias, and Ariyawansa 2013) described the applicability of offshore sand for use as a river sand substitute in reinforced concrete. According to the statements provided by Dias et al. (Dias, Seneviratne, and Nanayakkara 2008), it can be concluded that offshore sand extracted below 15 m of the ocean depth will not affect the coastal sediment budget. Generally, improved shape and texture characteristics of offshore sand particles help to provide better workable and good finish able concrete and mortar than river sand (Dolage, Dias, and Ariyawansa 2013; Subashini et al. 2016). Offshore sand may also give negative effects on concrete and mortar. The chloride content in offshore sand acts a vital role in corrosion of reinforcements, efflorescence, and reduction in load-carrying capacity (Girish, Tensing, and Priya 2015). To decrease this effect, offshore sand must be exposed to a considerable period of washing to bring the chloride content below the limits (Girish, Tensing, and Priya 2015). Moreover, shell content in offshore sand beyond the limit declines the fresh properties of mixes (Athira and Neethu 2016). Offshore sand particles could also impact the packing density, water absorption, specific gravity, void content, and cohesiveness of concrete and mortar (Branavan et al. 2020; Athira and Neethu 2016).

In addition, gradation and microfine content also influence the mechanical and durability properties of concrete and mortar. Particle size distribution and micro fines content of river sand and offshore sand cannot be controlled as they are naturally available and directly used in construction activities. Gradation

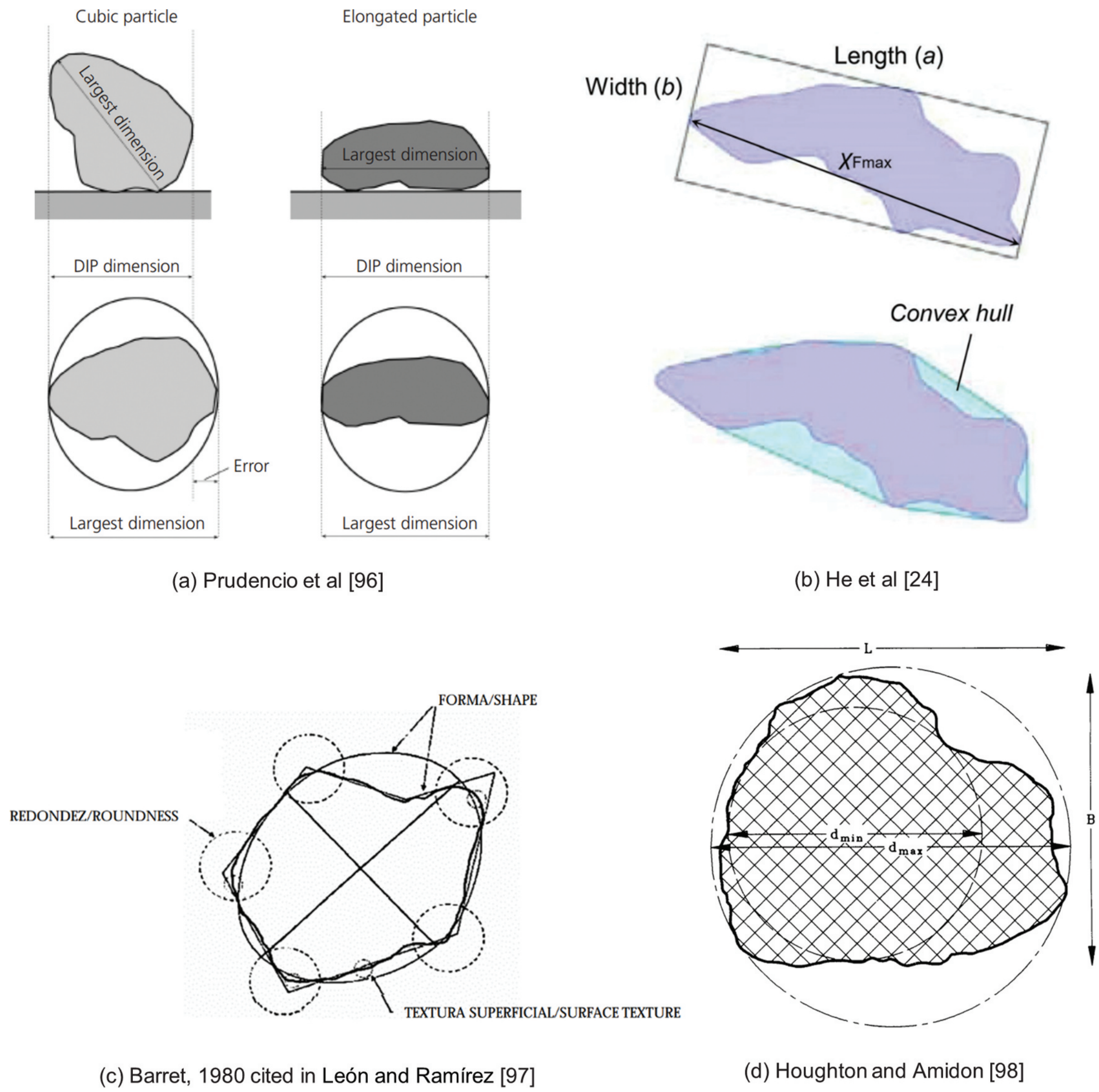


Figure 6. Image processing techniques for measuring particle angularity and roughness suggested by different studies.

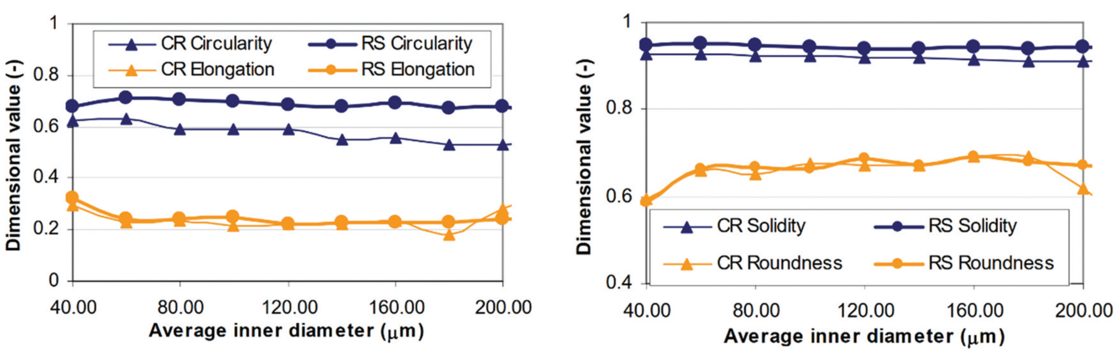


Figure 7. Comparison of angularity and elongation of river sand and crushed sand, ordinary method (left); convex hull bounding method (right) (He et al. 2016).

and microfine content of M Sand can be controlled as it is produced through several crushing stages (O'Flynn 2000; Cepurītis 2013). Gradation and micro fines content in fine aggregates greatly direct the water retentivity, bleeding, and permeability of the cement-based which are considered as the important properties of fresh concrete and mortar (Manasseh 2010). Some studies concluded that river sand always manifests better particle size distribution and lesser microfine content than the alternatives which results in lower void content, less packing density, less specific gravity, and higher bleeding (Branavan et al. 2020). However, M Sand has a considerable amount of microfine content that benefits concrete and mortar by lowering bleeding, permeability and increasing the water retentivity (Jadhav and Kulkarni 2013; Branavan et al. 2020). Important research made by Chow et al. (Chow, Yip, and Kwan 2013) showed the levels of the micro fines observed in different fine aggregates such as river sand with 0.5%, crushed rock fine with 8.6%, and M Sand with 2.1%. The authors also concluded that increasing micro fines significantly reduced the water, cement, and superplasticizer demand for concrete.

5. Validating concrete and mortar properties with optimum replacement levels

This section proves the validity of the merits and demerits of alternatives concerning the optimum replacement levels identified in the studies. The fresh, hardened, and durability properties of concrete and mortar were evaluated concerning the optimum replacement levels. Various parameters of fine aggregate may affect the properties of concrete and mortar. Here, two terms are used for sorting the literature and comparing the results as mentioned in Table 1. Simple bar illustrations are used for determining the variations of optimum replacement levels achieved by the previous studies for each property of concrete and mortar. Workability, water retentivity, compressive strength, indirect tensile strength, flexural strength, and shrinkage of concrete and mortar are considered here to investigate the optimum replacement levels achieved by the studies with different alternatives.

Each graph is plotted with the outcomes (i.e. positive, or negative) against the optimum replacement level suggested by the studies. Each bar in the figures represents a particular study on the property and the corresponding reference is provided within square brackets for each bar. Furthermore, a short review on durability properties also is reported at the end.

5.1. Fresh properties

5.1.1. Workability

Figure 8 and Figure 9 demonstrate the studies executed on investigating the workability of concrete and mortar with river sand alternatives respectively. From Figure 8, it can be identified that considerable studies have been executed on M Sand as a river sand substitution. Among them, more studies concluded negative trends with the workability of M Sand concrete. Based on the number of studies, more studies proved an optimum replacement range of 20–60% of river sand by M Sand in concrete. Among the studies that arrived with improved workability of concrete, most of them recommended a higher substitution range of 80–100%. Higher replacements of M Sand enhance considerable micro fines in the mix which can advance the workability due to the high rolling effect between sand particles and cement paste (Manasseh 2010). When comparing both positive and negative situations, they create a contradictory idea on the workability of concrete. However, a clear background can be observed when river sand is replaced with offshore sand, quarry dust, and sea sand in concrete, hence the studies with these alternatives arrived with only positive or negative outcomes.

When offshore sand was used as a river sand substitute, more studies proved an optimum possible replacement range of 40–60%. This makes an understandable conclusion with the workability of concrete with offshore sand substitution. A negative variation can be noticed with the studies made on quarry dust in concrete. The workability of concrete with quarry dust substitution does not provide an exact optimum replacement range as the results are much deviating. However, two studies proved the improvements in workability when river sand was fully replaced with quarry dust. Few studies evinced an optimum substitution range of 20–40% with sea sand in concrete which showed improved performances than control concrete. These results can be correlated with the trend of offshore sand as both graphs are attained with only positive outcomes. Hence, it can be concluded that when offshore sand and sea sand are used with the above-mentioned optimum levels, the workability of concrete can be advanced than river sand concrete. Special considerations should be made when M Sand and quarry dust are used in concrete which lessened the workability than concrete with river sand. M Sand and quarry dust are crushed fine products and the characteristics of the particles are completely different from offshore sand and sea sand (Shanmugapriya, Uma, and Meiraj 2014; Girish, Tensing, and Priya 2015). The physical properties of M Sand and quarry dust may resist the ball bearing action of sand particles and cement paste which ultimately results in reduced workability (Ingale et al. 2016; Rajput et al. 2014; Manasseh 2010).

Table 1. Abbreviations for analysing results.

Abbreviation	Expanded form	Results deviated from control mix*	Remarks on replacement level	Colour code
P.O	Positive outcome	Properties improved than control mix	Optimum replacing level among all positive replacements	
N.O	Negative outcome	Properties not improved than control mix	Optimum replacing level among all negative replacements	

*Control mix: Concrete and mortar incorporated river sand alone

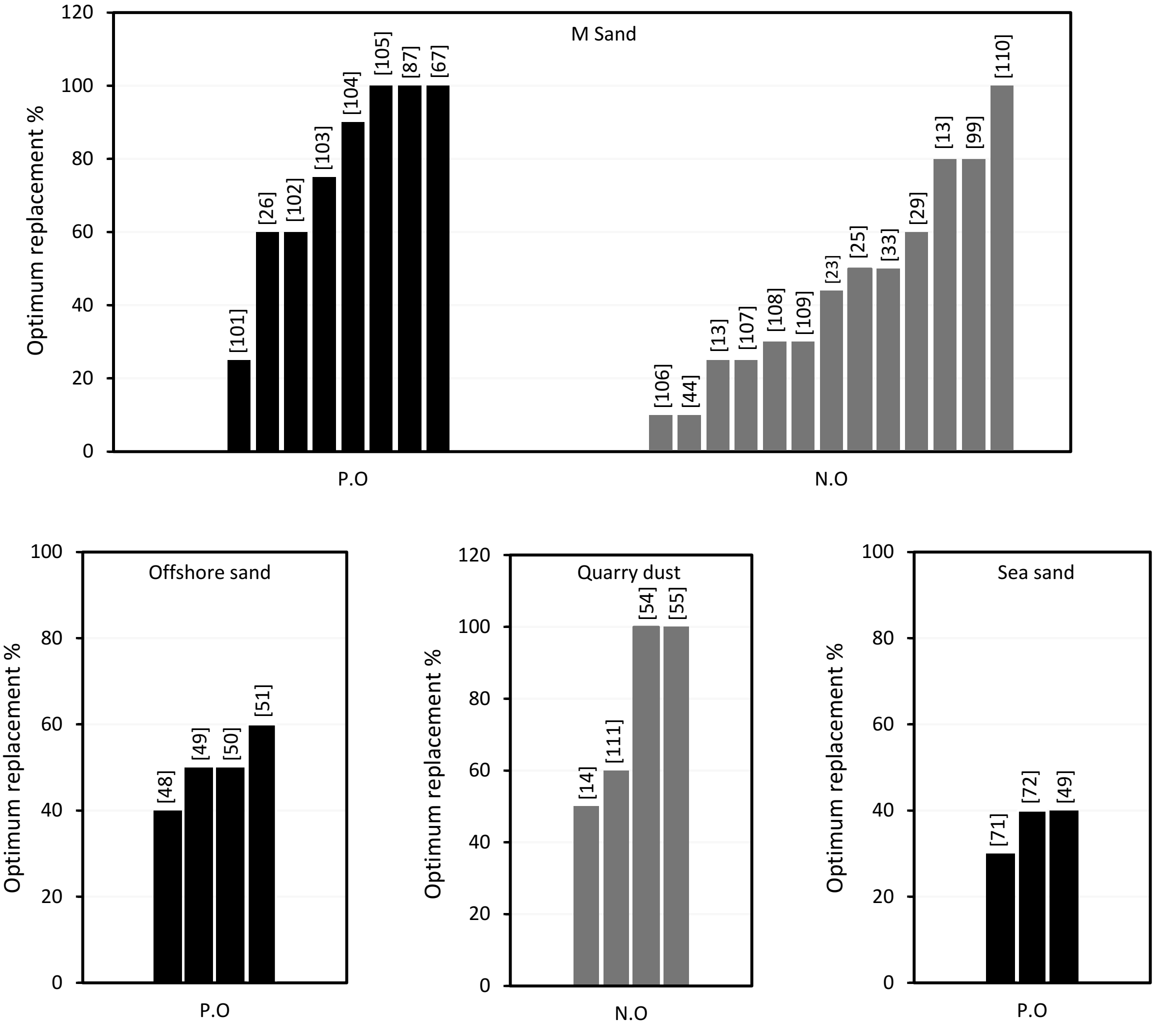


Figure 8. Effects on workability of concrete with river sand alternatives.

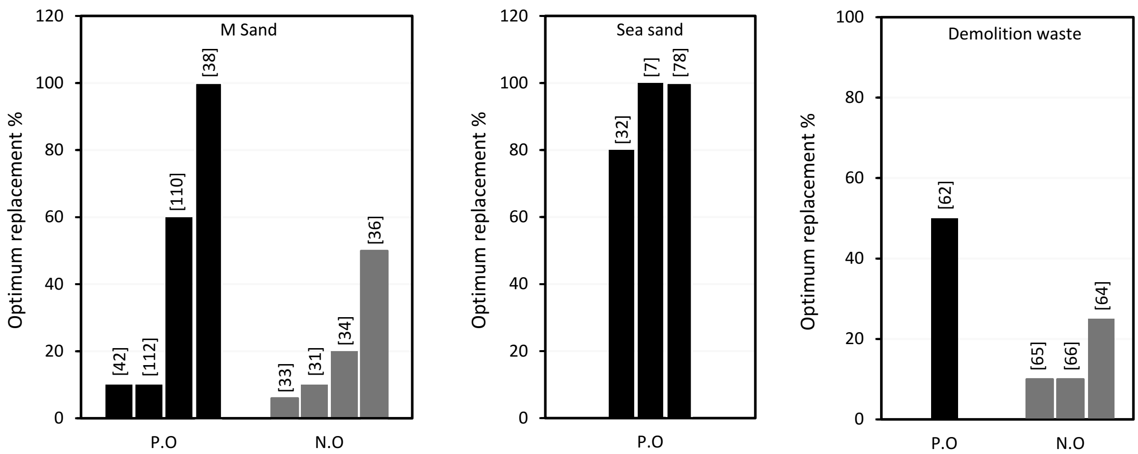


Figure 9. Effects on workability of mortar with river sand alternatives.

Very few studies have been carried out on the workability of mortar with river sand alternatives which are shown in Figure 9. Considering the studies with M Sand, the same trend can be noted as M Sand concrete. Results with M Sand mortar controvert to an optimum replacement range where studies showed both positive and negative outcomes. It can be observed that sea sand revealed positive outcomes with the workability of mortar where most studies fell within the optimum replacement range of 80–100%. Studies with demolition wastes also came up with both positive and negative outcomes. However, most of the studies revealed negative conclusions with the workability of mortar with an optimum replacement range of 0–40%.

5.1.2. Water retentivity

Another important fresh property of mortar is water retention. In general, to achieve the requirements, fresh mortar should resist the water available in the mix against external suction (Neno, Brito, and Veiga 2014; Bajad and Sakhare 2018; Martínez et al. 2016). When a mortar is freshly applied, the water content in the mix can be absorbed by the bricks/blocks/concrete surfaces (Bajad and Sakhare 2018). The constituents of mortar play a major role in resisting the water against the suction. Therefore, it is very important to analyse the water retentivity of mortars made with different alternatives. Very few studies have been conducted so far on the water retentivity of mortar with different alternatives and the referred studies are illustrated in Figure 10. Bajad & Sakhare (Bajad and Sakhare 2018) proved that an optimum replacement of 100% river sand with M Sand improved the water retention ability of mortar. A few more studies using demolition waste have manifested positive outcomes when the optimum replacement was 20%.

5.2. Mechanical properties

Some of the most important mechanical properties of concrete and mortar with the effects of using different river sand alternatives are reported here. The mechanical properties of both concrete and mortar could indeed be affected by various properties of the constituents in the mixes (Manguriu et al. 2013; Kozul and Darwin 1997; Branavan et al. 2020). For example, the fineness and grade of cement, physical properties of sand, the behaviour of coarse aggregates, curing period may significantly affect the mechanical performance of the cement-based mixes. However, this section only deals with the effects of river sand substitutions.

5.2.1. Compressive strength

From the concise literature review, it can be observed that all the studies executed experiments on investigating the compressive strength of concrete or mortar. Figure 11 illustrates the influence of alternatives on the compressive strength of concrete. The optimum replacement level of each reference is taken into account concerning the strength achieved after 28 days of curing. When considering the studies with M Sand, above 90% of them proved positive outcomes with the replacements. with an optimum substitution range of 40–80%. Furthermore, considerable studies showed the possibility of full replacement of river sand with M Sand. Most of the studies using quarry dust also manifested positive effects with the compressive strength of concrete at an optimum replacement range of 40–80%. In contrast, more than 50% of the studies with offshore sand and sea sand as a substitution to river sand in concrete arrived with negative outcomes with the compressive strength. Results verified that even the small replacements of river sand with offshore sand (i.e. 20–40% optimum replacement range) considerably reduced the compressive strength than control concrete.

Figure 12 shows the trends of the optimum levels of replacing river sand with M Sand, sea sand, and demolition waste on compressive strength of mortar. Here also, most studies showed positive effects when using M Sand. It is delightful to notice that more studies proved the possibility of an optimum substitution level of 100% river sand with M Sand which improved the compressive strength. A confident optimum replacement range cannot be obtained from the results with sea sand as the number of studies carried out on this concept is insufficient. However, the study made by Sun et al (Sun et al. 2020) only itself evinced the positive effect of fully replacement of river sand with

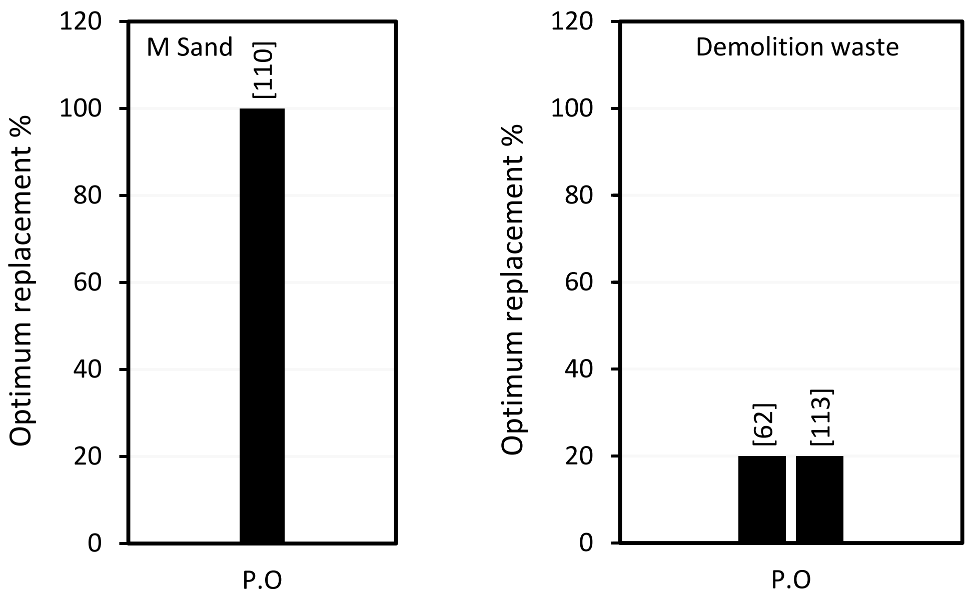


Figure 10. Effects on water retentivity of mortar with river sand alternatives.

sea sand on compressive strength of mortar. The number of research works implemented on replacing river sand with demolition waste in concrete and mortar is lower than other alternatives. Nevertheless, most of the reviewed studies attested negative outcomes with the compressive strength of mortar when demolition wastes were used as a substitution for river sand. Most of the studies revealed an optimum substitution range of 20–60% with demolition waste.

Some studies elucidated additional information regarding the compressive strength of concrete and mortar with different substitutions which are also reported here. The study carried out by Sanjeevan et al (Sanjeevan et al. 2006) on using dune sand and offshore sand concrete and mortar mixes revealed that 50% dune sand content showed higher compressive strength at 3, 7, and 28 days of curing. Furthermore, the study carried out by Ding et al. (Ding et al. 2016) predicted a comprehensive model for forecasting the long-term compressive strength of M Sand concrete with compressive strength ranges from 20 MPa to 70 MPa as mentioned in Equation 2 (Here, $f_{cu,t}$: compressive strength at t days, f_{ce}: compressive strength of cement at 28 days, m_w/m_c: water to cement ratio, ρ_c: unit weight of concrete) which can meet the requirement of engineering applications.

$$f_{cu,t} = 5.08 f_{ce}\left(clg\left(\frac{t}{28}\right)+1\right)\left(1+\frac{0.001\rho_c m_w}{m_c}\right)^{-1.89} \tag{2}$$

Pilegis et al (Pilegis, Gardner, and Lark 2016) carried out an appreciable work on the investigation of fully replacing river sand with M Sand produced from basalt, granite, limestone, and gritstone rocks. The authors also changed the micro fines content in fine aggregates and two types of mixes were prepared such as slump controlled mix and water to cement ratio controlled mix. River sand achieved the highest compressive strength at lower water to cement ratio of 0.48 while the lowest compressive strength was observed with basalt rock sand at 0.67 water to cement ratio. However, better compressive strength at 0.55 water to cement ratio was noticed with limestone crushed sand. When comparing the water to cement ratio controlled mixes, all the crushed sand types showed better compressive strengths than natural sand mix.

5.2.2. Indirect tensile strength

Based on the review, it can be identified that a considerable number of studies are available on analysing the tensile strength of concrete, but none of the studies analysed the tensile strength of mortar. Figure 13

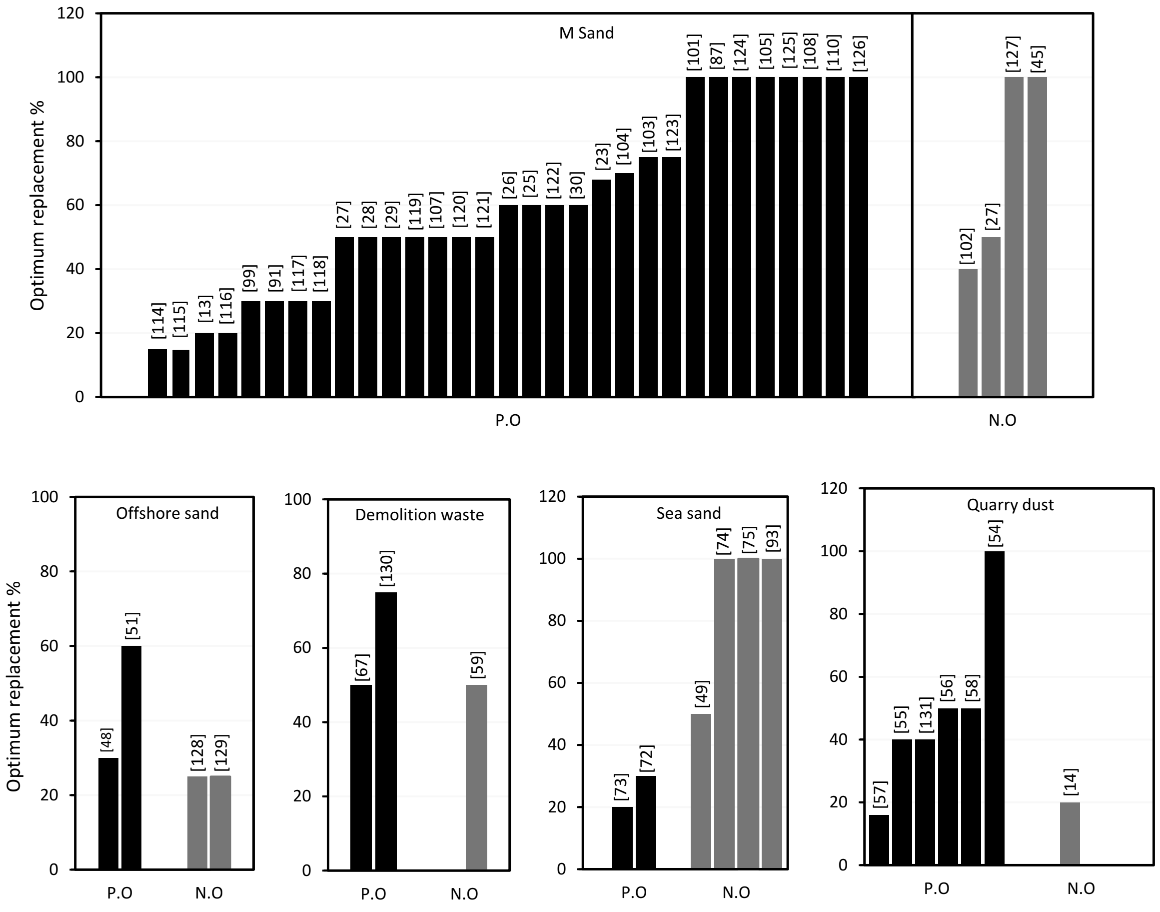


Figure 11. Effects on compressive strength of concrete with river sand alternatives.

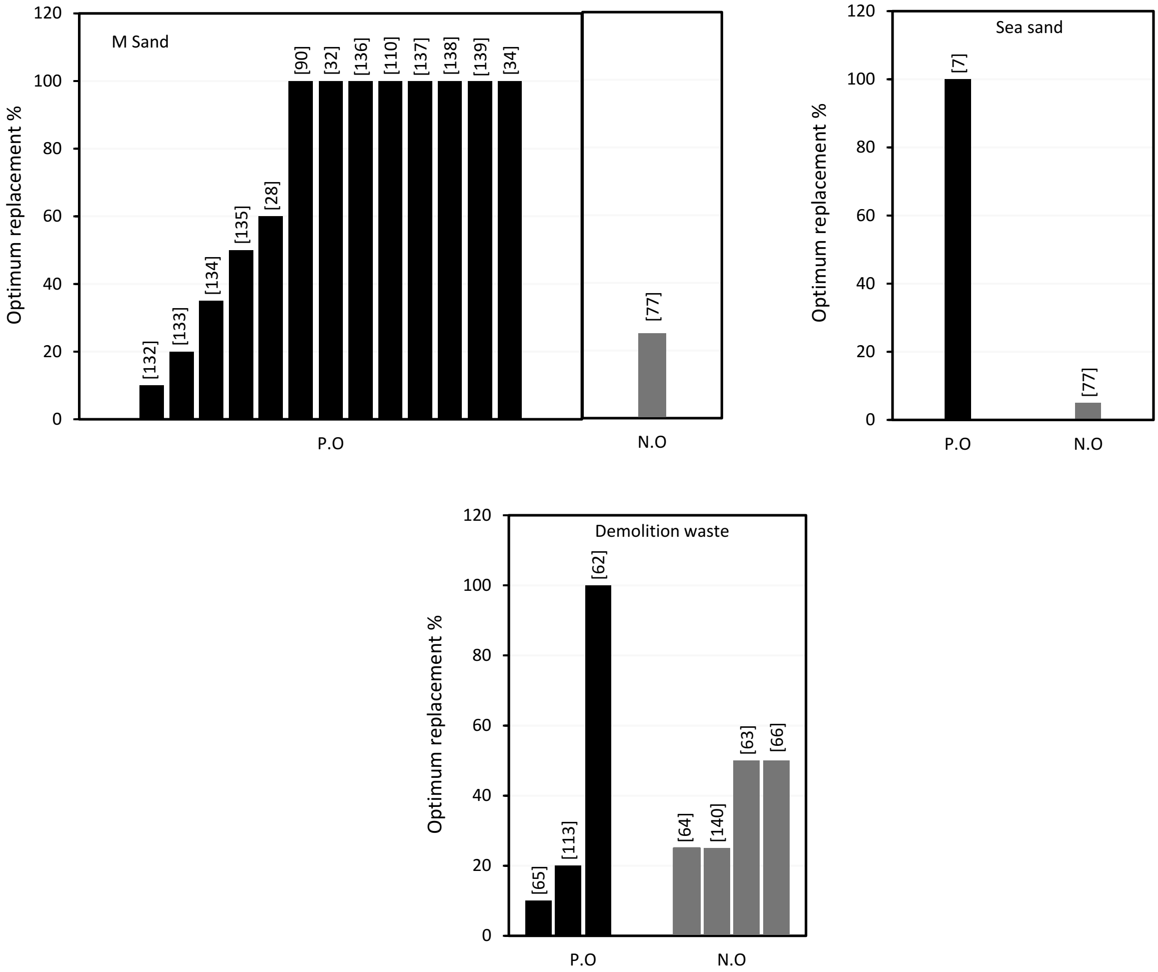


Figure 12. Effects on compressive strength of mortar with river sand alternatives.

illustrates the conclusions derived by the studies with M Sand, offshore sand, quarry dust, and sea sand on the optimum replacements in concrete. Most studies came up with positive outcomes with the indirect tensile strength of concrete when river sand was replaced with M Sand. A maximum possible replacement range of 40–80% with M Sand can be noticed. This replacement range is similar to the range obtained under Section 5.2.1 regarding the compressive strength of concrete which relates to the M Sand characteristics in both cases. Concrete with quarry dust also improved the tensile strength where most studies arrived with positive outcomes with an optimum substitution range of 20–60%. This replacement range falls near to the range obtained with M Sand (40–80%) which proves similar characteristics of M Sand and quarry dust. The tensile strength of concrete was declined with the inclusion of offshore sand and sea sand. The studies with offshore sand showed that the 20–40% substitution range helped to increase the tensile strength than other substitution levels. A clear replacement range cannot be attained with sea sand where a few studies are available on analysing the tensile strength of concrete with sea sand as the replacement for river sand.

5.2.3. Flexural strength

Flexural strength is also one of the principal strength properties of concrete and mortar. This section reports the conclusions derived by several research works executed on using river sand alternatives such as M Sand, offshore sand, demolition waste, quarry dust, and sea sand. Figure 14 presents the effects of sand substitutions on the flexural strength of concrete and Figure 15 shows the variations of the optimum replacement levels for mortar. Initially, when examining Figure 14, the same variation mentioned in Figure 11 regarding the compressive strength of concrete including M Sand can be noted here. It discloses the same optimum replacement range of 40–80% by most of the reviewed studies which were concluded with positive outcomes. Very few studies showed the negative outcomes when replacing river sand with M Sand in concrete. The studies with quarry dust also verified positive effects with the flexural strength of concrete when replacing river sand. The studies which were concluded with positive effects also suggested a maximum possible replacement range of 20–60%. A higher number of studies with offshore sand showed improvements with the flexural strength of concrete which completely differs from the results analysed in Section 5.2.1 and Section 5.2.2. The studies

(Girish, Tensing, and Priya 2015) and (Athira and Neethu 2016) were come up with the advanced flexural strength of concrete with the inclusion of offshore sand than concrete with river sand alone. The above studies resulted in the optimum replacement levels of 30% and 60% respectively from which a maximum allowable substitution range of 20–60% can be concluded.

The studies made with mortar by replacing river sand with M Sand manifested improved results with flexural strength. From Figure 15, it can be noticed that most of the studies recommended an optimum substitution range of 40–60% with M Sand. Few studies concluded negative effects on flexural strength of mortar when river sand was replaced with crushed demolition waste. This can be related to the results illustrated in Figure 12 regarding the compressive strength of mortar. In both cases, crushed demolition waste declined the strengths of mortar when partially replaced river sand. The study carried out by Sun et al (Sun et al. 2020) only investigated the flexural strength properties of mortar with sea sand as a substitution to river sand. The authors recognised that the mortar fully repacing river sand with sea sand revealed higher flexural strength than control mortar.

5.2.4. Shrinkage/Expansion

The research work carried out by Shi-Cong & Chi-Sun (Shi-Cong and Chi-Sun 2009) concluded that increased replacement levels of river sand by crushed fine sand reduced the drying shrinkage of concrete to an extent. The control mix showed a drying shrinkage of 680 microstrains while 100% replacement by crushed sand came up with 580 microstrains. Mingkai et al (Mingkai et al. 2008) briefly studied the drying shrinkage and creep of high-strength concrete made with M Sand. Stone dust content in M Sand was changed as 3.5%, 7%, 10.5%, and 14% to study the above parameters. Drying shrinkage showed a close correlation with stone dust content where 7% and higher stone dust levels manifested higher drying shrinkage than river sand concrete at 7 days of curing. Similarly, specific creep and creep coefficients were also revealed close values to the control concrete. The authors also proved that the inclusion of fly ash in concrete lowered the drying shrinkage irrespective of the type of fine aggregate used. Rajapaksha & Sooriyaarachchi (Rajapaksha and Sooriyaarachchi 2009) carried out a laboratory study to determine the shrinkage of concrete made with quarry dust. From the results, the authors identified that the shrinkage of

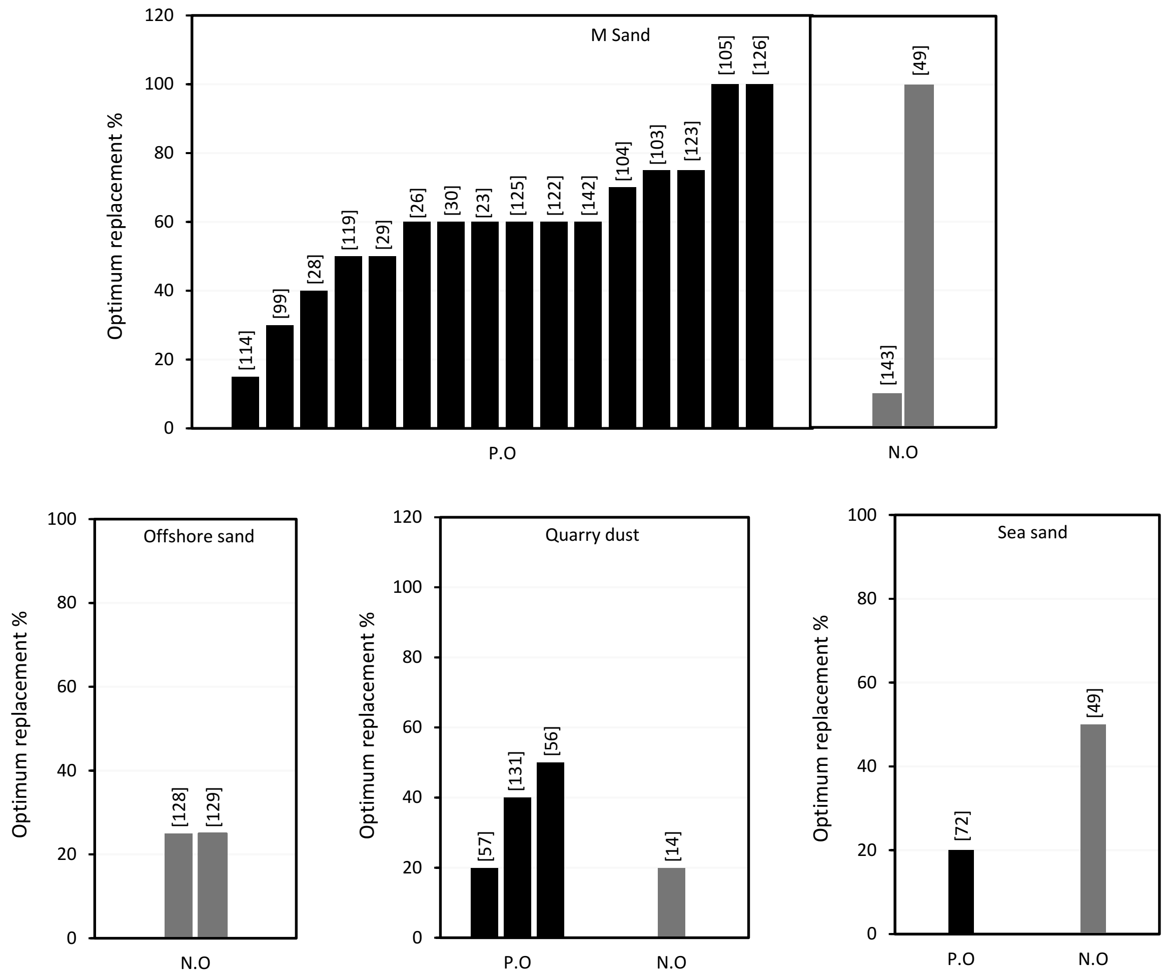


Figure 13. Effects on indirect tensile strength of concrete with river sand alternatives.

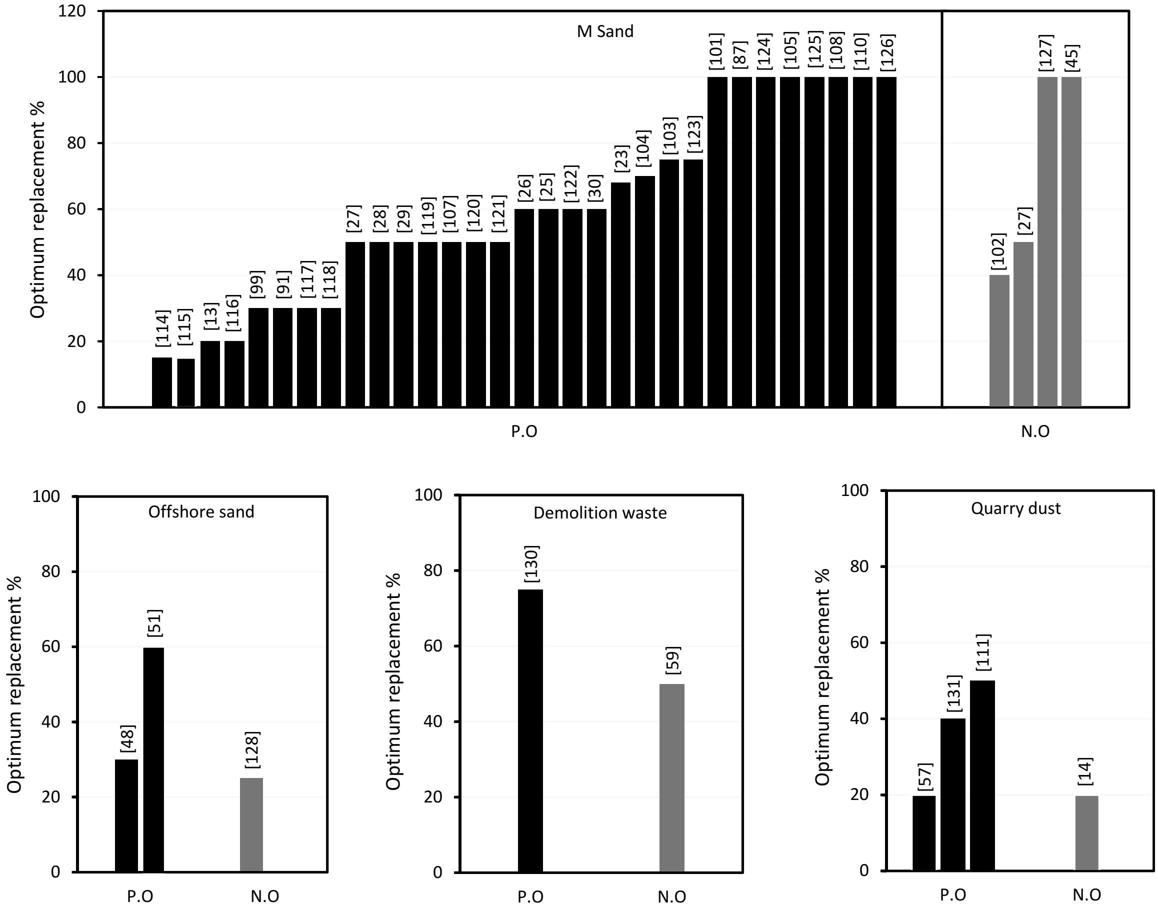


Figure 14. Effects on flexural strength of concrete with river sand alternatives.

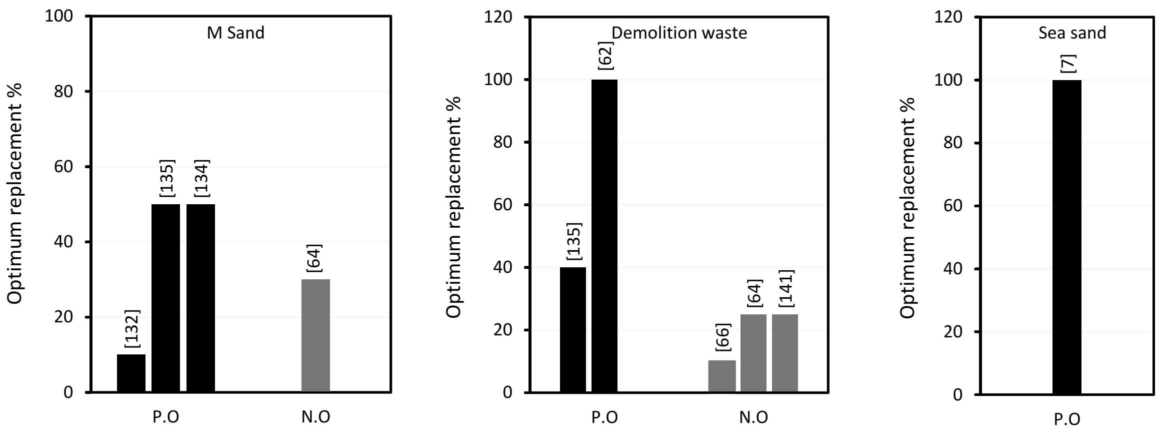


Figure 15. Effects on flexural strength of mortar with river sand alternatives.

all concrete specimens rapidly increased up to 7 days and showed a constant behaviour. Concrete with 100% quarry dust exhibited higher shrinkage than control concrete. However, the increased shrinkage was greatly reduced by fly ash. López et al (López, Pineda, and Gutiérreza 2015) studied the shrinkage of mortar by partially replacing river sand with furnace slag. Mortar bar samples were immersed in 5% sodium sulphate solution for 36 weeks and the length measurements were taken at each 2 weeks interval. The authors identified an increased expansion of mortar bars at the replacement levels of 60% and 80% by furnace slag. However, 20% and 40% replacements showed a marginal increase than the control mix. Neno et al (Mathew et al. 2016) investigated the shrinkage of mortar samples made with 80% river sand and 20% crushed recycled concrete aggregates. The authors carried out a 100-day shrinkage observation and identified the higher shrinkage of mortar which contained recycled concrete aggregates than mortar made with river sand. The study executed by Lima & Leite (Lima and Leite 2012) also proved a drastic increase in shrinkage of mortar made with 50% recycled concrete aggregates and river sand than the mortar bars made with river sand alone.

5.3. Durability properties

5.3.1. Water absorption

Water absorption through pores and capillaries is affected by the porosity of hardened samples. Figure 16 illustrates optimum replacement levels with different sand substitutions achieved by the studies on concrete. Based on the review, it can be identified that the work executed by Lohani et al. (Lohani et al. 2012) investigated the water absorption of concrete prepared with partial replacements by quarry dust. The authors concluded positive effects with water absorption and observed lower absorption of water by the concrete with 20% quarry dust. However, most of the studies which investigated the concrete with offshore sand were concluded with positive outcomes with the absorption of water. Many authors proved the possibility of higher replacement levels of river sand with offshore sand with a maximum permissible replacement range of 60–100%. Demolition waste as the sand replacement in concrete revealed negative effects with water absorption.

The past studies demonstrated that the inclusion of M Sand in mortar enhanced higher absorption of water than river sand. However, mortar at 20–40% of river sand with M Sand showed slight improvements than the other replacement levels. Studies carried out on mortar with demolition waste manifested positive effects with water absorption. From Figure 17, it can be noted that some of the studies suggested the full replacement of river sand with demolition waste, where the authors found the positive performance of mortar comprised of demolition waste alone.

5.3.2. Other durability properties

a. Studies with concrete

Levy & Helene (Levy and Helene 2004) investigated the carbonation depth of concrete prepared with demolition waste. The study proved increased carbonation depths at higher replacement levels. 20% and 50% replacements showed a considerably reduced depth. Vijaya & Selvan (Vijayalakshmi, Sekar, and Prabhu 2013) carried out an experimental investigation to identify the acid resistance, sulphate resistance, and rapid chloride permeability of concrete made with 60% M Sand. The authors used compressive strength loss of samples after 28 days of immersion in acid and sulphate solutions. It was identified that M50 grade concrete at 60% M Sand replacement showed a lower compressive strength loss and moderate chloride permeability than control concrete. Jayaraman & Kumar (Jeyaraman and Kumar 2013) proved the increased water absorption and higher chloride penetration levels of concrete samples made with 100% M Sand. Another durability study was implemented by Angelin & Kishore (Angelin and Kishore 2015) on M20 and M30 grade concretes at 20%, 40%, 60%, 80%, and 100% replacements of river sand with M Sand against HCl solution. The authors observed the strength loss of concrete samples after 28 days of immersion in acid solution. Decreased compressive strength losses of 7.12% for M20 and 5.73% for M30 concretes were noticed with 60% M Sand. Shi-Cong & Chi-Sun (Shi-Cong and Chi-Sun 2009) investigated the chloride ion permeability of the concrete prepared with crushed fine sand. As same as the drying shrinkage trend mentioned under Section 5.2.4, higher chloride ion penetration values were noticed with the control mix while the replacements significantly reduced the penetration rate. Concrete with 100% replacement manifested a total charge of 3500 coulombs where control concrete penetrated a total charge of 4300 coulombs. Vijayalakshmi et al. (Vijayalakshmi, Sekar, and

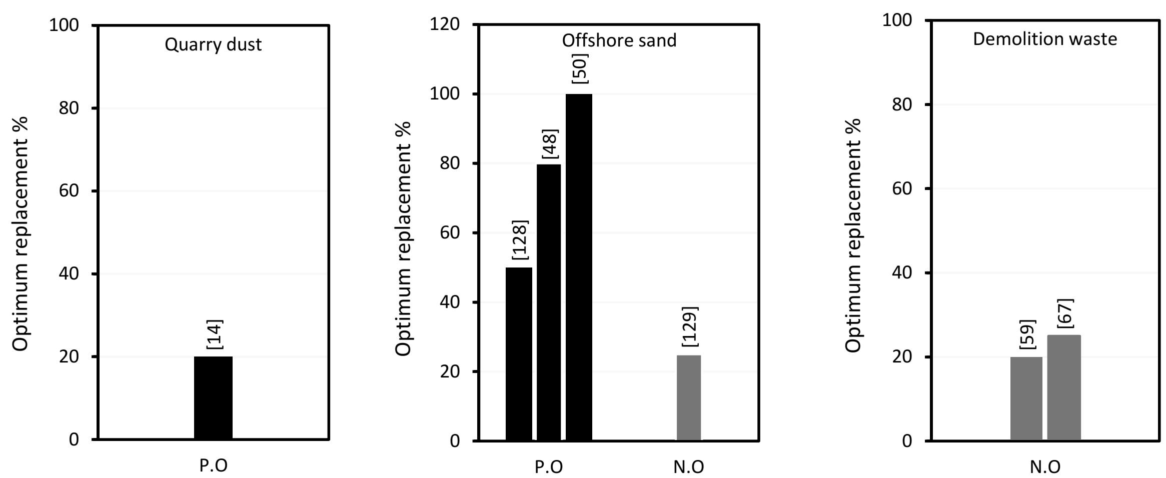


Figure 16. Effects on water absorption of concrete with river sand alternatives.

Prabhu 2013) carried out some tests to determine the chloride permeability, water permeability, carbonation depth, sulphate resistance, and electrical resistivity of concrete made with granite rock waste. The authors concluded that the chloride and water penetration rates were increased at higher replacement levels. The authors also noticed the chloride penetration and carbonation depth at 5%,10%, and 15% replacement levels which were relatively closer to the control concrete. Furthermore, ultrasonic pulse velocity was also checked and showed the same trend as chloride penetration and carbonation depth variation.

Luhar & Khandelwal (Luhar and Khandelwal 2015) studied the acid resistance, sulphate resistance, chloride resistance, sorptivity, water absorption, and accelerated corrosion of concrete with dredged marine sand by replacing 0%, 50%, and 100% river sand. The authors found that the inclusion of marine sand drastically reduced the acid and sulphate reactivity. However, negative results were observed with chloride resistance and corrosion level. Sorptivity showed a positive relationship with marine sand inclusion. Girish et al. (Girish, Tensing, and Priya 2015) performed rapid chloride penetration and performance against the alkalinity of concrete with dredged offshore sand. The authors concluded that with up to 70% replacement of river sand with offshore sand the chloride penetration was declined. However, concrete with 100% offshore sand revealed higher penetration than the control mix. From the study, it can also be observed that an optimum replacement of 80% revealed positive results with the alkalinity of concrete. Lohani et al. (Lohani et al. 2012) studied the durability of concrete made with quarry dust against 5% magnesium sulphate solution, 5% sodium chloride solution, and 2 N hydrochloric solution. The authors studied the compression strength loss of concrete incorporated 50% quarry dust after 28 days and 91 days of complete immersions. Results manifested that no considerable strength losses were noticed with magnesium sulphate and sodium chloride solutions comparing to the samples immersed in normal water. However, the samples immersed in HCl solution significantly lost both weight and compressive strength. The work carried out by Huiguang et al. (Huiguang et al. 2011) predicted a comprehensive model for the durability of concrete produced with sea sand. The authors used the chloride ion diffusion coefficient (D_{cl}) as the dependent variable and water to cement ratio (w/c), curing time (T), water consumption rate per cubic metre (W_o) as the independent variables. The predicted model was tested with a null hypothesis. Equation 3 shows the model suggested by the authors which can be used for future works related to the durability of concrete contains sea sand.

$$D_{cl} = 1.0117 + 4.2798\left(\frac{w}{c}\right) - 0.0062T + 0.0053W_o \tag{3}$$

Ratnayake et al. (Ratnayake et al. 2014) investigated the influence of chloride content in sea sand on the performance of concrete. The authors collected fresh sea sand and washed sea sand samples after 1, 2, 5 years of washing for the experiments. For each year of washing, three representative samples were collected at the bottom, middle, and top parts of the corresponding stockpile. The study concluded that sea sand samples collected after 1 year and 2 years of washing showed acceptable chloride contents for use as a fine aggregate in concrete. Rao et al. (Rao, Sravana, and Rao 2016) carried out Cantabro abrasion and surface abrasion resistance tests with cylindrical concrete samples made

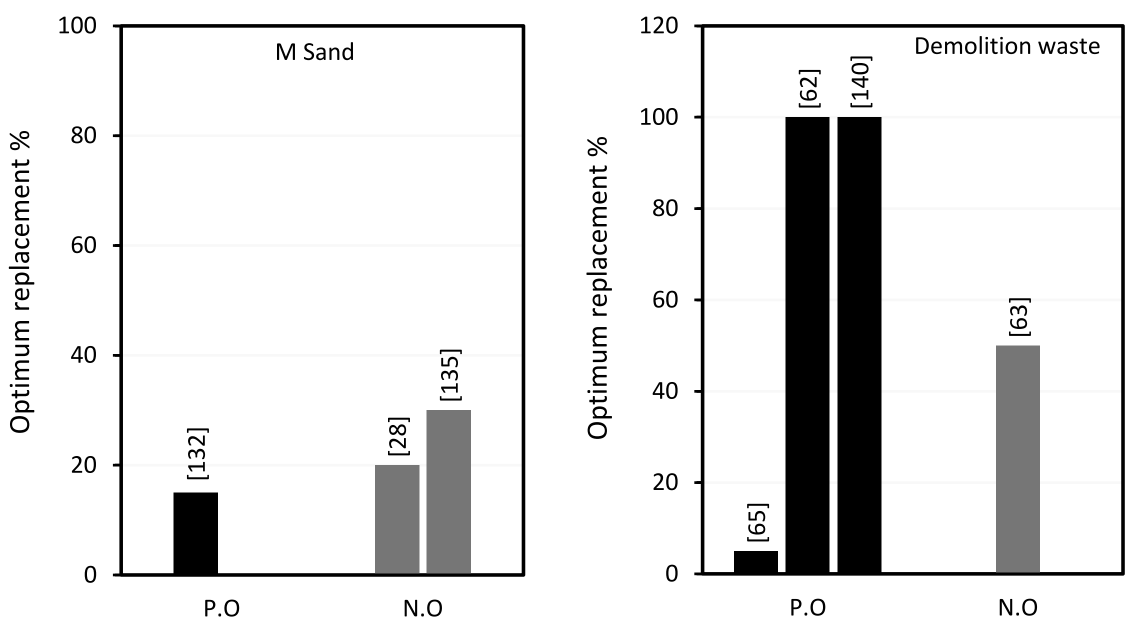


Figure 17. Effects on water absorption (capillary suction) of mortar with river sand alternatives.

with 100% river sand, 100% M Sand and 50% replacement of river sand with M Sand. The authors also used ground granulated blast furnace slag (GGBS) as the cementitious material with 10% to 60% replacements at 10% increments. Non-linear variations were noticed regarding the Cantabro loss, surface abrasion, compressive strength, and flexural strength. The authors also investigated the abrasion of samples at regular intervals of revolutions by analysing the shapes of cylindrical samples. The work concluded the increased abrasion resistance of concrete made with M Sand alone than other sand inclusions.

b. Studies with mortar

Bederina et al. (Bederina et al. 2013) carried out a detailed study on the durability of mortars made with river sand and crushed sand concerning the base and acid solutions. Mass variations were determined in the open air, lime environment, and HCl environment at each 20 days interval until 180 days from casting. Furthermore, the authors also investigated the strength properties and capillary water absorption of mortars. The study concluded that all mortars gained mass in the lime environment while lost in the HCl environment. It was observed that in all environments both compressive and flexural strengths of mortar made with crushed stone showed better performance than river sand. Ledesma et al. (Ledesma et al. 2014) carried out an experimental study on determining the water vapour permeability of mortar made with recycled concrete aggregate at 5%, 10%, 20%, and 40% replacement levels. The authors noted that mortar with recycled concrete aggregates drastically reduced the vapour permeability than river sand. Sun et al. (Sun et al. 2020) checked the frost resistance of mortar made with sea sand by fully replacing river sand. Mass and strength losses of river sand and sea sand mortar samples were measured after 90, 270, and 450 freeze-thaw cycles. The authors identified that mortar contained sea sand revealed higher strength and mass loss than river sand mortars. Benslafa et al (Benslafa et al. 2015) also studied the durability of mortar made with 5%, 10%, 15%, and 20% replacements of river sand by dredged sea sand in HCl and H_2SO_4 solutions. The authors found that the weight loss of mortars in HCl solution was higher than H_2SO_4 solution for all sand inclusions. However, mortar with 5% dredged sea sand manifested the lowest weight loss and highest compressive strength than control mortar among the selected replacement levels.

6. Relationship between particle characteristics and properties of concrete and mortar

In this section, the results reported in Section 5 are briefly analysed to study the effects of the physical characteristics of different fine aggregates on the fluid, mechanical, and durability properties of concrete and mortar. To achieve this, the optimum replacement ranges which were satisfied by most of the studies were identified from the graphical illustrations (Figure 8 – Figure 17) for each selected alternative and property. The upper limit of each optimum replacement range (OR) is plotted for the selected properties such as workability, water retentivity, compressive strength, tensile strength, flexural strength, and water absorption as shown in Figure 18(a-f). Here, the bars lie above the horizontal axis represent the positive outcomes observed with the corresponding alternative and vice versa.

As provided in Figure 18(a), studies evinced negative results with the workability of concrete and mortar when M Sand and quarry dust were used as partial replacements for river sand. Also, a small deviation can be noticed between the upper limits of OR of M Sand and quarry dust which could be due to the variations of particle characteristics. Regarding the replacement of river sand with offshore sand and sea sand, studies were concluded with positive results which contradict the studies with the rock-based fine aggregates. Here, it can be simply identified that the physical properties of particles such as angularity, surface roughness, and grain distribution significantly influenced the workability of concrete and mortar. The workability of fresh cement-based mixes is influenced by the lubricating effect between the sand particles and cement paste. Therefore, the involvement of different particles could determine the degree of lubrication at the fresh stage. The crushing of rocks enables more angular and rougher texture M Sand and quarry dust particles which reduces the lubricating effect due to the particle resistance and thus increases the harshness of the mix. However, offshore sand and sea sand may increase the effect as they are more rounded and having smooth texture because of the years of attrition. Demolition wastes contain all types of construction and building wastes which can allow higher inclusion of coarse particles (Aboutaleb et al. 2017). This could decline the workability due to the non-uniform gradation (Branavan et al. 2020; Aboutaleb et al. 2017).

The water retentivity of mortar can be directly related to the density of the mix when it is in the fresh stage. When concerning Figure 18(b), clear observations can be made where studies used M Sand and demolition waste arrived with positive outcomes with the water retentivity of mortars. The primary rationale for the possibility of 100% replacement could be the higher packing density of M Sand as a result of the increased micro fines than river sand (Branavan et al. 2020; Nataraja and Priyanka 2016). Therefore, M Sand can create the mortar with less permeability and thus improve the repellent of the mixture. In most cases, demolition wastes are utilised as a fine aggregate after several crushing processes which may allow some fine particles. This could improve the packing density of mortars where positive outcomes were noticed in the studies.

Regarding the compressive strength of concrete and mortar with alternatives, as provided in Figure 18(c) it can be identified that the rock-based alternatives such as M Sand and quarry dust proved positive results. Here, the more angularity and surface roughness of these particles could enhance an increased particle interlocking and thus create good bonding characteristics between the cement paste (Ding et al. 2016). This advanced bonding characteristic could result in more resistance to failure of concrete and mortar when the external stress is applied. For example, this effect is well described in the study made by Alnahhal et al. (Alnahhal et al. 2018) which was carried out using recycled concrete aggregates as the natural sand replacement. The clear background for this effect can be studied from the images of the interfacial transitional zone (ITZ) of concrete that the authors referred to for their study (see Figure 19). As similar to M Sand and quarry dust, the recycled aggregates contain more angular and rough surface particles where the ITZ of recycled aggregate concrete is more entangled than the natural aggregate concrete. As stated before, due to the excessive roundness and polish surfaces of offshore sand and sea sand particles, the ball-bearing effects are created when the external stress is applied. This could increase the slip ability of particles which may considerably decrease the resistance to external stress. This can be proved from the negative outcomes with the compressive strength of concrete with offshore sand and sea sand as mentioned in Figure 18(c).

In addition to the particle characteristics, the compressive strength may significantly be affected by deleterious contents such as clay, mud, and other organic impurities (PCA). These particles act as a coating between the aggregates and cement paste that enhance weaker bond characteristics. Because of this, during the stressing of hardened concrete/mortar the zones of weakness are created along with the aggregate-paste

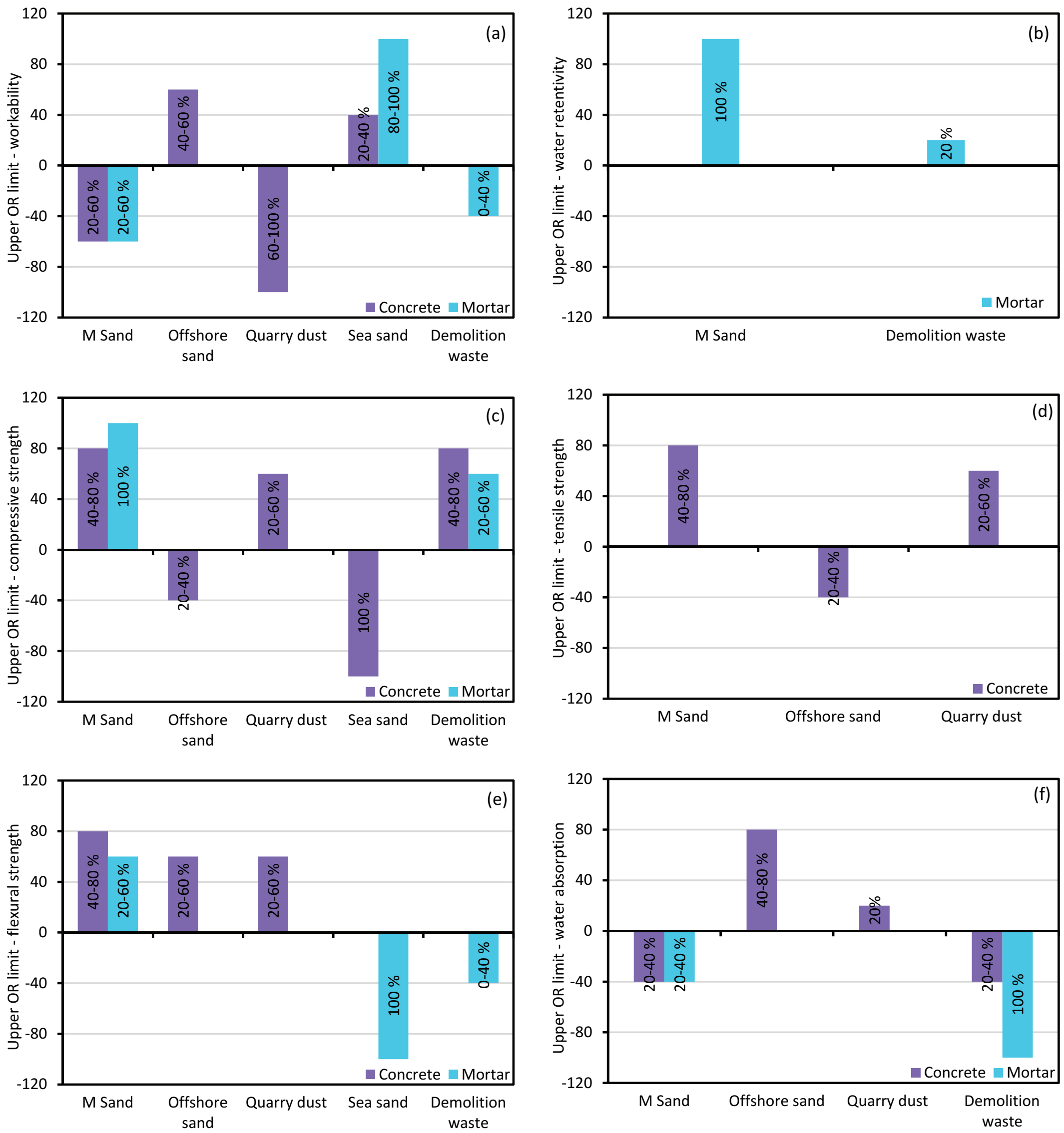


Figure 18. Upper limits of optimum replacement ranges with the alternatives for concrete and mortar.

interface which leads to quick failure. River sand extracted these days always contain these harmful constituents due to improper mining and processing (Gavriletea 2017). Similarly, offshore sand and sea sand may also consist of these contents as they are naturally obtained, and this could also be a reason for the reduced compressive strength of concrete or mortar. However, these deleterious contents are absent when using M Sand as they are purely crushed products from parent rocks (Lohani et al. 2012; Branavan et al. 2020; Chitlange and Pajgade 2010).

When concerning the performance of river sand concrete and mortar with partial addition of demolition waste, studies evinced positive results on the compressive strength when comparing with the river sand concrete and mortar. The characteristics of demolition waste are completely different from the mineral resources. Before the application in concrete and mortar, the collected demolition waste is usually crushed to attain the required gradation (Aboutaleb et al. 2017). This crushing process could enable cubical particles of different materials such as bricks, blocks, hardened mortars, etc. which may advance the positive effects on the bonding between cement paste with the assistance of particle interlocking.

The above rationales behind the effects of the particle characteristics and presence of impurities can also apply to the results obtained with regards to the tensile and flexural strength of concrete and mortar. Based on the few studies, it can be observed that the concrete made with partial replacements of river sand with M Sand and quarry dust ended up with higher tensile strengths than the river sand concrete where the inclusion of offshore sand inconcrete manifested negative outcomes (refer to Figure 18(d)). Irrespective of the application of stress, all the factors including the bonding characteristics between aggregate and cement paste and the formation of weaker zones are similar to those discussed with the compressive strength of concrete. Similar trends can also be noticed with the flexural strength of concrete according to Figure 18(e). Here, in contradiction to the above variations, few studies concluded positive outcomes when river sand was partially replaced with offshore sand in concrete, which requires a future study on this concept. Branavan et al. (Branavan, Konthesingha, and Nanayakkara 2021) briefly explained a few more reasons behind the effects of fine aggregate characteristics on the flexural strength of mortar. The authors declared that a higher flexural strength could be achieved when the reaction forces created from the particles are greater than the action forces from the external loading. Also, the creation of the reaction forces is indirectly proportional to the void content of mortar (see Figure 20). These statements can be further validated from the study made by Hild et al. (Hild, Forquin, and Da Silva 2011) where the authors found a reduction in the strength with increased internal pores of high-strength concrete (refer to Figure 21) for a typical internal pore structure arrangement at the fractured surface of concrete under a three-point flexural test.

Figure 18(f) exhibits the upper limits of OR achieved by the studies concerning the water absorption of concrete and mortar with different alternatives. As observed, some studies proved that the concrete and mortar incorporated partial addition of M Sand declined the performance against water suction, where the authors found increased water absorption than the river sand concrete and mortar. On the other hand, it can be observed that offshore sand as a partial replacement of river sand significantly reduced the water absorption of concrete than concrete made with river sand alone. A contradictory outcome can be noticed on the concrete made with a replacement of river sand with quarry dust. The partial replacement of river sand with demolition waste also increased the water absorption of concrete and mortar. The total specific surface and porosity of fine aggregates may act a vital role in the water absorption of concrete and mortar (Branavan, Konthesingha, and Nanayakkara 2021).

As discussed above, different river sand alternatives could influence the size and amount of pores present in concrete and mortar after hardened due to the variation in the angularity of particles. Several studies proved a rapid water absorption at

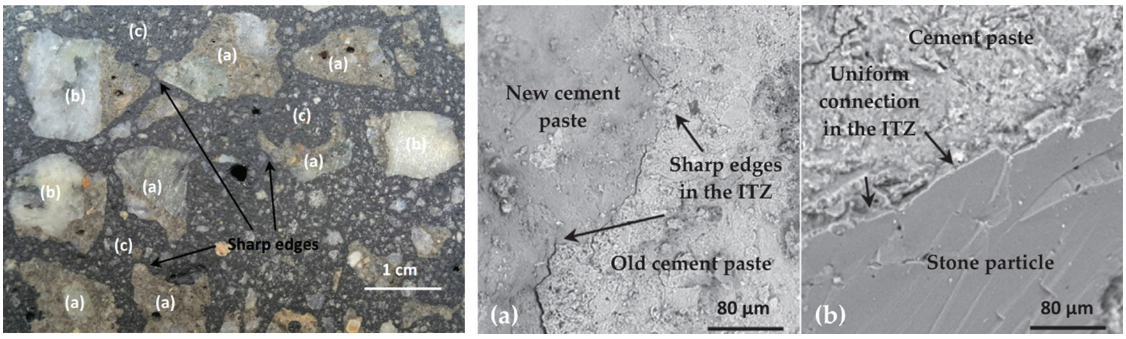


Figure 19. Left: Micro-image of bonding between RA particles and mortar; Right: ITZ of recycled aggregate concrete (a) & natural aggregate concrete (Alnahhal et al. 2018).

the initial stages after the contact with water which was followed by a constant variation. The study made by Branavan et al. (Branavan, Konthesingha, and Nanayakkara 2021) discloses that the short-term water absorption is mainly influenced by the total specific surface while the long-term water absorption is affected by the presence of pores in the specimens. Lim et al. (Lim, Lee, and Kawashima 2018) used back-scattered electron (BSE) images and software modelled and processed images and to identify the possible types and segmentation of pores respectively that could present in the cement-based mixes. As represented by Figure 22, the authors identified large-capillary pores, medium capillary pores, and gel pores as in the order of decrease in size which may affect the rate of absorption. Therefore, these pores could be significantly influenced by the addition of alternatives with varying angularity particles.

7. Cost analysis and future demands

Due to the surged growth of construction industries, each part around the world is facing many difficulties with the escalated demand for river sand and increased cost for consumption. United Nations estimated that around 40 billion tons of sand are mined every year (Cross 2019). The study also provided some information regarding the predicted sand demand in New York as 500 million tons in the future (Cross 2019). Edwards (Edwards 2015) studied the variation of sand consumption for concrete in the past decade. The authors mentioned the extreme sand consumption of 26 billion metric tons in 2012 from 11 billion metric tons in 1994 which was estimated by the United States Geological Survey (USGS). Constantino (Constantino 2017) mentioned the future forecast made on sand aggregate demand by the global construction aggregate market which was estimated as 62.9 billion metric tons in 2024

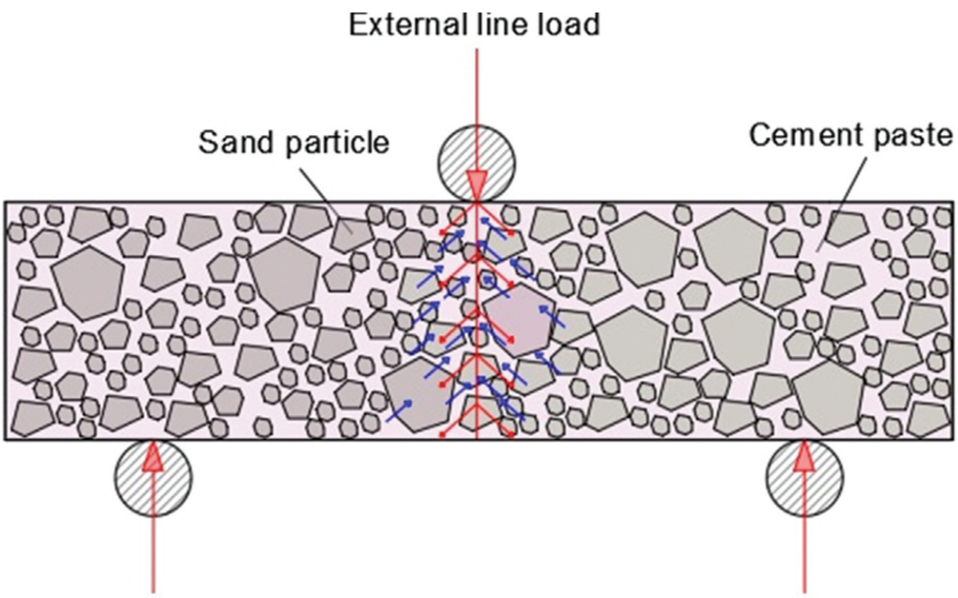


Figure 20. Action and reaction forces during the flexural stress (Branavan, Konthesingha, and Nanayakkara 2021).

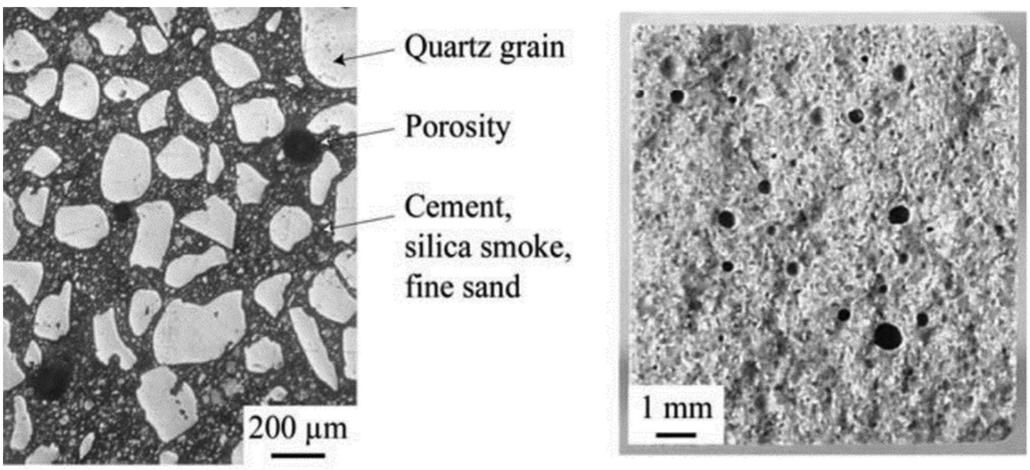


Figure 21. Microstructure of high-strength concrete (left); fractured surface after flexural stress (right) (Hild, Forquin, and Da Silva 2011).

with a growth rate of 4.85 in 2016 to 2024. Local statistics of Sri Lanka executed by the Construction Industry Development Authority (CIDA) (Construction Industry Development Authority (CIDA) 2020) defined the variation of the price index of river sand comparing with the price index of cement as illustrated in Figure 23. It can be noticed that the price index of river sand inflated from 285 in 2000 to 3850 in 2020 which highlights the drastic growth of construction industries and scarcity of river sand for the construction works. The above statistics also mentioned the market price of river sand as 86.65 USD in 2019 and 93.42 USD in 2020. Jayatilleke (Jayatilleke 2020) explained the sand requirements of Sri Lanka in the future which will be around 10 million cubic metres. The author also clearly stated the availability of alternatives such as 8 million cubic metres of sea sand and 2 million cubic metres of M Sand to fulfill the future river sand demand.

Some studies were found with cost analysis from the experimental works when alternatives were substituted for river sand. Vaidya et al. (Kona and Reddy 2015) did a comprehensive case study on the cost analysis of concrete made with river sand and M Sand considering different structural elements such as slab, beam, and staircase. The authors used three data sets of different construction sites with the same concrete grade and 30%, 60%, and 100% replacement levels by M Sand for each element. Each construction site showed that 100% replacement reduced the overall cost by around 5% while 30% and 60% replacements minimised around 1.3% and 3.2%. Belay (Malaviarachchi and Takasu 2011) briefly investigated the cost analysis based on the influencing factors such as production cost and transportation cost. The latest price indexes were used for the analysis. The cost difference range between control mix and mix with 100% M Sand was observed as 2.8% to 8.9%. The authors noticed a considerably lower cost when M Sand fully replaced river sand. Dolage et al. (Girish, Tensing, and Priya 2015) marginally described the cost of offshore sand based on the sand suppliers available in Sri Lanka. The authors mentioned that offshore sand market price indexes were cheaper than the cost for river sand. Also, the reliability of the quality of offshore sand was differed based on the varying chloride contents.

8. Availability of standards for using fine aggregates

Different limits are imposed on various fine aggregates for use in concrete and mortar. A brief review of current product standards is mandatory to investigate the suitability and availability of limitations for different fine aggregates. Table 2 lists the limitations imposed on the most determining parameters of different fine aggregates. These days, the most common standards in practice among the construction industries are the British standard, BS 882 (British Standard 1992), and the American standard, ASTM C33 (ASTM Standard 1999). Both standards are applicable for river sand as well as crushed sand and the combination of both in concrete. British standard defines the maximum allowable microfine content in fine aggregate concerning the type and application. American standard shows some limitations on various deleterious substances such as clay lumps, friable particles, coal, ignites, and micro fines. However, there is no information provided on the tolerable chloride and shell content in the American standard which is available in the British standard. Moreover, gradation limits are well defined in the British standard than the American standard. BS EN 12620 (British Standard 2002a) and BS EN 13139 (British Standard 2002b) are the two British adoptions of European standards which suggest natural sand, M Sand, recycled aggregates, and mixtures of the above in concrete and mortar respectively. The above two standards also provide information on maximum allowable limits on deleterious substances and gradation. Sri Lankan standard, SLS 1397 (Sri Lanka Standard 2010) for aggregates has been issued recently which covers only the application of fine aggregate for concrete and mortar.

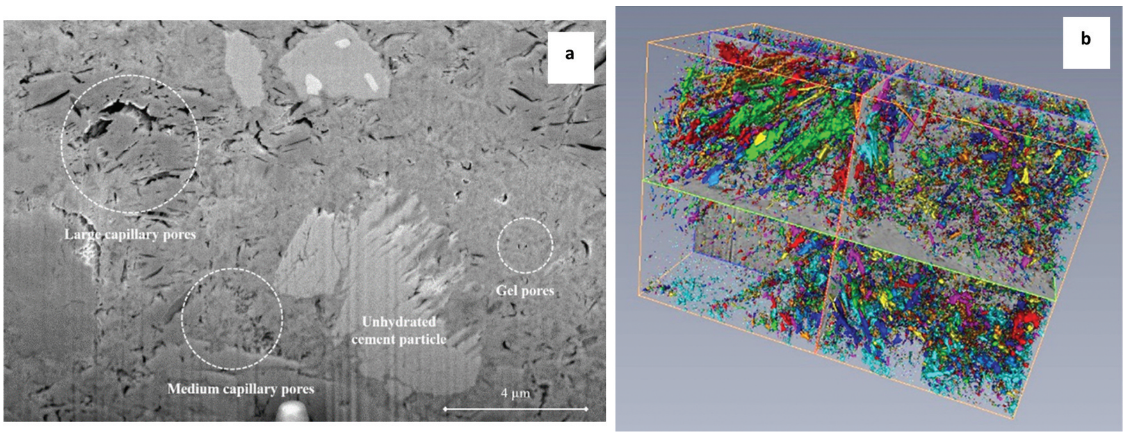


Figure 22. Common types of pores in cement-based mixes (a); segmentation of pores with a 3D model of cement-based matrix (Lim, Lee, and Kawashima 2018).

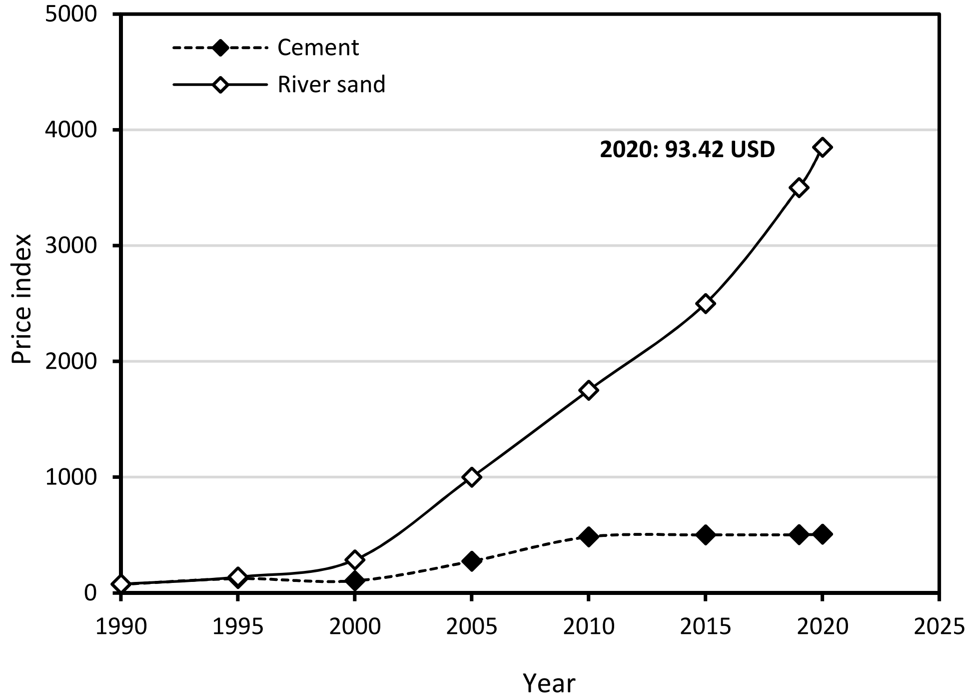


Figure 23. Evolution of the price index of river sand comparing with cement (Construction Industry Development Authority (CIDA) 2020).

Most of the requirements specified in this standard have been derived from the two European standards BS EN 12620 (British Standard 2002a) and BS EN 13139 (British Standard 2002b).

ISO 19595 (ISO 2017) is one of the international standards prepared by the International Organization for Standardisation which mentions the quality and requirements of natural and manufactured aggregates for concrete. Furthermore, the Australian standard AS 2758.1 (Australian Standard 2009), Indian standard IS 383 (Indian Standard 1970), New Zealand standard NZS 3121 (New Zealand Standard 2015), Hong Kong standard CS3 (Hong Kong Standard 2013), Israeli standard IS3 (Israeli-Standards 2018), Chinese standards GB-T 14684

Table 2. Standards and limitations for fine aggregates.

Standard	Applicable sand type	Fines content limit	Fineness modulus	Shape index	Shell & Chloride limits
ASTM C33 (ASTM Standard 1999)	Natural, M sand, Combined sand of the above	5%[a*], 7%[b*]	2.3–3.1	Not defined	Not defined
BS 882 (British Standard 1992)	Uncrushed, Crushed rock/gravel, Combined sand of the above	4%[a], 16%[b]	Not defined	Partially defined	0.01–0.05% (Ch.) 0% (Sh.)
AS 2758.1 (Australian Standard 2009)	Natural, M sand, Combined sand of the above	7%[a], 15%[b]	Not defined	Partially defined	Not defined
ISO 19595 (ISO 2017)	Natural, M Sand	10%	Not defined	Not defined	Not defined
NZS 3121 (New Zealand Standard 2015)	Natural, M sand, Combined sand of the above	7%[a], 15%[b]	Not defined	Partially defined	Not defined
IS3 (Israeli-Standards 2018)	Natural	15–20%	Not defined	Not defined	Not defined
CS3 (Hong Kong Standard 2013)	Natural, recycled	10–14%	Not defined	Partially defined	0.01–0.05% (Ch.) 0% (Sh.)
IS 383 (Indian Standard 1970)	Natural, Crushed stone, Crushed gravel	3%, 15%	2.2–3.2	Partially defined	Not defined
GB-T 14684 (Chinese Standard 2011)	Natural, M sand	1%[a], 3%[b], 5%[a*], 7%[b*]	Not defined	Not defined	Not defined
JGJ 52 (Chinese Standard 2006)	Natural, M sand	2%[a], 5%[b]	Not defined	Not defined	Not defined
BS EN 12620 (British Standard 2002a)/13,139 (British Standard 2002b)	Natural, M sand /recycled & mixture	3%[a*],	10%[b*]	Not defined	Not defined

Not defined

[a] For uncrushed sand types in concrete
[b] For crushed rock/gravel sand types in concrete
[a*] For uncrushed sand types in mortar
[b*] For crushed rock/gravel sand types in mortar

(Chinese Standard 2011) and JGJ 52 (Chinese Standard 2006) are available which also define the requirements of fine aggregates for using in concrete. SLS 1397 (Sri Lanka Standard 2010) standard restricts aggregate sizes and types of aggregates for concrete and mortar to a specified limit. These limits are extended in BS EN 12620 (British Standard 2002a) standard which includes a wide range of aggregate sizes and types. BS 882 (British Standard 1992) mentions the usage of crushed gravel sand and blended sand in concrete. BS 1199 & 1200 (British Standard 1976) defines some grading limits for natural sand and crushed sand for masonry works with different applications including external rendering, internal plastering, plain and reinforced brickwork, and block-walling masonry. BS 882 (British Standard 1992), BS 5328 Part 1 (British Standard 1997) and ACI 201 (American Standard 2001) define the chloride content limitations. BS 882 (British Standard 1992) sets some limits on shell content in the coarse aggregate, but no information is provided for fine aggregates. ACI 201 (American Standard 2001) briefly explains some possible chemical reactions between fine aggregates and hydraulic cement paste in concrete which can be used as a basis for selecting appropriate sand types. It is delightful to see that the Australian standard, Hong Kong standard, and Indian standard have started investigations on implementing various limitations for the deleterious fines available in M Sand. Cement Concrete & Aggregates Australia (Cement Concrete & Aggregates 2008) carried out some preliminary investigations to identify the correlations between the physical properties of M Sand produced from limestone and igneous rocks and the properties of selected rocks. However, the above study did not identify any sensitive correlation between the physical properties of M Sand and the rock types selected. Nevertheless, the authors observed a relationship between the physical properties and the mineralogical content in the rocks. The work done by ASTM C294 (ASTM International 2017) is appreciable which describes various harmful mineral constituents in aggregates and corresponding adverse effects to concrete and mortar.

9. Remarks and recommendations

The present study briefly reviewed the usage of different alternative fine aggregates for river sand in concrete and mortar. This paper includes the existing environmental problems due to continuous extraction of river sand, alternative sand types suggested in various studies, advantages and disadvantages of the most used substitutions, availability of standards for using different fine aggregates in concrete and mortar, and the effects of partial replacements of alternatives on the fresh and hardened properties of concrete and mortar. This concise literature review is summarised with general remarks, key findings, and some recommendations for future studies.

9.1. General remarks

Previous studies suggest many possible alternatives for river sand however, the contribution to those substitutions by the construction industries is still questionable. River sand is still used as the main fine aggregate by most of the construction industries. The environment and ecosystems face serious threats these days due to continuous sand extraction. M Sand, offshore sand, quarry dust, and sea sand are identified as the common rock-derived and sea-based mineral alternatives for river sand replacement. Researchers are now trying to include demolition waste in concrete and mortar as a partial substitution for river sand in the present days to effectively utilise the waste that arose in the construction sites. A small contribution to other waste materials such as marble powder, blast furnace slag, recycled glass, and waste plastics was also noticed from the brief review study executed in the present work.

The rock-derived aggregates are much deviated from the sea-based resources because of differences in the sources for production and process of formation. M Sand and quarry dust are produced by blasting and crushing hard rocks which enable more angular and rough surface particles. However, river sand, offshore sand, and sea sand are naturally available which are subjected to attrition by water. This creates particles with a more rounded and smooth surface. These variations significantly impacted the fresh, mechanical, and durability properties of concrete and mortar.

Studies proved that the fresh state properties of concrete and mortar could be significantly advanced when river sand is partially replaced with offshore sand and sea sand. However, M Sand and quarry dust as a partial replacement for river sand could decline these fresh properties. Literature showed contradictory results on the fresh properties of mortar when river sand is partially replaced with demolition waste. Because of the improvement of strength of concrete and mortar, several studies suggested the use of M Sand and quarry dust as the partial substitution for river sand for producing high-strength cement-based mixes. Studies with offshore sand and sea sand as partial replacements proved a reduction in the strength of concrete and mortar. The present review of studies demonstrated that partial inclusion of M Sand and demolition waste increased the water absorption of concrete and mortar.

Several studies proved that incorporating M Sand and offshore sand can effectively diminish the overall cost for concrete and mortar (in the range of 2.8–8.9%) than river sand through laboratory-based experiments. Various standard guidelines are available for applying natural sand, M Sand, and a combination of both in concrete and mortar. Most of the standards set limitations on allowable micro fines content however, few standards are absent with the constraints on fineness modulus, shell content, and chloride content.

9.2. Key findings

To relate the fresh, mechanical, and durability properties of concrete and mortar made with different alternatives, the particle characteristics such as angularity, surface roughness, total specific surface/packing density, void content, and presence of potentially harmful materials were studied from the past literature. As the properties of cement-based mixes, the workability, water retentivity, compressive strength, tensile strength, flexural strength, and water absorption were selected.

Based on the quantitative and qualitative investigations made by the previous studies, Table 3 shows the variations of the sand characteristics against river sand and other mineral alternatives considered in this study. As provided, the angularity, surface roughness, and total specific surface are increasing from the sea-based resources to the rock-derived aggregates where river sand lies in the middle. However, the presence of harmful substances is decreasing in the same order. These trends manifested a significant role when they were related to the properties such as workability, strength, and water absorption of concrete and mortar.

The studies with offshore sand and sea sand as a partial replacement concluded increased workability of concrete and mortar which was due to the lower angularity and smooth surface particles. However, because of the more angularity and rough surface particles, the M Sand and quarry dust considerably declined the workability of mixes. Some studies were come up with reduced workability of mixes when river sand was partially replaced with demolition waste.

The rock-based aggregates such as M Sand and quarry dust considerably improved the compressive, tensile, and flexural strengths of concrete and mortar where more studies demonstrated the possibility of high optimum replacement ranges. Nevertheless, contrast behaviour was observed with offshore sand and sea sand where literature reported negative results when river sand was partially replaced. The present work noticed a good relationship between the angularity, surface roughness, and the number of deleterious contents of alternatives and strengths of cement-based mixes.

Previous studies evinced negative outcomes on the water absorption of concrete and mortar when river sand was partially substituted with M Sand and demolition waste, on the other hand, some studies proved positive results with offshore sand and quarry dust. This review identified a primary role of the total specific surface and the porosity of alternatives on the short-term and long-term water absorptions respectively. Here, a contradictory result was observed with the studies made on quarry dust which has similar characteristics to M Sand and this needs further investigation in the future.

9.3. Recommendations

- Mineral and chemical compositions of rocks may directly influence the hardened and durability properties of concrete and mortar when M Sand and quarry dust are incorporated as the river sand alternatives. Therefore, a complete investigation is required on the above compositions of the most common parent rocks used for producing M Sand and quarry dust.
- The brief review proved that the workability of concrete and mortar are highly affected when M Sand and quarry dust were used as the river sand replacements. However, no studies are found analysing the influence of various admixtures which could be able to improve the fluidity of concrete and mortar.
- Offshore sand and sea sand are abundant with shell content which may lower the fresh properties of concrete and mortar due to the elongated particles. None of the studies were found scrutinising these and the standards are not addressing it. Hence, a thorough investigation is necessary regarding the impacts of available shell content before and after the processing of offshore sand and sea sand.
- Due to the conflicting characteristics of rock-based sands and marine-based sands, an innovative concept on a blending of both sand types can be implemented for a complete replacement of river sand in concrete and mortar. This method is expected as an economical solution to outcome the improvements in fresh and hardened properties.
- The available standard guidelines are restricted to apply few types of fine aggregates in cement-based mixes. Also, limitations on some of the most determining parameters of fine aggregates are still absent. Therefore, the standards should be updated incorporating these requirements to enhance the higher levels of application.

Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Table 3. Key outcomes regarding the mineral alternatives.

Fine aggregate characteristics				Sand types	Properties of concrete and mortar		
Angularity	Surface roughness	Total specific surface	Presence of deleterious contents		Work ability	Strength	Water absorption
				Offshore sand			
				Sea sand			
				River sand			
				M Sand			
				Quarry dust			

ORCID

Branavan Arulmoly http://orcid.org/0000-0001-9058-6567

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