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Research article

Behaviour of rubberised concrete with waste clay brick powder under varying curing conditions

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ABSTRACT

Recently, there has been a worldwide scarcity of pure water for curing concrete and this has called for alternative curing conditions including utilisation of sea water. An experimental study was conducted to examine the mechanical behaviour of rubberised concrete with waste clay brick powder (WCBP) under different conditions of curing including water and sea water. The samples of rubberised concrete incorporated with WCBP were cured in water and sea water for 90 days curing period. The findings showed that the conventional and modified concrete mixtures which were cured in sea water illustrated reduced compressive and split tensile strengths compared with corresponding mixes cured in water. Among specimens cured in each curing condition, concrete mixes with 5% WCBP showed increased compressive and split tensile strengths compared with the control concrete mixes. The lowest compressive and split tensile strength findings were noticed with rubberised concrete incorporated with WCBP. The comparisons of densities of specimens cured in water and sea water showed no significant distinctions between the curing conditions. Compressive strength seemed to be less sensitive to conditions of curing compared with split tensile strength. From the findings, minor reductions in compressive strengths for samples cured in sea water compared with those cured in water were suggested to be reflections of possibility of utilising sea water as a curing agent in areas where pure water is very scarce. The findings in this study seem to suggest that the use of sea water in concrete curing should not be feared and could be welcome, particularly in offshore constructions and isolated islands.

1. Introduction

The challenge of sustainable development is associated with the management of environment and utilisation of alternative construction materials including waste materials [1]. Such waste materials include waste tire rubber (WTR) substituting coarse aggregate and waste clay brick powder (WCBP) replacing cement during concrete production. The attention towards the utilisation of WTR is occasioning from the environmental perspective and significant improvement of concrete properties such as ductility [2,3]. It has been observed that WCBP inclusion in concrete improves concrete mechanical properties [4–6]. Nevertheless, it is recognised that concrete

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may suffer from different conditions of curing leading to considerable reductions of mechanical properties compared with curing condition of immersion in pure water. An example of this condition of curing is sea water which has demonstrated reductions in mechanical behaviour of structural concrete and fibre reinforced concrete [7–9]. Despite the limitations of concrete curing in sea water, the scarcity of pure water for curing concrete necessitates alternative conditions of curing including sea water [7]. Moreover, in some cases, it seems inevitable to expose concrete in sea water especially submerged bridge concrete piles in sea water [10]. To clarify on the behaviour of concrete in various conditions of curing, experimental works are required. However, comparative research works on behaviour of rubberised concrete with WCBP cured in water and sea water have received little attention in literature. This research is an extension of experimental work by Sinkhonde et al. [11] on mechanical performance of rubberised concrete incorporated with WCBP.

Wastes from industries are used as full or partial replacements of fine aggregates or coarse aggregates. Also, concrete with WTR aggregates of lesser graded particle sizes partially replacing sand has shown higher strength and lower water permeability compared with conventional concrete [12]. It is recognised that coarse aggregate can be partially or fully replaced with essential materials. Several studies ([13–15], and the references therein), have observed that scrap tire chips, waste glass, bamboo aggregate, cockle shell and recycled concrete aggregate have the potential of being used in concrete as substitutes of natural coarse aggregate. Interestingly, recycled aggregates substituting coarse aggregates have to some extent exhibited acceptable concrete properties compared with control concrete. Among the recycled aggregates, the utilisation of WTR aggregates has gained most prominence because of its acceptable ductility performance [4,6,16]. Owing to increasing demand for coarse aggregate in construction industry [17], substituting coarse aggregate with tire rubber decreases pollution of the environment [18]. In addition, incorporation of WTR in concrete is recommended for vibration damping and absorption of energy applications [19]. It is confirmed that huge quantity of WTR is being generated every day posing disposal problems and considerable environmental issues [20].

Artificial pozzolans include rice husk ash, brick powder, moler (burnt diatomaceous earth), burnt clay and shale and pulverised-fuel ash [21]. Artificial pozzolans such as silica fume, blast furnace slag, sugarcane bagasse ash and fly ash are largely found in several industrialised countries [22–24], wherein the use of pozzolans for concrete production has greatly advanced [22]. Various research works are being conducted in assessing the possibility of adopting the utilisation of brick powder as cement substitute material. Concrete materials are comprehensively utilised in the construction sector. The crucial concrete ingredient, OPC, is generally costly and leads to carbon dioxide emissions during production [25]. Environmental and social concerns of sustainability and conservation of energy drive the lowering of production of cement and partial cement substitution with alternate cementitious materials in cement industry. Partial substitution of cement using materials of essential properties can conserve natural materials and decrease emissions of CO_2 into the atmosphere [26]. It has been found that disposal of waste to the nearby sites spoils the land and atmosphere and also disturbs outlook of urban environment [26]. The usage of waste materials for production of concrete will not only render it inexpensive, but also reduces dumping problems thereby making it an environmental friendly way to waste disposal [27]. Pozzolans encompass natural or artificial inorganic materials that harden when reacted with calcium hydroxide ($Ca(OH)_2$) in the existence of water. These siliceous and aluminous materials do not contain any intrinsic cementitious components in themselves but participate in chemical reaction with calcium hydroxide in powder form and in the existence of moisture [28]. Although the usage of WCBP and tire rubber in concrete has been reported by several researchers, details on effects of curing regimes on behaviour of rubberised concrete incorporated with WCBP have received little attention in literature.

Research has established that curing is a crucial factor in enhancing capability of holding water and providing enough moisture for cement hydration [7,29]. A properly cured concrete has been observed to have decreased permeability, reduced plastic shrinkage, higher durability and increased surface hardness [7,29]. It has been observed that various conditions of curing have different effects on concrete microstructure and concrete mechanical performance [30]. Although sea water curing is found to be an area of interest for researchers, it is still requiring further research for behaviour of rubberised concrete incorporated with WCBP. It is generally recognised that some structures are built under exposure conditions to sea water [31]. In addition, there is shortage of pure clean water sources for construction purposes and utilisation of sea water for curing purposes is suggested to be an alternative [31]. It is reported that there are a lot of archipelagic countries including Japan, Indonesia and others countries, where many people live in isolated and distant islands and transporting fresh water in such locations has proved to be very costly [32]. Given these circumstances, the use of sea water in some cases and locations is unavoidable. However, prior to adopting rubberised concrete incorporated with WCBP curing in sea water, it is necessary to scrutinise its effect on modified concrete. Scrutiny and assessment of findings of other researchers strengthen the belief in concrete curing using sea water despite the existence of compounds leading to concrete deterioration. Concrete curing using sea water is also found to be economical in coastal regions [30].

Several issues regarding curing and behaviour of concrete are to be addressed. First, pure water is scarce in some countries and a possible solution could be the use of alternative curing conditions including sea water. The second important issue with curing concrete is that the straightforward use of sea water in curing concrete leads to reduced properties of concrete [31–34]. The performance of concrete in sea water is validated on conventional concrete and behaviour of rubberised concrete incorporated with WCBP cured in sea water has received less attention. It is also clear that curing of rubberised concrete in sea water could lead to reduced strength. Other solutions to reduced strength of rubberised concrete of prior treatment of tire rubber and use of silica fume have been reported with several degrees of success [35–39]. Unfortunately, very limited attention is being given to studies focusing on pozzolanic activity of WCBP using various curing environments which may contribute significantly in providing better findings in rubberised concrete. A practical aspect of this research could be the indication of curing environments of sea water and water which are suggested to contribute to strength of rubberised concrete incorporated with WCBP. Such information could assist in establishment and assessment of suitable curing environments during fabrication of rubberised concrete incorporated with WCBP. This study could therefore provide considerable guidance on which curing practices might be acceptable and much attention is paid to rubberised concrete incorporated with WCBP which can probably be prone to reduced properties compared with conventional concrete.

2. Materials and methods

2.1. Materials

The materials utilised for tests in the development of concrete mixes were ordinary Portland cement (OPC) CEM I, water, coarse aggregates, fine aggregates, WTR and WCBP produced by ball milling. The diagrammatic summary providing insight on process of ball milling is presented in Fig. 1. Coarse aggregates showed specific gravity of 2.55 and were partially replaced by tire rubber having specific gravity of 1.14. In contrast, OPC was partially replaced with 5% WCBP having specific gravity of 2.69. OPC was class 42.5 in conformity with specifications in the standard [40], and showed a specific gravity of 3.12. WBCP passed through 75 μm sieve and showed excellent pozzolanic characteristics according to the standard [28]. For this research, river sand acted as fine aggregate and was utilised in conformity with the standard [41]. The fine aggregates showed specific gravity of 2.59. Tire rubber aggregates were generated from used tires obtained from dumping sites in Nairobi. Coarse aggregates and WTR aggregates had dimensions spanning from 5 to 20 mm in accordance with the standard [41]. The gradations of fine aggregate, coarse aggregate and tire rubber are depicted in Figs. 3–5 respectively. Feasible construction materials (WCBP and WTR) generated from waste materials are depicted in Fig. 2. Portable water from Jomo Kenyatta University of Agriculture and Technology was utilised in preparing concrete mixes. The sea water used in concrete curing was taken from Indian Ocean in Mombasa, Kenya.

2.2. Methods

2.2.1. Soundness, chemical compositions and mineral compositions tests

The cement soundness was examined by Le-chatelier technique in accordance with specifications in the standard [42]. X-ray fluorescence (XRF) test examined the chemical characteristics of OPC and WCBP. The experiments were performed at the Ministry of Petroleum and Mining in Nairobi, Kenya. The experiments use current of 50–100 mA and voltage of 30–60 kV. X-ray diffraction (XRD) examination of OPC and WCBP was performed on a diffractometer (Bruker D2 Phaser) having a graphite monochromator.

2.2.2. Scanning electron microscopy and image analysis

The morphology and microstructure of OPC and WCBP were examined using scanning electron microscope (SEM) of higher voltage system. The model of the equipment utilised to scan the specimens was the JEOL NeoScope JCM-7000 SEM machine. Prior to conducting the experiments, the samples were cleaned and dried in an attempt to enhance exposure of surfaces. Samples from OPC and WCBP were sprinkled on conductive adhesive tape and the process was accompanied by appropriate positioning of the samples in the equipment. The images were then captured using an accelerated electron beam having low energy which radiated the samples and scanned the surfaces of the samples. In an effort to understand the morphology of WCBP and cement, image analysis was used. For this research, image assessment seemed to be an appropriate method to assess SEM images that seem to possess similar characteristics. The particle areas and surface roughness attributes of OPC and WCBP were examined using ImageJ and Gwyddion software packages. Quantifying the root mean square roughness (R_q) values of WCBP and cement was achieved using Gwyddion. Detailed procedures of image analysis are presented elsewhere [43,44].

2.2.3. Mix proportions

The mix ratios produced in this study comprised OPC, sand and coarse aggregates in conformity with the code [45]. The mix designs were performed for three concrete characteristic strengths of 20 MPa, 25 MPa and 30 MPa at day 28 in accordance with British Research Establishment (BRE). Procedures of the mix designs are discussed in another study [46]. Ratios for concrete characteristic strength of 20 MPa of 1:2.05:4.16 (cement: fine aggregate: coarse aggregate) were obtained using BRE method of mix design. Concrete

Fig. 1. Process of ball milling: unmilled clay brick fragments (left) and grinding fragmented bricks using ball mill (right).

Fig. 2. Generated non-conventional construction materials (a) WCBP (b) WTR.

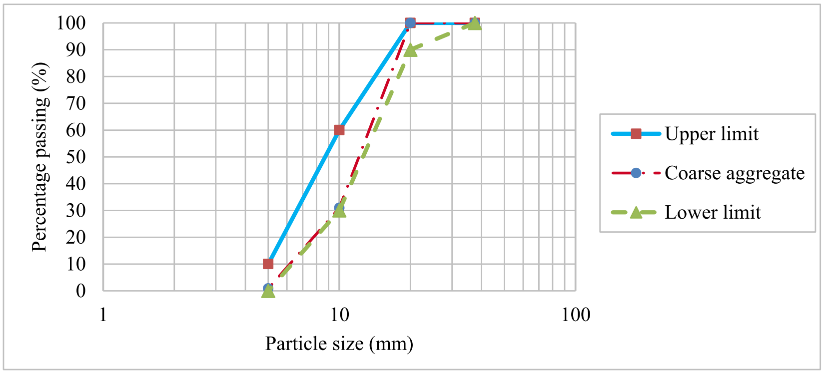

Fig. 3. Particle size distribution of coarse aggregate.

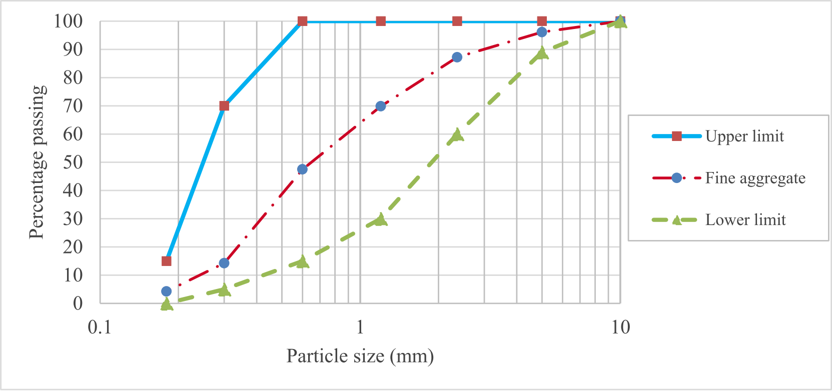

Fig. 4. Particle size distribution of fine aggregate.

characteristic strengths of 25 MPa and 30 MPa utilised ratios of 1:1.81:3.75 and 1:1.54:3.36 respectively. The conventional concrete mixes comprised OPC, fine aggregates and coarse aggregates all at 100%. Different from control concrete mixes, the rest of the mixtures had 5% of WCBP and distinct quantities of WTR. During the latter case, coarse aggregates were partially substituted with tire rubber using volume replacement method whilst OPC was partially substituted with WCBP by mass in conformity with other researchers [5,47]. The details about experimental matrix utilised in this study are illustrated in Table 1. The concrete mixtures had the following codes; 0P0T (Control), 5P0T (5% WCBP + 0% WTR), 5P10T (5% WCBP + 10% WTR) and 5P20T (5% WCBP + 20% WTR). In this research, 5% substitutions of OPC with WCBP in Table 1 were made to constitute 15.45 kg/m^3, 17.00 kg/m^3 and 18.89 kg/m^3 for

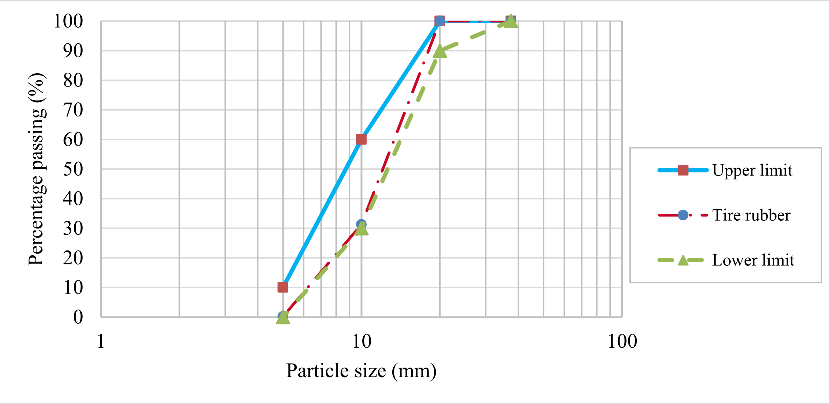

Fig. 5. Particle size distribution of WTR aggregate.

Table 1
Typical experimental matrix utilised in this experimental work.

Class	Level			
	Control	Level 1	Level 2	Level 3
20 MPa	0% WTR + 0% WCBP	0% WTR + 5% WCBP	10% WTR + 5% WCBP	20% WTR + 5% WCBP
25 MPa	0% WTR + 0% WCBP	0% WTR + 5% WCBP	10% WTR + 5% WCBP	20% WTR + 5% WCBP
30 MPa	0% WTR + 0% WCBP	0% WTR + 5% WCBP	10% WTR + 5% WCBP	20% WTR + 5% WCBP

concrete characteristic strengths of 20 MPa, 25 MPa and 30 MPa respectively. Substitutions of coarse aggregates with 10% WTR utilised amounts of 50.87 kg/m^3, 50.42 kg/m^3 and 50.14 kg/m^3 for concrete characteristic strengths of 20 MPa, 25 MPa and 30 MPa respectively. Lastly, substitution requirements of coarse aggregates with 20% WTR, included WTR amounts of 101.74 kg/m^3, 100.85 kg/m^3 and 100.30 kg/m^3 which were utilised for concrete characteristic strengths of 20 MPa, 25 MPa and 30 MPa respectively.

2.2.4. *Concrete casting, mixing and curing*

To achieve a homogenous concrete, concrete mixing was conducted with a concrete mixer, shovels, metal plates and trowels accompanied by control mechanisms preventing water losses. Metal casting moulds were brushed by utilising oil in an attempt not to allow concrete adherence to metal moulds. To expel air, concrete mixes were compacted using poker vibrator after being cast in moulds. A total of 6 cubes and 6 cylinders were cast for each mix. The cubes of dimensions of 100 × 100 × 100 mm and cylinders of diameter of 100 mm and height of 200 mm were utilised during placing of concrete in moulds. Cube and cylinder samples were taken from the metal moulds after 24 h of concrete casting. Afterwards, the samples were placed in curing tanks containing sea water and water. The curing environments were coded C1 (water) and C2 (moist curing and sea water). The curing environment of C1 is the standard curing whilst C2 curing environment conformed to the requirements in the standard [48]. Details about curing environments of concrete are presented in Table 2. During moist curing, concrete samples were covered by wet gunny bags which were kept wet throughout the period of curing. During the curing period, the range of curing temperature for sea water and water was measured as 21.7 °C–26.5 °C. It must also be remarked that because WCBP and tire rubber decrease concrete workability, additional water was required to concrete mixes in an attempt to maintain workability. The framework flow chart is illustrated in Fig. 6.

2.2.5. *Determination of fresh concrete properties*

Fresh concrete properties were determined using slump test in accordance with the standard [49], and the slump range adopted was 10–30 mm.

2.2.6. *Measurements of compressive strengths*

Concrete compressive strength was found in accordance with the standard [50]. The tests were conducted on 72 cube samples after 90 days. The universal testing machine (UTM) with the load capacity of 1500 kN was utilised at a rate of loading of 0.5 kN/s. The samples were mounted appropriately on the UTM before loading in an attempt to avoid buckling. Each sample was compressed by the

Table 2
Curing environments of concrete.

Code	Days in mould	Days under moist curing	Days in immersed curing (water)	Days in sea water
C1	1	0	89	0
C2	1	27	0	62

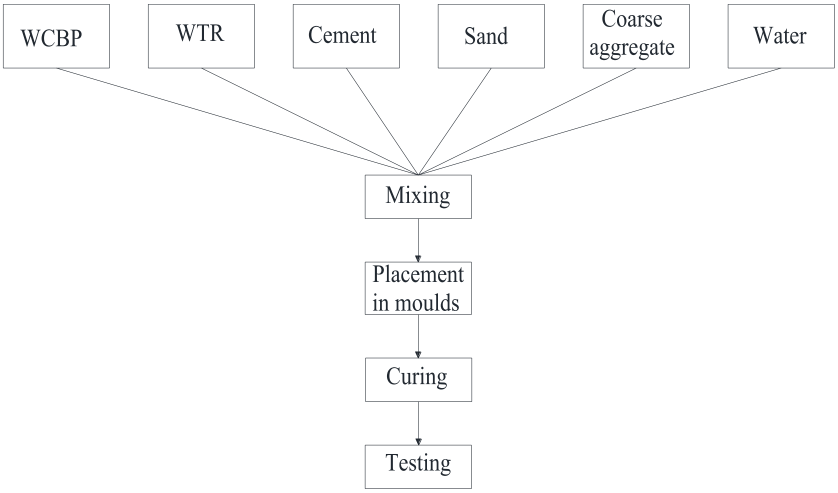

Fig. 6. Framework flow chart for concrete production.

compressive load from a movable cross head and the maximum load resulting in collapsing of the sample was indicated using the load indicator. The compressive strength value for every specimen was calculated by dividing the maximum load applied on the cube specimen by the cube cross-section area in conformity with British standard testing method [51]. The mean compressive strength values for the samples were obtained and reported.

2.2.7. *Measurement of tensile splitting strength*

Determination of the tensile splitting strength was conducted on 72 cylinder specimens in conformity with the standard [52]. Like compressive strength experiments, three samples were tested for each mix. The surfaces of the bearing of the loading rollers were cleaned in an effort to get rid of any material resting on the surfaces. Concrete cylinders were cast and cured in sea water and water for curing duration of 90 days before receiving diametrical loads along cylinder lengths using a UTM. These loads applied at loading rate of 0.5 kN/s caused cracking on the samples. To determine the tensile splitting strength, the maximum loading that caused failure of every sample was divided by geometric parameters as illustrated by Equation (1).

$$\sigma_{\mathrm{ct}} = \frac{2\mathrm{P}}{\pi \times l \times \mathrm{d}} \tag{1}$$

where P is the maximum load (in kN), *l* is the length of the specimen (in mm) and d is the diameter of specimen cross-section (in mm).

2.2.8. *Measurement of density of concrete*

The concrete density was determined in conformity with the standard [53]. A balance calibrated to a precision of 0.1% was utilised for mass measurements. Before weighing each specimen, surplus water was wiped off from the surfaces with a moist cloth. The mass of every sample was found by weighing on a balance and then recorded in kilograms. Volume of every sample in cubic metres was calculated in accordance with clause 6 of the standard [53]. The density of every specimen was computed by dividing the weighed sample mass by the calculated volume.

2.2.9. *Limitations of the study*

The findings in this study are only limited to those obtained after 90 days curing period and behaviour of rubberised concrete with WCBP at curing periods beyond 90 days has not been established. Experiments on concrete used only 20 MPa, 25 MPa and 30 MPa concrete grades. The study did not explore the performance of rubberised concrete with WCBP at early curing periods. Because all the data on concrete were collected at 90 days duration only and for 20 MPa, 25 MPa and 30 MPa concrete grades, there is neither a claim of generalisation to all other curing periods nor all other concrete grades.

Table 3
Chemical compositions of OPC and WCBP.

Material	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Ba	S	LOI
Cement	15.45	4.55	2.81	62.45	–	0.48	1.01	0.47	0.12	1.29	0.05	2.75	7.47
WCBP	64.36	12.86	8.71	2.00	–	1.82	3.05	2.13	0.68	1.18	1.18	–	0.97

3. Results and discussion

3.1. Soundness, chemical compositions and mineral compositions of cement and WCBP

Table 3 lists the chemical compositions present in cement and WCBP. The table compares the amounts of each chemical in OPC and WCBP. From Figs. 7 and 8, the XRD patterns of OPC and WCBP are illustrated respectively. From Table 3, the dominant chemical is silica (SiO_2) followed by iron oxide (Fe_2O_3). Computed sum of the percentages of ($SiO_2 + Fe_2O_3 + Al_2O_3$) is 85.93% and this amount constitutes over 70% of the total weight of WCBP. It is noticed that WCBP is fully compliant with the standard [28], as a pozzolan and can react with $Ca(OH)_2$ following commencement of hydration reaction. The standard prescribes that class N pozzolans exhibit a minimum value of ($SiO_2 + Fe_2O_3 + Al_2O_3$) and maximum loss on ignition (LOI) value of 70% and 10% respectively. From the results, the pozzolanic characteristics demonstrated by the levels of SiO_2, Fe_2O_3 and Al_2O_3 in WCBP suggested the potential usage of WCBP as a cement substitute in sustainable construction.

The absence of MgO in OPC is noticed to result in acceptable soundness properties [54]. In this research, the cement soundness was also conducted and 5.7 mm was found as a soundness value. Value of soundness of less than 10 mm illustrates that no severe expansion is induced by boiling [42]. It is recognised that the utilisation of OPC with increased expansion is problematic in relation to durability of structures [54]. Instances of greater changes in volume after setting of OPC are understood to result in cracks which influence durability of concrete structural members [54]. Failure of cement in soundness originates from excessive magnesium oxide content and the maximum limit is found to be 5% in accordance with the standard [40]. In this perspective, it is explicit that the absence of magnesium oxide in cement was anticipated to contribute to desirable Le-chatelier cement soundness. The compositions of OPC and WCBP depicted in Table 3 give percentage sums of around 91.43% and 97.97% respectively. The presence of SiO_2 in WCBP is found to contribute to pozzolanicity. In contrast, the existence of rutile (TiO_2) is characterised by some small peaks and this observation has also been reported by other researchers [55]. Such existence of TiO_2 arises since the compound is introduced as a colorant throughout the clay bricks production process to enhance the mechanical behaviour of bricks [56].

The intensities in XRD assessment reveal estimated quantities of compounds available in the sample [57]. The occurrence of gypsum in OPC and silicates in WCBP is associated with creation of calcium silicate hydrates (C–S–H) which contribute to strength. It is worth noting that SiO_2 is a principal compound detected in the spectrum for several mineral compounds and is strongly associated with pozzolanicity [58,59], whereas $CaCO_3$ is noticed to contribute in hydration process of C_3A to generate monocarboaluminate [60]. The creation of calcium monocarboaluminate takes place by the involvement of C_3A and carbonate ions in reaction as reported by several researchers [61,62]. Additionally, other researchers [63], have found evidence that the occurrence of TiO_2 in WCBP enhances the mechanical behaviour of concrete.

3.2. Scanning electron microscopy and image analysis

Fig. 9 shows SEM images obtained using SEM method. The SEM technique was employed to assess the typical particle surface textures in addition to shapes of the particles. This technique is adequately able to study the morphology, formation, size distributions and sizes of materials by scanning the samples on fine scaling [64,65]. Fig. 10 illustrates the 3-d surface structure reconstructions of OPC and WCBP using ImageJ and Gwyddion. The comparisons between surface roughness and details on pore mouths of both OPC and WCBP are presented in Fig. 10. It must be remarked that the reconstructions in Fig. 10 are established based on relative brightness levels of different structures of SEM images from which the depth (third dimension) of the structures is generated [66,67].

From Fig. 9, it is clear that WCBP particles of this study are neither spherical nor smooth. Nonetheless, the particles establish sharp and irregular corners that are noticed to formulate slits. Although SEM images are presented, it still seems difficult to conclude from only those two micrographs that WCBP contains reduced particles compared with cement. In an attempt to improve the interpretation of SEM micrographs of OPC and WCBP, image characterisation was used. Using ImageJ software, average particle areas for WCBP and

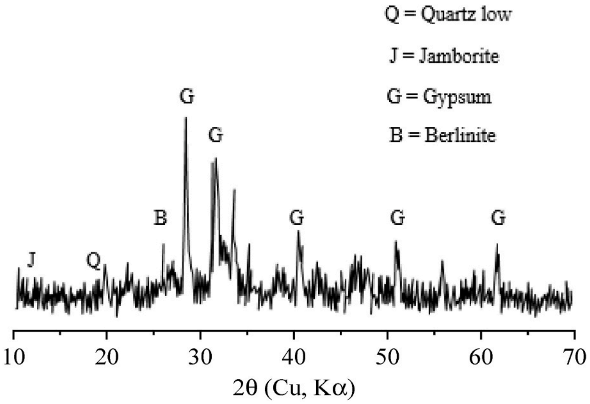

Fig. 7. The mineral compositions of cement using XRD spectrum.

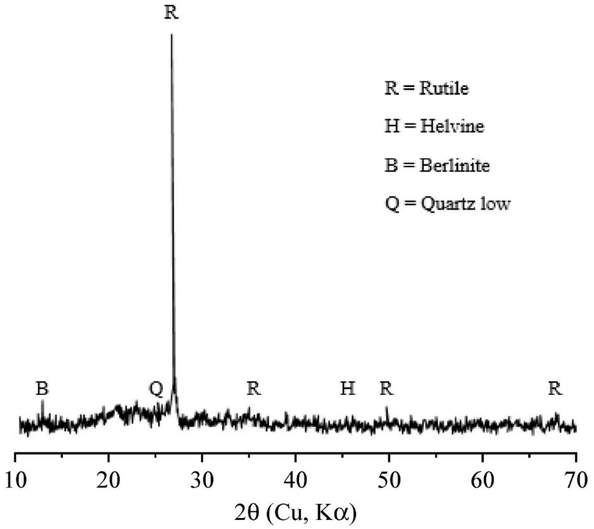

Fig. 8. The mineral compositions of WCBP using XRD spectrum.

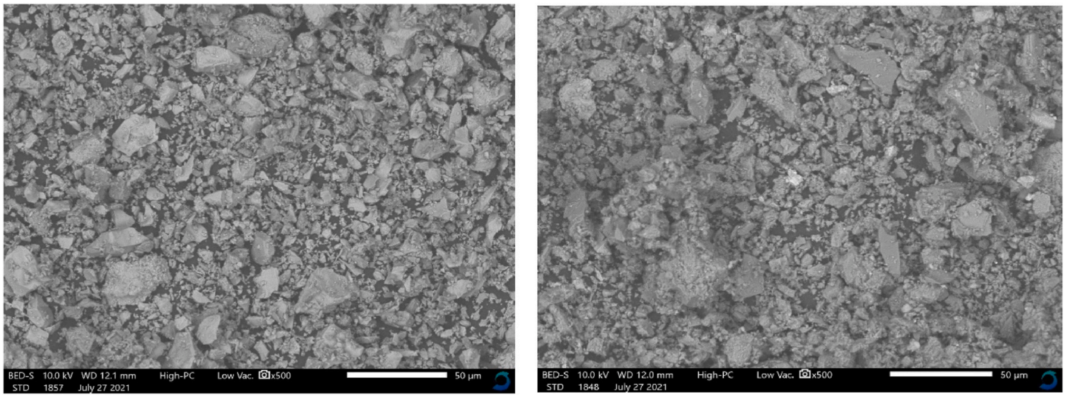

Fig. 9. SEM pictures of cement (left) and WCBP (right).

OPC were noted to be 1.08 μm^2 and 1.27 μm^2 respectively. This observation could be of significant effect on workability of concrete containing WCBP and pozzolanic reaction of concrete blended with WCBP. This observation of particle sizes combined with visible observation of reduced particles abiding in slits and notches of bigger particles suggest that water demand for concrete incorporated with WCBP would be increased thereby impeding the workability performance of fresh concrete. Other researchers [56], have also attempted to correlate particle sizes of WCBP with fresh concrete workability and have established that WCBP impedes the fresh concrete workability. In addition, it has been found that brick powder with finer particles absorbs higher amounts of water resulting in reduced slump and increased consistency of cement paste [68]. There is a general belief about initiation of concrete early days hydration due to reduced sizes of WCBP [69]. This early days hydration is believed to be the consequence of creation of crystallisation nucleus that increases the hydrated products propagation. The utilisation of WCBP in cement paste and concrete is therefore concluded to occasion reduction in slump and early concrete and cement paste strengths.

The 3-d reconstructions in Fig. 10 illustrate a fair representation of membrane surface topography. A fair correlation is noticed between surface topography reconstructions using ImageJ and Gwyddion. Fig. 10 illustrates wrinkles for OPC and WCBP which might be a reflection of rough surfaces for both materials. It was also important to measure surface roughness using Gwyddion and it was found that the R_q values for OPC and WCBP were generated as 101.136 nm and 104.192 nm respectively. Using R_q values, it seems clear that membranes of WCBP have higher roughness compared with cement. Although no major distinction was noted between the indicated roughness values, the combination of roughness and average particle sizes previously presented was noticed to be suitable to unambiguously interpret workability findings of concrete incorporated with WCBP. The incorporation of WCBP possessing rough surfaces in cement-based composites is found to cause reduced slump of cement-based composites [68]. It is worth emphasising that smaller sizes of WCBP are noticed to be less workable compared with larger ones at a constant water-binder ratio [70].

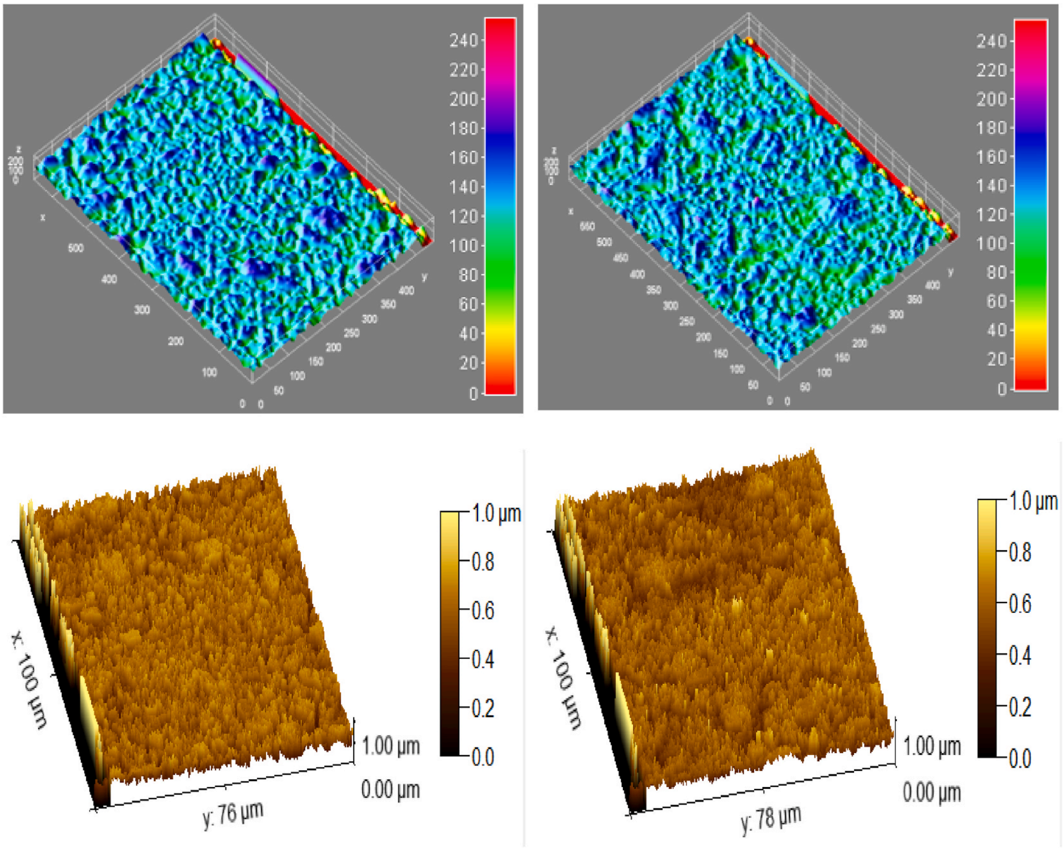

Fig. 10. 3-D reconstructions of OPC (left) and WCBP (right) using ImageJ (top row) and Gwyddion (bottom row).

3.3. *Fresh concrete properties*

In this study, the measured slump values were spanning from 15 to 26 mm. The low workable concrete is reported to enhance the durability of concrete in marine environments [71]. Concrete production accompanied by incorporation of WCBP and tire rubber for fixed water-cement ratio is noticed to develop reduced workability [39,72]. Concrete and cement paste owing to existence of various pozzolanic materials including WCBP develop increased stiffness in the mixtures [73,74]. WTR incorporation is also noticed to decrease concrete workability [39,75]. The decrease in workability performance of concrete attributed to WCBP and tire rubber inclusion was compensated by additional water. Compensation of reduction in workability is necessary and in such way, the effect of physical attributes of non-conventional concrete constituent materials is possible to analyse [76]. Additional water is noticed to lead to reduced friction between particles via the process of particle lubrication consequently enhancing concrete workability [77]. Also, it is

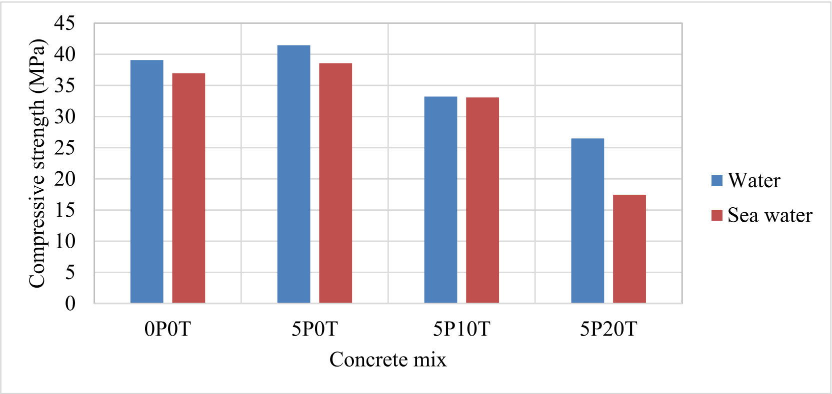

Fig. 11. Compressive strength findings for 20 MPa concrete grade mixes cured using sea water and water.

suggested that comparing concrete mixtures is easily accomplished when slump values are within specific slump ranges [78]. In addition, concrete with decreased workability is reported to be appropriate for mass dam structures or road pavements [79].

3.4. Compressive strength behaviour of modified and control concrete mixtures

Figs. 11–13 show the influence of various curing environments on behaviour of concrete mixtures for 20 MPa, 25 MPa and 30 MPa concrete grades respectively. Concrete mixes cured using sea water environment were noted to exhibit reduced compressive strength values compared with those cured using water. For instance, 30 MPa concrete grade mixtures of 0P0T, 5P0T, 5P10T and 5P20T cured using sea water had 4.64%, 3.21%, 12.05% and 12.69% reductions in compressive strength values respectively, in comparison with their corresponding mixes cured using water. The outcomes of incorporating WCBP and WTR in concrete have also been displayed in Figs. 11–13. From these figures, it seems clear that introducing WTR led to reduced compressive strength values of modified concrete mixtures compared with control concrete mixtures for both curing conditions.

The reductions in compressive strength values were noted at 90 days curing period for samples cured in sea water compared with those cured using water. Possibly, this was partly because of moist curing conducted during the 27 days in accordance with the standard [48]. It is to be noted that it could seem to be misleading when considering that the samples cured using sea water were not immersed in sea water for the whole 90 days duration. In compliance with the standard [48], the samples were moist cured for 27 days before being cured using sea water. Thus, the 90 days curing using sea water could not be fully appreciated. Presumably, this scenario might have contributed to reduced compressive strengths for concrete samples cured using sea water compared with those cured using water. Another probable reason might have been the occurrences of magnesium sulphate ($MgSO_4$) and potassium sulphate (K_2SO_4) in sea water and are concluded to participate in the reactions with calcium hydroxide in OPC leading to the creation of gypsum [80,81]. These reactions were noted to initiate sulphate attack resulting in reduced concrete strength elsewhere [82]. It is also known that concrete immersed in sea water undergoes wetting by salt solutions usually sodium chloride and magnesium sulphate [83]. It is important to explain that there were no significant distinctions in curing temperatures between sea water and water and the range of curing temperature values of 21.7 °C–26.5 °C was determined in this study. Therefore, this implied that curing temperature did not significantly contribute to differences in compressive strengths between the two curing conditions. It was established that, though compressive strength findings of samples were decreasingly affected by curing using sea water, the decreasing effects were not very pronounced. From such findings, it was suggested that the use of sea water in concrete curing should not be feared and could be welcome particularly in offshore constructions and isolated islands [84].

Increments in compressive strength values were noticed as OPC was partially replaced with 5% WCBP in all grades of concrete compared with control concrete mixes for both curing methods. This might have been a good indication of extents of pozzolanicity from WCBP. XRF and XRD studies previously discussed, have shown increased contents of silica and alumina and this fairly might be a good assessment of pozzolanicity of WCBP at 90 days curing period. After comparing pozzolanic activity of WCBP for various curing periods, other researchers [85], concluded that increased degree of pozzolanic activity of WCBP is experienced between 60 and 90 days curing periods. The superior performance in compressive strengths of concrete mixtures incorporated with WCBP was believed to be the consequence of enhanced pozzolanic activity at longer curing period. Discernible reductions in compressive strength values when WTR was introduced were due to reduced bonding existing between WTR aggregates and concrete ingredients [18]. It should also be mentioned that the behaviour of rubberised concrete with WCBP beyond 90 days was not established in this research and is recommended for further studies.

3.5. Split tensile strength findings for modified and control concrete mixtures

Figs. 14–16 illustrate graphs of split tensile strength findings of rubberised concrete incorporated with WCBP for 20 MPa, 25 MPa and 30 MPa concrete grades respectively. Curing concrete using sea water had an effect on concrete split tensile strengths in similar

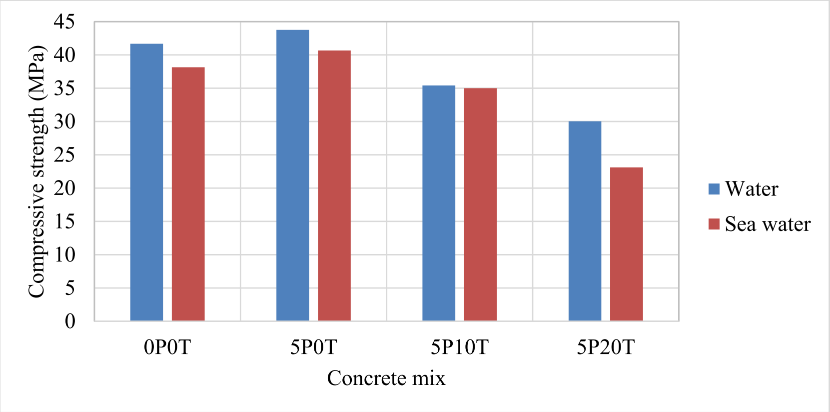

Fig. 12. Compressive strength findings for 25 MPa concrete grade mixes cured using sea water and water.

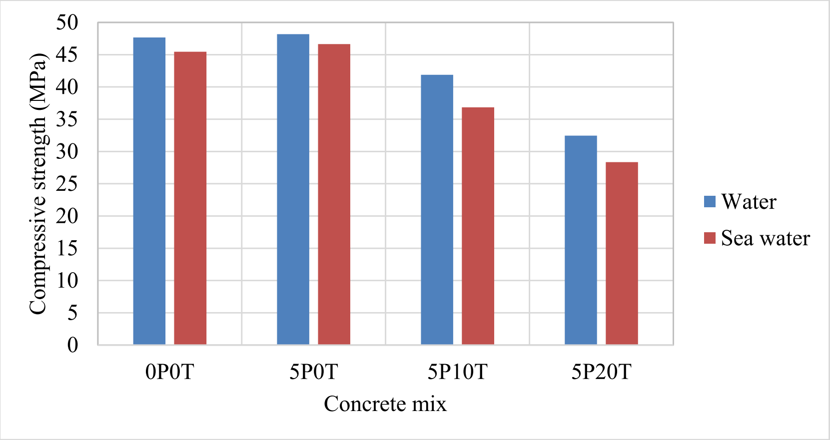

Fig. 13. Compressive strength findings for 30 MPa concrete grade mixes cured using sea water and water.

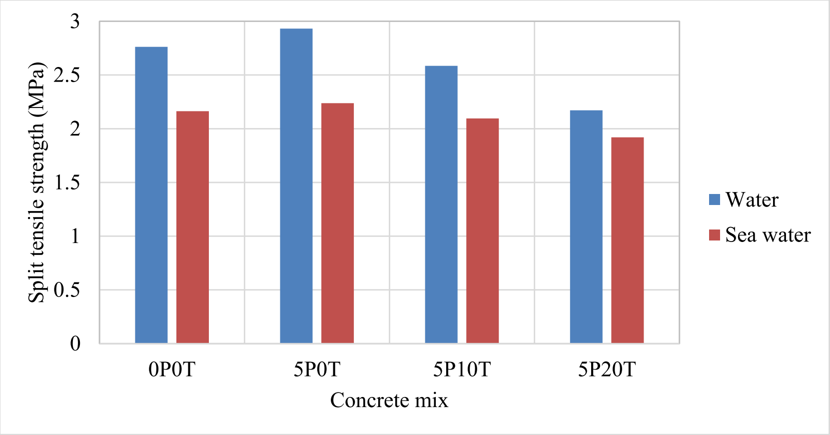

Fig. 14. Split tensile strength findings for 20 MPa concrete grade mixes cured using sea water and water.

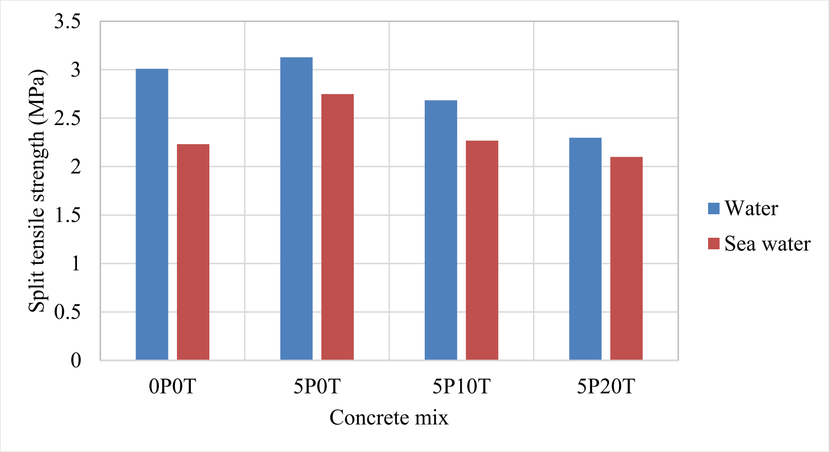

Fig. 15. Split tensile strength findings for 25 MPa concrete grade mixes cured using sea water and water.

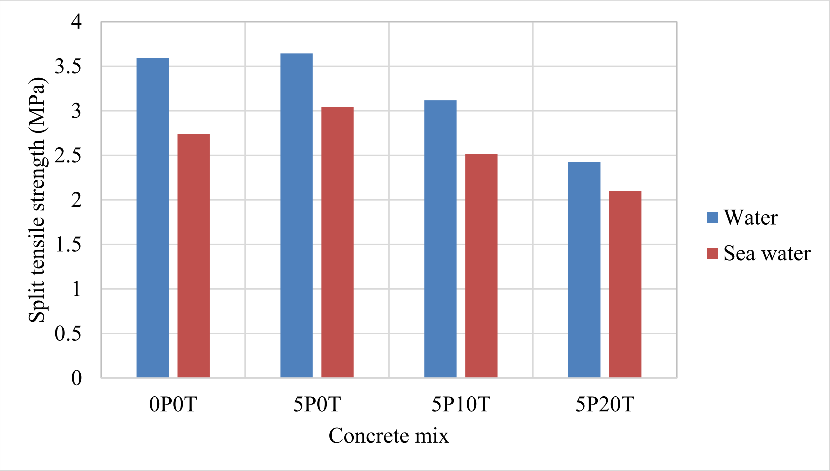

Fig. 16. Split tensile strength findings for 30 MPa concrete grade mixes cured using sea water and water.

way it had on compressive strength findings. For instance, 20 MPa concrete grade mixtures of 0P0T, 5P0T, 5P10T and 5P20T cured using sea water had 21.69%, 23.66%, 18.94% and 11.60% reductions in split tensile strength values respectively, in contrast with their corresponding mixes cured using water.

The reductions in split tensile strength values of samples cured using sea water compared with those cured using water were probably reflections that sea water curing had detrimental effects on concrete tensile splitting strength. There is a higher possibility that magnesium sulphates and potassium sulphates occurring in sea water caused concrete attack in a process called crystallisation. It is recognised that magnesium sulphates and potassium sulphates participate in reactions with calcium hydroxide in OPC created following hydration of tricalcium silicate and dicalcium silicate [8]. Compared with potassium sulphate attack, magnesium sulphate attack is reported to be severe as it forms a soluble magnesium hydroxide resulting in the creation of gypsum [86]. Other researchers [10], have found that reductions in strength performances of concrete mixtures as a consequence of sea water curing environment are usually experienced at longer curing periods and no reductions are experienced at shorter curing periods. For this research, the hypothesis reported in the foregoing study was only adhered to at 90 days and could not be established at shorter curing periods. As such, further future studies are recommended to capture this interesting aspect for behaviour of rubberised concrete incorporated with WCBP at shorter curing periods.

The additions of 5% WCBP were noticed to improve the modified concrete split tensile strength performances compared with control concrete mixes for both curing methods. The increments in split tensile strength values for concrete mixtures with 5% WCBP compared with control concrete mixtures were because of the previously explained enhanced pozzolanic activity of WCBP at longer periods of curing. The occurrence of higher quantity of SiO_2 in WCBP seemed to be the cause of increased pozzolanic reaction. Since SiO_2 reacts with calcium hydroxide to create calcium silicate hydrates (C–S–H), it could be possible that this reaction caused increased split tensile strengths in modified concretes compared with control concrete mixtures. Experiments have verified that WCBP can enhance durability of concrete structures exposed to alkali-silica reaction and sulphate attack elsewhere [87,88]. The reductions in

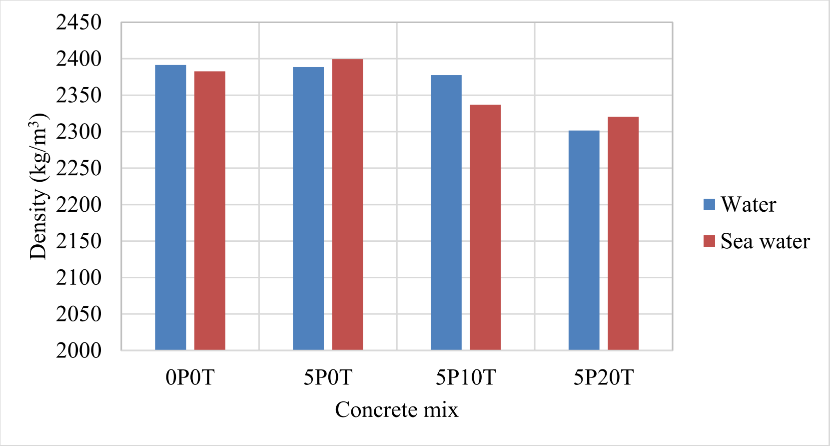

Fig. 17. Density findings of cylinder specimens for 20 MPa concrete grade mixes cured using water and sea water.

split tensile strength values were more pronounced in concretes when WTR aggregates were introduced. Segregation of surfaces between WTR and cementitious paste occurring during crack expansions was reasoned as the cause of such performance [89]. The incorporation of WTR was noticed to decrease the split tensile strengths of modified concrete mixtures in contrast with control concrete mixtures. Reduced bonding occurring between WTR and cementitious paste is reported to cause cracking [90]. In addition, interface zones existing between cement paste and WTR are found to behave like micro-cracks because of reduced bonds thereby increasing concrete failure [89].

3.6. Density of samples

Figs. 17–19 show density findings of samples cured using water and sea water for 20 MPa, 25 MPa and 30 MPa concrete grades respectively. The figures display no meaningful trends between density findings of concrete samples cured using water and sea water. From the perceptive of concrete density, this might be one of the explanations as to why it might be interesting to consider curing concrete samples using sea water. The incorporation of WTR aggregates was found to decrease densities of concrete mixtures in contrast with control concrete mixtures for all concrete grades.

From Figs. 17–19, it is clear that no meaningful distinctions are observed between density values of samples cured using sea water and water. Using this observation, it was concluded that sea water curing did not significantly influence the densities of concrete mixtures compared with samples cured using water. The additions of WTR aggregates were noted to decrease the densities of concrete mixes for both curing conditions. It is recognised that densities of concrete samples are dependent on types of aggregates used. As far as the concrete densities are concerned, incorporations of WTR aggregates reduce the densities of concrete [91]. The reductions in concrete densities of rubberised concrete mixtures incorporated with WCBP were because of reduced bulk density of WTR aggregate. In this research, WTR aggregates gave compacted bulk density and percentage of voids values of 567.55 kg/m^3 and 49.33% respectively. Compacted bulk densities of materials are of significant importance in concrete production. It is recognised that aggregates showing compacted bulk densities of less than 1000 kg/m^3, 1000–1700 kg/m^3 and greater than 1700 kg/m^3 are classified as lightweight aggregates, dense aggregates and extra dense aggregates respectively [82]. As a consequence of reduced compacted bulk density of WTR aggregates, substituting coarse aggregates with 10% and 20% WTR was expected to decrease the concrete density. In contrast, the reduced specific gravity of WCBP of 2.69 compared with that of OPC (3.12) implied that WCBP is marginally lighter than cement. Thus, replacing OPC with 5% WCBP was not believed to be sufficient enough to cause substantial decrease in concrete density. This explains why concrete mixtures of 0P0T and 5P0T display no meaningful trends in density for 20 MPa, 25 MPa and 30 MPa concrete grades.

3.7. Changes in diameters of samples

It is to be mentioned that no changes in diameters were noted on cylindrical samples cured using water and sea water. There appeared to be no proof that diameters of cylindrical samples increased or decreased after removal from sea water and water. Other researchers [10], have explained that sea water curing causes concrete expansion and deterioration of concrete elements as a result of the presence of salts. Another study [9], reached at a similar conclusion that existence of salts leads to enhanced expansion because of the creation of extra alkali hydroxide in pore solutions of concrete. Although studies have illustrated concrete expansion during curing using sea water, in this study, no meaningful variations in diameters of the cylinders were evident for samples cured using sea water. It was thought that effects of sea water curing in this research were not translatable to any visible diameter changes. It was suggested that this might have been because of limited curing period. Had the curing periods been increased, it was suspected that diameter changes might have probably been experienced.

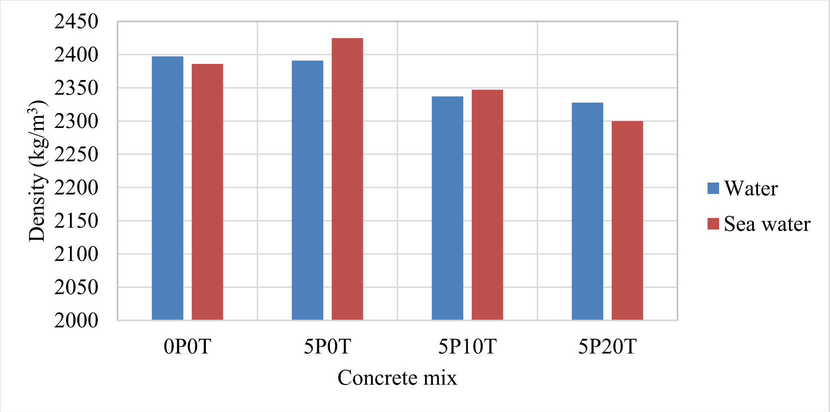

Fig. 18. Density findings of cylinder specimens for 25 MPa concrete grade mixes cured using water and sea water.

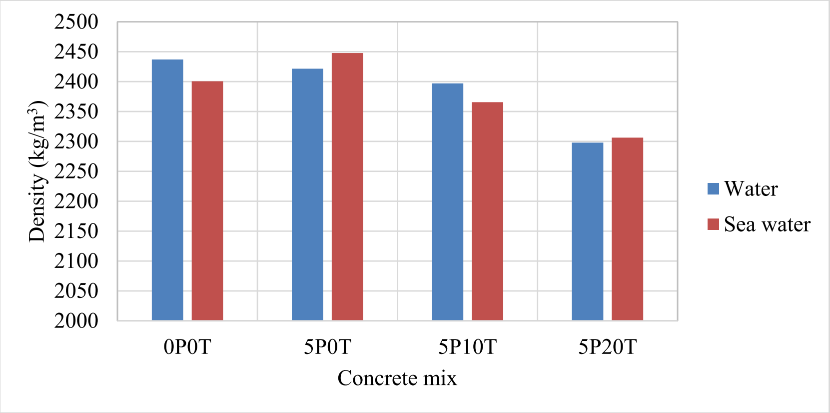

Fig. 19. Density findings of cylinder specimens for 30 MPa concrete grade mixes cured using water and sea water.

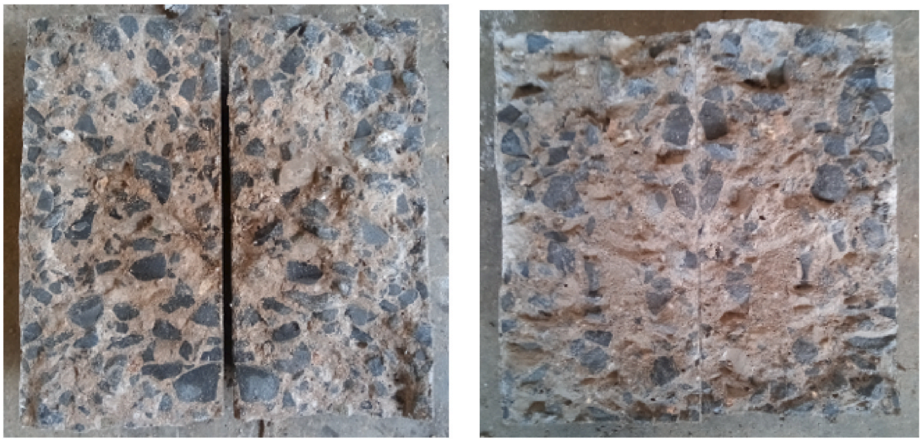

Fig. 20. Cross-sections of representative split tensile strength cylinder samples for 20 MPa concrete grade; 0P0T (left; cured using water) and 0P0T (right; cured using sea water).

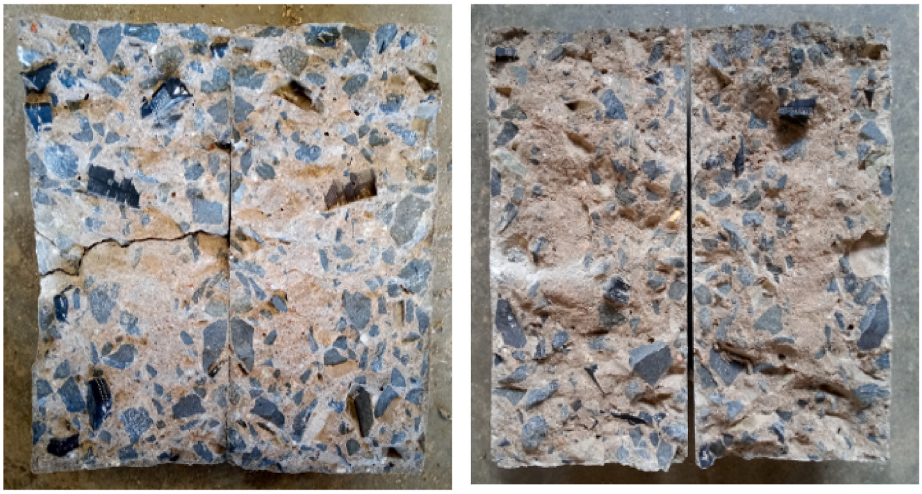

Fig. 21. Cross-sections of representative split tensile strength cylinder specimens for class 25 MPa concrete grade; 5P10T (left; cured using water) and 5P10T (right; cured using sea water).

3.8. Visual inspection

The cylindrical samples broken after 90 days of sea water and water curing are illustrated in Figs. 20 and 21. In this research, the surface attributes of the broken specimens were carefully analysed to understand the effects of the various curing environments on behaviour of rubberised concrete incorporated with WCBP samples. It should be remarked that only representative specimens have been illustrated in Figs. 20 and 21.

From Figs. 20 and 21, it seems that sea water ingression into the samples was very pronounced compared with water ingression. Another study [81], citing several works, indicates that concrete exposed to sea water permits concrete wetting with salt solutions, primarily magnesium sulphates and sodium chlorides. This was confirmed in this study through visible wetting of concrete samples cured using sea water compared with concrete samples cured using water. It was suspected that the occurrences of magnesium sulphates and sodium chlorides in sea water caused high wetting of concrete samples in this study. This behaviour might have probably led to the previously explained reduced compressive and split tensile strength values of concrete samples. However, to fully understand the behaviour of concrete cured using sea water, further future studies are proposed especially in the actual sea water environment.

4. Conclusions

The following important conclusions were established from this study.

1. The curing environments affected the concrete compressive and split tensile strength values. Conventional and modified concrete mixtures cured using sea water showed reduced compressive and split tensile strength values in contrast with corresponding mixes cured using water. The occurrences of magnesium sulphates ($MgSO_4$) and potassium sulphates (K_2SO_4) in sea water might have probably participated in reactions with calcium hydroxide in OPC leading to the creation of gypsum which causes losses in concrete strength.
2. Concrete mixtures with 5% WCBP illustrated increased compressive and split tensile strength values in contrast with the conventional concrete mixes. This might be an explanation of pozzolanic reaction of WCBP associated with longer curing period.
3. No meaningful distinctions were obtained between densities of samples cured using sea water and samples cured using water. This suggested that densities of conventional and modified concrete mixtures cured using sea water were similar to those mixtures cured using water.
4. From the perceptive of curing environments, compressive strength seemed to be less sensitive to curing environments compared with split tensile strength. Compressive strength reductions between samples cured using sea water and water seemed not to be very pronounced compared with split tensile strength losses between the two curing conditions.
5. Visible high wetting of concrete was noticed with samples cured using sea water than those cured using water. This suggested that sea water ingression in concrete samples was greater than ingression of water in concrete samples.
6. There seems to be evidence to propose that curing using sea water could still be utilised in areas where pure water is very scarce. Minor reductions in compressive strengths for samples cured using sea water compared with those cured using water might be reflections of possibility of utilising sea water as a curing agent. Utilisation of sea water in curing concrete could progressively be a promising alternative for construction works near the beaches and sea-ward structures.
7. The behaviour of rubberised concrete containing WCBP at longer curing periods beyond 90 days has not been established in this study. Further future studies on curing rubberised concrete containing WCBP at longer curing periods beyond 90 days are proposed.

Author contribution statement

David Sinkhonde: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Richard Ocharo Onchiri, Walter Odhiambo Oyawa, John Nyiro Mwero: Conceived and designed the experiments; Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of interest’s statement

The authors declare no conflict of interest.

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