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Research article

A study on mechanical properties of rubberised concrete containing burnt clay powder

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ABSTRACT

An experimental study was conducted to investigate the mechanical performance of rubberised concrete containing Burnt Clay Powder (BCP). Waste Tire Rubber (WTR) and BCP were used to replace coarse aggregate and Ordinary Portland Cement (OPC) respectively. Class 20, 25 and 30 concrete mixes based on British Research Environment (BRE) were cast and tested for compressive, split tensile and flexural strengths. The findings of the tests revealed reductions in compressive and split tensile strengths for concrete mixes with 5% BCP compared to control concrete mixes for 7, 28 and 56 days curing periods. However, inclusion of BCP in concrete seemed to increase the compressive and split tensile strengths of concrete compared to control concrete at 90 days curing period. The findings also demonstrated that WTR content as high as 20% by aggregate total volume could be used to generate rubberised concrete containing 5% BCP with compressive strengths of 18–33 MPa for class 20, 25 and 30 concrete mixes. The flexural strength of unreinforced beams decreased due to inclusion of 5% BCP compared to control concrete after 28 days of curing. Rubberised concrete with BCP was observed to promote ductile failure of concrete cubes while control concrete cubes exhibited brittle failure. The inclusion of 5% BCP in concrete seemed to decrease compressive and split tensile strengths at lower curing periods while still presenting improved results at longer curing period.

1. Introduction

The shortage of natural aggregate is posing a challenge to the construction industry. As a result, many countries are restricting the production of natural aggregate and its crushing [1]. In order to overcome this challenge, partial replacement of coarse aggregate with Waste Tire Rubber (WTR) is proposed. Owing to increased demand for coarse aggregates in construction sector [2], replacing coarse aggregates with WTR reduces environmental pollution [3]. Also, inclusion of WTR in concrete has been recommended for vibration damping and energy absorption applications [4]. However, performance of concrete is dependent on its properties. It is known that strength of concrete constitutes the basis of rejection or acceptance of concrete performance. The crucial kinds of concrete strengths are compressive, split tensile and flexural strengths. Concrete compressive strength indicates the capability of a particular concrete mix in resisting axial compressive load [5]. Some studies [6, 7, 8, 9], have indicated that concrete compressive strength is affected by type of cement, rate of loading, admixtures, pozzolanic materials, concrete maturity, concrete age and curing. The split tensile strength is a significant concrete property and its ignorance could result in durability and serviceability problems [10]. It is known that crack control and propagation are heavily associated with concrete split tensile strength [10]. The foregoing study reported that concrete split tensile strength in the design of reinforced concrete members is usually neglected. Meanwhile, flexural strength is the determination of tensile strength of concrete slabs or beams. In practice, the measurement of concrete flexural strength is a relevant design criterion for structures such as rigid pavements [6].

The goal of sustainable construction has been to use waste materials economically and efficiently to substitute concrete constituents. Often such advancements tend to be faced with reductions in mechanical properties of concrete due to inferior properties associated with some waste materials. An example is the inclusion of WTR which induces intense loss of concrete compressive strength [11, 12]. A

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considerable disparity existing between rubber elastic modulus and cementitious paste and weakened interfacial transition zones are generally responsible for such decrease in strength [13]. It has been found that coarse aggregate replacement by 5% tire rubber appears to be practical with regard to compressive strength [12]. Zheng et al. [14] observed that 30% coarse aggregate replacement with WTR led to 48% compressive strength reduction in comparison with control concrete. In another study [15], 15% was established as a maximum coarse aggregate replacement with tire rubber in concrete. To avoid substantial compressive strength reductions, other investigators [16], have recommended 20% as maximum replacement of coarse aggregates with tire rubber. Moreover, Thomas et al. [17] observed that high strength rubberised concrete can be resilient to adverse environments.

The splitting tensile strength test conducted on concrete cylindrical specimens is used to determine concrete tensile strength. Almaleeh et al. [18] reported that splitting tensile strength reduced up to approximately half of the strength of control mix upon replacing sand and gravel by 50% of fine and coarse rubber aggregates respectively. The normal concrete was observed to split into well-defined failure patterns than the rubberised concrete in another study [3]. The authors in the foregoing study reasoned that weak bonding between concrete ingredients and tire rubber particles was the cause of such failure. At an extreme note, Guneyisi et al. [19] observed that 50% volume of total aggregate substitution with WTR decreased splitting tensile strength by 80% compared to control concrete. Regarding avoiding such extreme reduction in mechanical properties, a number of investigators have suggested that the maximum WTR content should not exceed 20% [16], 25% [20] and 30% [14]. Other studies [15, 21], have illustrated that crumb rubber inclusion in concrete results in reduced mechanical properties losses compared to chipped rubber aggregates. On the other hand, flexural strength is the determination of the resistance to bending failure in unreinforced concrete slab or beam [22]. For 5%, 10% and 15% volumetric substitutions of coarse aggregate with tire particles, 4%, 14% and 16% reductions of flexural strength were discerned respectively, compared to control concrete [2]. These reductions in flexural capacity of the rubberised concrete were reported to be because of weakened bonding between WTR and the cementitious paste. Sree et al. [23] found that 5% of crumb rubber content led to loss of flexural strength of concrete by 10%.

The use of Burnt Clay Powder (BCP) as an artificial pozzolanic material has been observed to lower the consumption of energy and emissions of CO_2 during cement production [24, 25]. The hydration kinetics and mechanisms between BCP and lime to form hydrated products have been studied by several researchers [26, 27, 28]. In principle, pozzolanic reaction of clay brick powder has been found to be majorly dependent on its composition [29]. A recommendation of brick powder for pozzolanicity was illustrated through the substantial presence of SiO_2, Al_2O_3 and Fe_2O_3 meeting pozzolanic requirements in some researchers' work [27]. In another study [28], significant quantities of hydraulic oxides revealed the potential of brick powder to undergo pozzolanicity. Fundamentally, significant pozzolanic characteristics of BCP are concluded to make them attractive for partial cement replacement in concrete. Ample evidence illustrating improvement of compressive strength of concrete containing BCP compared to control concrete has also been reported in literature [30, 31, 32].

Attempts have been made to reduce mechanical properties losses in rubberised concrete. Prior treatments of tire rubber aggregates are suggested to minimise strength losses in rubberised concrete in literature [33, 34, 35, 36]. Guneyisi et. al [19] observed that inclusion of silica fume reduced the rate of strength loss of rubberised concrete. Unfortunately, not much attention has been paid to research focusing on possibility of minimising mechanical properties losses using BCP. This work is driven by the idea that enhanced pozzolanic reaction and micro-aggregate filling effects of BCP could be attractive to provide better results in rubberised concrete.

2. Materials and methods

2.1. Materials

The materials used for experiments to generate concrete mixtures were Ordinary Portland Cement (OPC) CEM I, coarse aggregate, fine aggregate, WTR and BCP produced by mechanical grinding using ball mill. Coarse aggregate of specific gravity of 2.55 was partially substituted by WTR whereas cement was partially substituted by 5% BCP of specific gravity of 2.69. WTR showed a specific gravity of 1.14. OPC class 42.5 in conformity with the standard [37], and with specific gravity of 3.12, was used. BCP passed through 75 μm sieve and showed excellent pozzolanic characteristics according to the standard [38]. In this research, fine aggregate used was river sand in accordance with the code [39]. This fine aggregate had specific gravity of 2.59. Coarse aggregate and WTR of sizes ranging from 5 - 20 mm were used in conformance with the code [39]. The gradations of fine aggregates, coarse aggregates and WTR are shown in Figures 1, 2, and 3 respectively.

2.2. Methods

2.2.1. Chemical and mineral compositions tests

X-Ray Fluorescence (XRF) experiment explored the chemical compositions of BCP. This test was conducted at the Ministry of Petroleum and Mining in Nairobi, Kenya. The test employs voltage of 30 – 60 kV and current of 50–100 mA. The typical elemental compositions of cement were also investigated for comparison. Besides, X-Ray Diffraction (XRD) analysis of cement and BCP was conducted on a diffractometer (Bruker D2 Phaser) equipped with a graphite monochromator.

2.2.2. Scanning electron microscopy

The microstructure morphology of cement and BCP was assessed using high-resolution Scanning Electron Microscope (SEM) of a 15 kV high voltage system. The equipment model used to scan the samples was the JEOL NeoScope JCM-7000 SEM machine. Before the experiment, the samples were cleaned and dried to increase surface exposure. Samples from brick powder and cement were sprinkled on the conductive adhesive tape followed by appropriate sample positioning in the equipment. The images were then captured using an accelerated electron beam which scanned the surfaces of the samples.

2.2.3. Hydrometer analysis of burnt clay powder

Hydrometer analysis covered quantitative measurements of particle sizes of BCP of less than 0.075 mm. The test was conducted in accordance with the standard [40], using a sample mass of 50 g. One litre solution was made by dissolving 33 g of sodium hexametaphosphate and 7 g of sodium carbonate in distilled water. The hydrometer reading was taken after 1 min followed by gentle removal of the hydrometer. Thereafter, the hydrometer was rinsed in distilled water and placed in distilled water with a dispersant to measure meniscus reading. The hydrometer was then reinserted in the suspension to take other readings after 2 min, 4 min, 8 min, 15 min, 30 min, 1 h, 2 h, 4 h, 8 h and 24 h periods from beginning of sedimentation. The temperature of the suspension was also recorded for each reading to an accuracy of ±0.5 °C. Eqs. (1) and (2) were used to compute effective depth, H_R and equivalent particle diameter, D respectively.

$$H_R = H + \frac{1}{2}\left(h - \frac{V_h}{900}L\right) \tag{1}$$

$$D = 0.005531\sqrt{(\eta H_r/(\rho_s - 1)t)} \tag{2}$$

where H is the length in mm from the neck of bulb to graduation, Hr is the effective depth in mm at which the density of the suspension is measured, h is the length of the bulb (in mm), V_h is the volume of hydrometer bulb (in mL), L is the distance in mm between the 100 mL and the 1000 mL

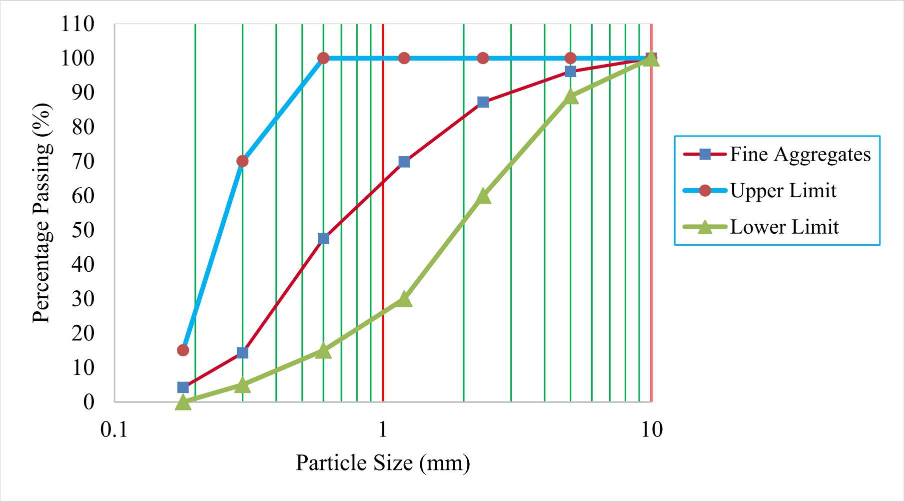


Figure 1. Particle size distributions of fine aggregate.

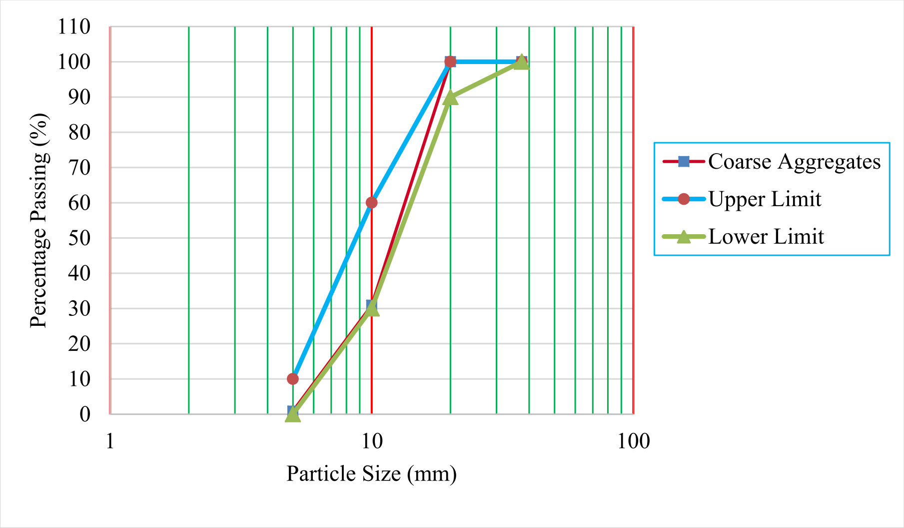


Figure 2. Particle size distributions of coarse aggregate.

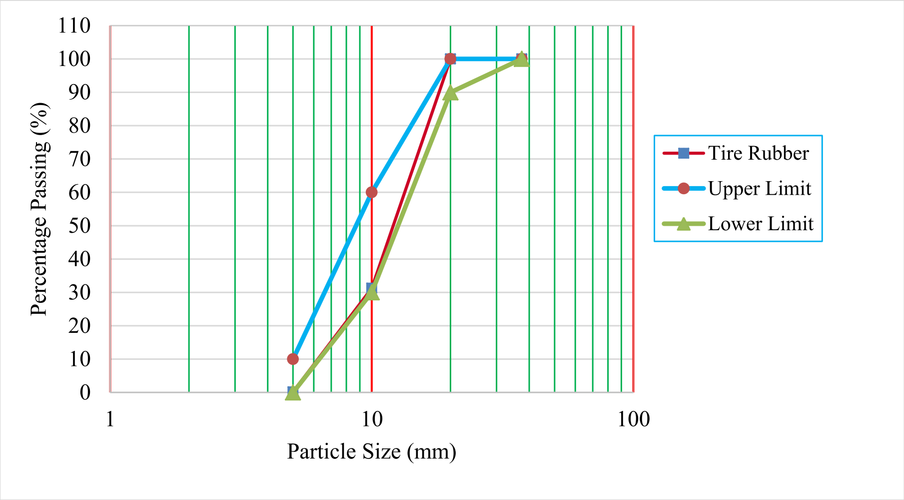


Figure 3. Particle size distribution of tire rubber aggregate.

scale markings, ρ_s is the particle density in Mg/m^3, η is the dynamic viscosity of water (in MPa·s), t is the elapsed time and 0.005531 is a constant.

2.2.4. Mix proportions

The mix ratios adopted for this study consisted of cement, fine aggregates and coarse aggregates in accordance with the standard [41]. The mix designs were performed for three concrete grades of 20 MPa, 25 MPa and 30 MPa at day 28 in conformance with British Research Environment (BRE). This method is detailed in another study [42]. Mix proportions for grade 20 concrete of 1:2.05:4.16 (cement: fine aggregate: coarse aggregate) were generated using BRE method. Concrete grades of 25 MPa and 30 MPa used mix proportions of 1:1.81:3.75 and 1:1.54:3.36 respectively. The control concrete consisted of cement, sand and coarse aggregates all at 100%. The remaining mixes had 5% of BCP and different amounts of WTR. In the latter case, coarse aggregate was partially replaced with WTR by volume whereas cement was partially replaced with BCP by mass in accordance with other studies [30, 43]. The experimental matrix is as shown in Table 1. The mixtures were coded 0P0T (Control), 5P0T (5% BCP + 0% WTR), 5P10T (5% BCP + 10% WTR) and 5P20T (5% BCP + 20% WTR). In this study, 5% replacements of cement with BCP in Table 1 were designed to have 15.45 kg/m^3, 17.00 kg/m^3 and 18.89 kg/m^3 for class 20, 25 and 30 concrete grades respectively. On the other hand, replacements of coarse aggregate with 10% WTR used quantities of 50.87 kg/m^3, 50.42 kg/m^3 and 50.14 kg/m^3 for class 20, 25 and 30 concrete grades respectively. Finally, to replace coarse aggregate with 20% WTR, rubber contents of 101.74 kg/m^3, 100.85 kg/m^3 and 100.30 kg/m^3 were used for class 20, 25 and 30 concrete grades respectively.

2.2.5. Casting and mixing of concrete

The mixing was done using a concrete mixer, metal plate, shovels and trowels with a control mechanism to prevent the water losses. In this way, a homogenous concrete was achieved. Brushing of metal casting moulds using oil was done to inhibit concrete adherence to metal forms. Concrete was then placed in metal casting moulds and compacted by poker vibrator to expel entrapped air. A sum of 12 cubes, 12 cylinders and 3 beams were cast for each mix. The cubes of dimensions of 100 × 100 × 100 mm, cylinders of 100 mm diameter and 200 mm height and beams of dimensions of 150 × 150 × 530 mm were used during concrete placements. Cube, cylinder and beam samples were removed from the moulds following 24 h of casting. Thereafter, the specimens were cured in a curing tank for 6, 27, 55 and 89 days. The curing temperature range was 21.7 °C – 26.5 °C. Because BCP and WTR reduce workability, water was added to concrete mixes to maintain workability.

2.2.6. Measurements of fresh concrete properties

Before hardened concrete studies, fresh properties were assessed using slump test in conformity with the standard [44]. The slump values ranged from 10 – 30 mm in order to maintain the workability of concrete mixtures.

2.2.7. Measurement of compressive strength

The concrete compressive strength tests were done on 144 cube samples which were cast and tested after curing periods of 7, 28, 56 and 90 days. The Universal Testing Machine (UTM) was used at a loading rate of 0.5 kN/s in accordance with the standard [45]. Each specimen was mounted appropriately on the testing equipment prior to loading to prevent buckling. Compressive load from a movable cross head was exerted on the specimen and maximum load at which the specimen collapsed was recorded by the load indicator. The compressive strength of every cube was computed by dividing up the maximum applied load to the cube by the area of cross-section of the cube in conformity with the standard [46].

2.2.8. Measurement of tensile splitting strength

Measurements of the tensile splitting strength were carried out on 144 cylinder specimens in accordance with the standard [47]. Cleaning the bearing surfaces of the loading rollers was conducted to remove any material resting on them. Concrete cylinders cast and cured for 7, 28, 56 and 90 days then received diametrical load along cylinder length from a UTM. This load at a loading rate of 0.5 kN/s stimulated cracking on the specimen. The maximum load at failure of specimen was divided by geometric parameters as illustrated by Eq. (3) to get the tensile splitting strength.

$$\sigma_{ct} = \frac{2P}{\pi \times l \times d} \tag{3}$$

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

2.2.9. Measurement of flexural strength of unreinforced beams

Flexural strength tests were done on rubberised concrete containing 5% BCP specimens in accordance with the standard [48]. Besides, 3 beams in absence of BCP and WTR were evaluated for comparison for each concrete class. A total of 36 specimens were cast and tested for characteristic strengths of 20 MPa, 25 MPa and 30 MPa. The specimens were tested following 28 days of curing in water. Prior to mounting on the flexural test assembly of the UTM, the specimens were marked to have a clear span of 450 mm. With 2 point loads, the specimens were loaded using a loading rate of 0.5 kN/s until the mechanisms failed. The flexural strength derived from the maximum flexural load was reported.

3. Results and discussion

3.1. Chemical and mineral compositions

The chemical compositions and loss on ignition (LOI) values of cement and BCP are shown in Table 2. The most abundant chemical is silica (SiO_2) accompanied by iron oxide (Fe_2O_3). As expected, quantified percentages of SiO_2, Fe_2O_3 and Al_2O_3 generated a sum of 85.93% and this explains the pozzolanic properties in BCP. Materials revealing a minimum percentage of 70% for (SiO_2 + Fe_2O_3 + Al_2O_3) are categorised as class N pozzolans in accordance with the standard [38]. From the results, feasibility of using BCP as a pozzolanic material is established. The XRD patterns for cement and BCP are presented in Figures 4 and 5 respectively.

The compositions of cement and BCP presented in Table 2 account for approximately 98.90% and 98.94% respectively. The remaining minimal quantities (1.1% for cement and 1.06% for BCP) were due to undetected elements by XRF. Meanwhile, the presence of SiO_2 in BCP is observed to

Table 1. Experimental matrix used in the study.

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

Table 2. Chemical compositions of BCP and cement.

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
BCP	64.36	12.86	8.71	2.00	-	1.82	3.05	2.13	0.68	1.18	1.18	-	0.97

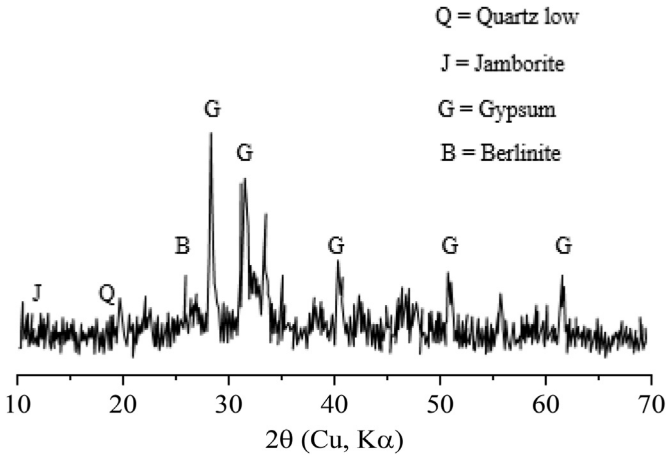


Figure 4. The mineral compositions of cement using XRD spectrum.

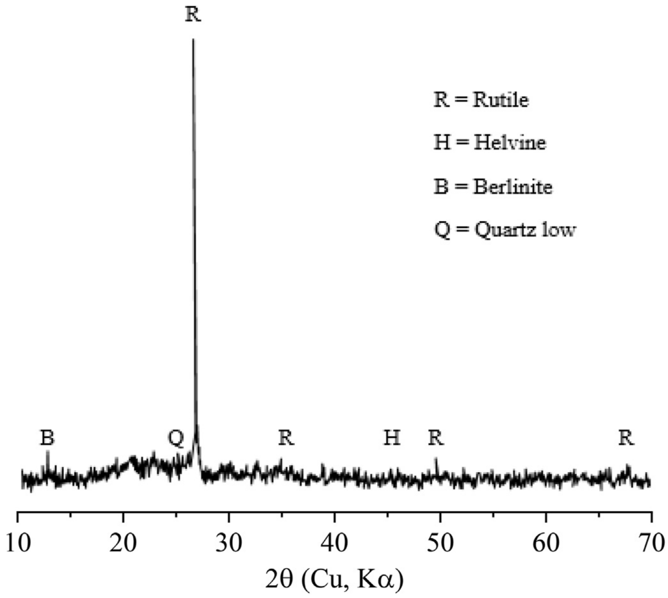


Figure 5. The mineral compositions of BCP using XRD spectrum.

participate in a pozzolanic reaction. The existence of rutile (TiO_2) is characterised by some small peaks and this is in good agreement with other investigators [49]. Such existence of TiO_2 is likely as the compound is introduced as a colorant during clay bricks production to increase mechanical strength of bricks [50].

3.2. Scanning electron microscopy

Figures 6(a-d) and 7(a-d) show images captured using SEM technique for cement and BCP respectively. The SEM method was used to study typical particle surface texture and shapes of the particles. This method is sufficiently capable to examine the morphology, formation, size and size distribution of materials by probing the specimens on fine scaling [51, 52].

It is evident from Figure 7(a-d) that BCP particles in this study are neither smooth nor spherical. Nevertheless, the particles demonstrate irregular and sharp corners which are observed to formulate slits. The finer particles are observed to abide in the slits and notches of bigger sizes when the particles are subjected to higher levels of magnification. Accordingly, this peculiar arrangement enhances the water demand and impedes the workability characteristics of fresh concrete [50]. The SEM images captured for BCP visibly reveal finer particles in comparison with SEM images of cement. Hydrometer analysis findings presented hereinafter also revealed finer particles of BCP. It is known that finer brick powder absorbs more water which results in reduced slump and increased consistency of cement paste [53]. The finer particles of BCP are also responsible for the early age hydration [25], and this phenomenon is attributed to the formation of crystallisation nucleus which enhances the propagation of hydrated products. The use of BCP in cement paste and concrete is therefore suggested to result in reduced slump and early strength of cement paste and concrete.

3.3. Hydrometer analysis of burnt clay powder

Figure 8 shows a curve for particle size distribution of BCP. The parameters of percentage finer and particle diameter are presented to illustrate data gathered for 24 h for 50 g of BCP. More information about elapsed actual times and corrected hydrometer readings has been presented in Table 3. The particle diameters of the sample ranged from 0.0014 to 0.055 mm. The percent finer reduced from 70.4 to 20.4 % in the 24 h period.

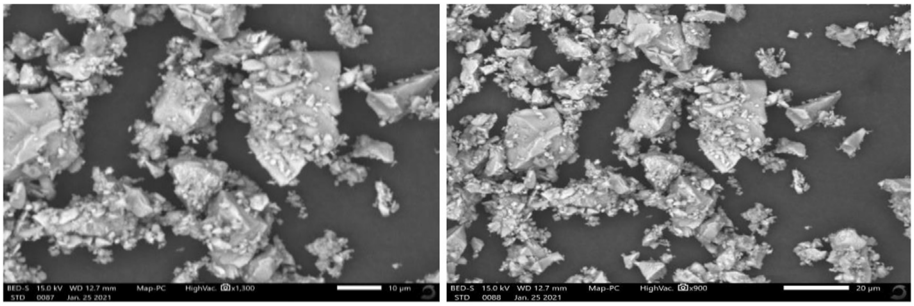
The diameters shown in Figure 8 show that BCP in this study mainly comprised of finer particles that lied between 1 μm and 75 μm. This fineness is associated with increased pozzolanic reaction resulting in concrete with superior compressive strength [54]. The use of BCP with increased fineness is noted to reduce the alkali-silica reaction expansion in concrete consequently reducing mechanical properties losses [55]. This foregoing study observed that the alkali-silica reaction is altered because of introduction of brick powder thereby leading to a less expansive product. When the quantity of brick powder is small, finer brick powder is also able to fill the spaces between particles of cement and this improves flexural strength and durability properties of concrete [56].

3.4. Fresh concrete properties

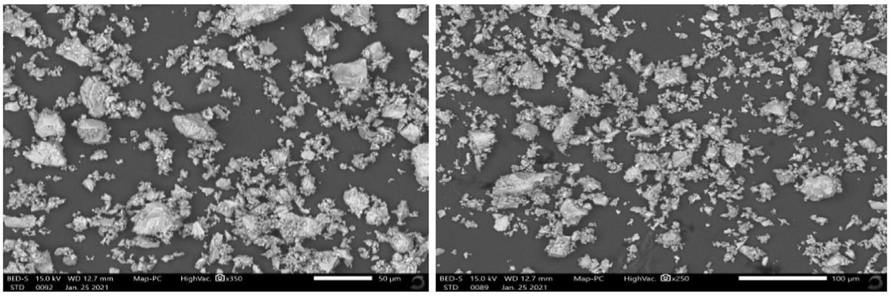
The measured slump values ranged from 15 to 26 mm. Reduction of workability for fixed water-cement ratio is noticed because of inclusion of BCP and WTR in concrete production [19, 57]. This reduction in workability attributed to BCP and WTR incorporation in concrete was compensated by adding water. Additional water is observed to decrease friction between particles through particle lubrication process thereby increasing concrete workability [58]. This is because some pozzolans including BCP increase concrete stiffness of mixtures [59]. WTR inclusion is also observed to decrease concrete workability [13, 19]. It is suggested that comparison between concrete mixes is easily achieved when slump measurements are within a specified slump range [60]. Moreover, low workable concrete is reported to be suitable for road pavements or mass dam structures [61].

3.5. Compressive strengths of control and modified concretes

Figures 9, 10, and 11 illustrate the influence of including BCP in concrete for class 20, 25 and 30 control and modified concretes respectively. The figures also display the effect of including WTR in concrete.

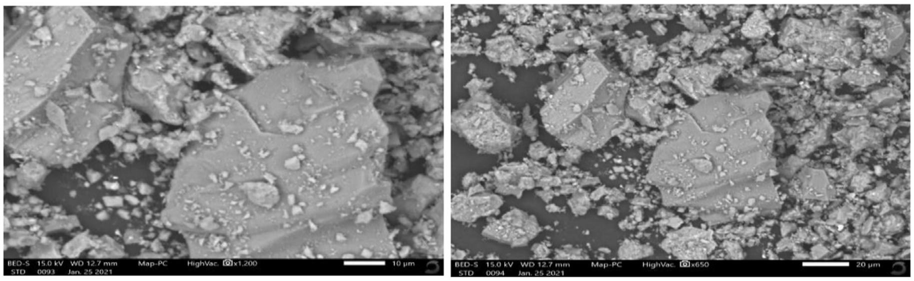


(a) Scale bar: 10 µm (b) Scale bar: 20 µm

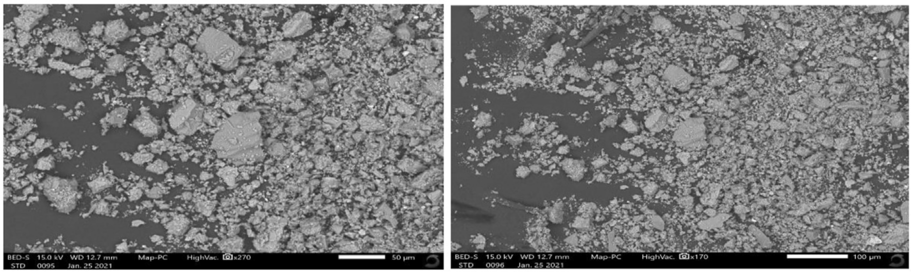


(c) Scale bar: 50 µm (d) Scale bar: 100 µm

Figure 6. SEM images of cement.



(a) Scale bar: 10 µm (b) Scale bar: 20 µm



(c) Scale bar: 50µm (d) Scale bar: 100 µm

Figure 7. SEM images of BCP.

Note that the error bars are added in the figures to easily establish the influence of these waste materials in concrete. With the error bars, the influence of BCP and WTR in concrete is postulated for every mix. It is also more appropriate to mention that the use of error bars for small sample sizes (for example $n = 3$) has its limitations including lack of precise estimates [62]. As such, the use of high n values is greatly recommended. Nevertheless, because investigators currently still use small n values, it is still necessary to interpret findings from error bars [62].

In this study, the curing temperature and pH of water of 24.2 °C and 7.07 were measured at a specific time respectively. In general, concrete with 5% replacements of cement with BCP showed compressive strengths less than reference concrete mixes for all classes at 7, 28 and 56 days curing periods. This influence was more significant at 7 days than 28 days for all classes of concrete. For instance, 5% replacements of cement with BCP in class 20 concrete mixes gave 8.42% and 4.54% compressive strength reductions at 7 and 28 days respectively, compared to normal concrete mixes. Such reduced strength loss in concrete with brick powder is anticipated due to increased pozzolanic reaction rate as curing period increases [63]. This is also desirable behaviour in concrete production since it implies that BCP inclusion can potentially maintain or outweigh compressive strength of control mix. The decrease in compressive strength was also observed as tire rubber was incorporated at a constant BCP content.

The increased early strength in compressive strength was noticed at 7 days curing period. It is now possible to realise early compressive strength of concrete by using ordinary cement based concrete mixes [64].

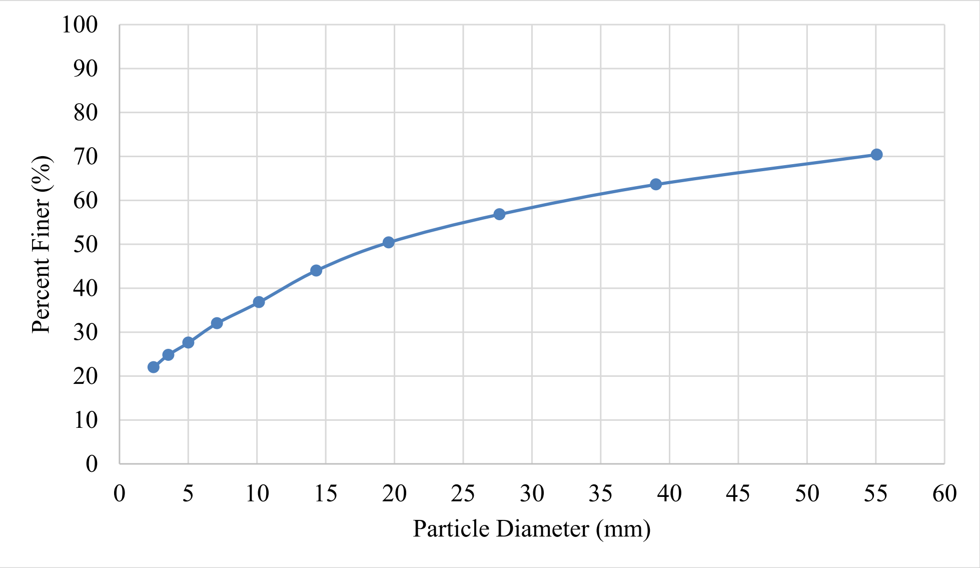


Figure 8. Graph of percent finer versus particle size of BCP.

Table 3. Hydrometer calculations for BCP.

Date & time of reading	Elapsed time (min)	Temperature °C	Actual hydrometer reading, R_h	Corrected hydrometer reading, Ra	Percent finer (%)	Hydrometer length (mm)	Diameter (μm)
3/3/2021 8:06	0	-	-	-	-	-	-
3/3/2021 8:07	1	21.0	0.0028	0.0035	70.4	167.49	55.08
3/3/2021 8:08	2	21.0	0.0025	0.0032	63.6	168.10	39.02
3/3/2021 8:10	4	21.0	0.0021	0.0028	56.8	168.71	27.64
3/3/2021 8:14	8	21.0	0.0018	0.0025	50.4	169.29	19.58
3/3/2021 8:21	15	21.0	0.0015	0.0022	44	169.87	14.32
3/3/2021 8:36	30	21.0	0.0011	0.0018	36.8	170.51	10.15
3/3/2021 9:06	60	21.0	0.0009	0.0016	32	170.95	7.10
3/3/2021 10:06	120	21.0	0.0007	0.0014	27.6	171.34	5.02
3/3/2021 12:06	240	21.0	0.0005	0.0012	24.8	171.60	3.56
3/3/2021 16:06	480	22.0	0.0004	0.0011	22	171.85	2.49
4/3/2021 8:06	1440	23.0	0.0003	0.0010	20.4	171.99	1.44

At curing temperatures of over 20 °C, ordinary cement based concrete mixes exhibit higher strength at 7 days curing period compared to other curing temperatures [65]. The curing temperature range of 21.7 °C – 26.5 °C measured in this study was believed to have resulted in early strength of concrete. The inclusion of finer particles of BCP in concrete was also thought to have resulted in early strength of concrete. BCP has been found to yield early strength of concrete due to propagation of hydrated products occasioning from crystalisation nucleus formation [25]. This

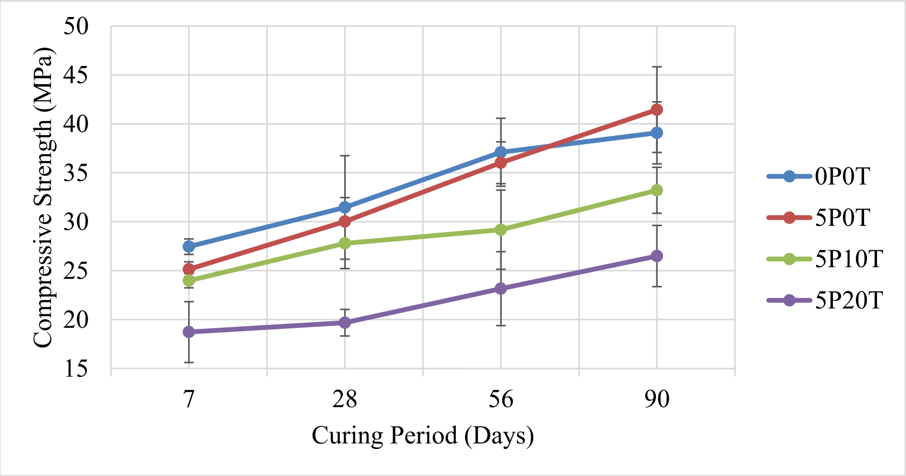


Figure 9. Compressive strength results for class 20 control and modified concretes. The findings are presented as the mean values for $n_{sample} = 3$. The error bars are also included.

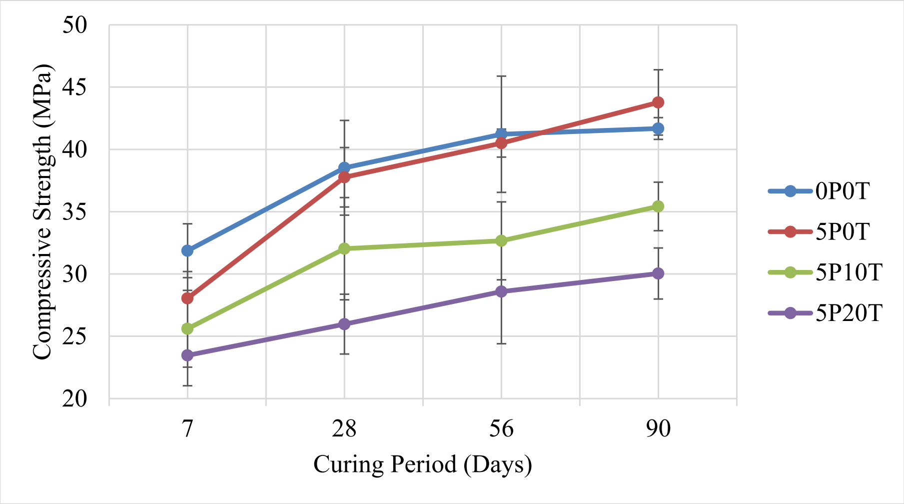


Figure 10. Compressive strength results for class 25 control and modified concretes. The findings are presented as the mean values for $n_{\text{sample}} = 3$. The error bars are also included.

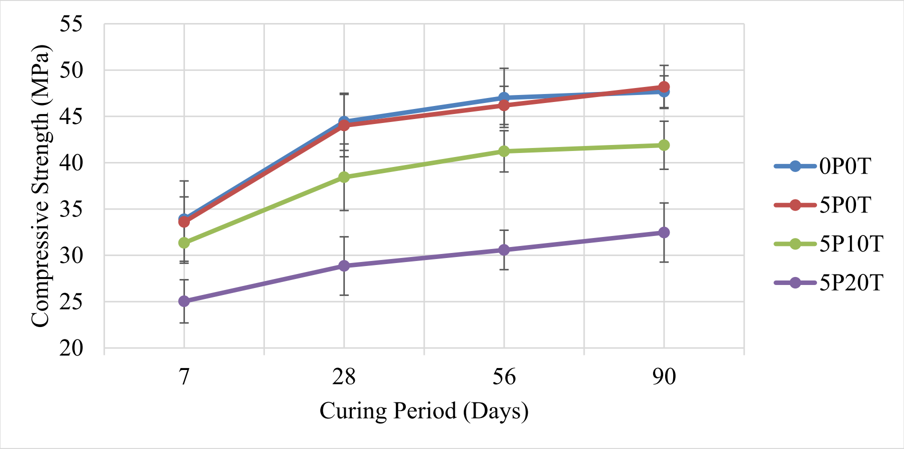


Figure 11. Compressive strength results for class 30 control and modified concretes. The findings are presented as the mean values for $n_{\text{sample}} = 3$. The error bars are also included.

early strength development is desirable in heavily trafficked concrete pavement and bridge deck [64].

The decrease in compressive strength was observed as cement was partially substituted with 5% BCP at 7, 28 and 56 days curing periods in all concrete classes. The poor strength development due to incorporation of BCP is expected due to slow pozzolanic reaction process [66]. These results are consistent with other researchers [67], but contradict another study [68], which observed increments on 7, 14 and 28-days compressive strengths of concrete mixes incorporated with BCP compared to control concrete mixes. This foregoing study reported increments in compressive strength for 10% and 20% cement replacements compared to control concrete mixes. Meanwhile, the initial decrease in compressive strength is attributed to dilution effect of BCP [53], and is evident in low curing periods as is the case in this study because of reduced levels of $Ca(OH)_2$ to react with SiO_2 [69]. Also, the superior performance in compressive strength is expected at longer curing periods as pozzolanic reaction of BCP is more evident with such periods due to increased rate of pozzolanic reaction [70]. A noticeable decrease in compressive strength due to introduction of tire rubber in concrete can be explained by weak bonding between concrete ingredients and particles of tire rubber [3]. It is also worth mentioning that error bars included in Figures 9, 10, and 11 seem to be relatively short. An important conclusion can be drawn that data are clumped around the means and this could be a reliable justification of the interpretation of findings in this study.

The findings illustrate that compressive strengths of concrete containing BCP did not exceed those of control concrete mixes at 7, 28 and 56 days curing periods for all concrete classes. However, the behaviour of concrete mixes incorporated with BCP at 90 days curing period for all concrete classes seemed to be characterised by higher compressive strengths compared to control concrete mixes. For instance, at this curing period, the compressive strength of concrete containing BCP surpassed that of control concrete by 2.381 MPa for class 20 concrete. Other investigators [70], have concluded that the pozzolanic reaction of BCP is primarily experienced between 60 and 90 days curing periods. Other researchers [32], observed that 5% cement replacement with BCP compensated strength losses of concrete with recycled aggregates at longer curing periods. Considering this, 5% BCP inclusion in rubberised concrete was suggested to reduce strength losses of rubberised concrete at longer curing periods.

3.6. Compressive strength and failure mechanism

Figure 12 shows the failure modes of cubes following compressive strength test. According to Figure 12(a), failure development for control

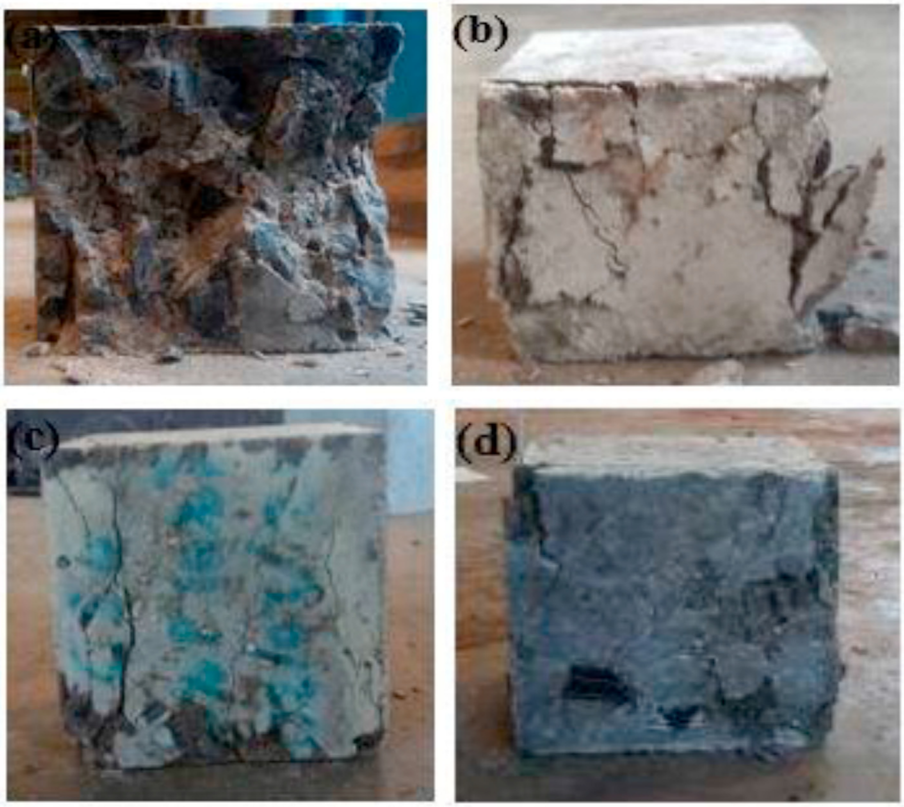


Figure 12. Failure modes of class 30 control and modified concrete mixes (a) 0P0T (b) 5P0T (c) 5P10T (d) 5P20T.

concrete is demonstrated with brittleness failure mode. Concrete with 5% BCP showed brittle failure which was characterised with nearly spalled pieces (Figure 12(b)). Unlike the brittle failure discerned in normal concrete, rubberised concrete with BCP exhibited a pseudo-ductile tensile performance and improved capacity in dissipation of energy. The patterns of failure for concrete mixes satisfied the failure modes indicated in the standard [71].

By including WTR (10% and 20% replacing coarse aggregates), modified concrete developed significantly increased ductility and did not exhibit brittle performance (Figures 12c and 12d). The figures depict well defined cracks and the fractures were not explosive. In comparison with Figure 12d, 5P10T concrete mix in Figure 12c illustrates wider cracks propagating from top surface to bottom surface. The crack widths of 5P20T concrete mix remained relatively minimal and it appeared that this was a contribution of 20% WTR replacing coarse aggregate. This observation was somewhat not surprising considering that inclusion of WTR in concrete is reported to reduce crack width. The decrease in crack width could be owed to a decline in compressive load due to the inclusion of tire rubber, resulting in increased ductility. Control concrete exhibited brittle failure compared to modified concrete and this was attributed to higher compressive strength values illustrated by control concrete compared with rubberised concrete containing BCP. The applied compressive load coupled with friction of surface were responsible at hindering more crack distribution (Figure 12a). It is known that

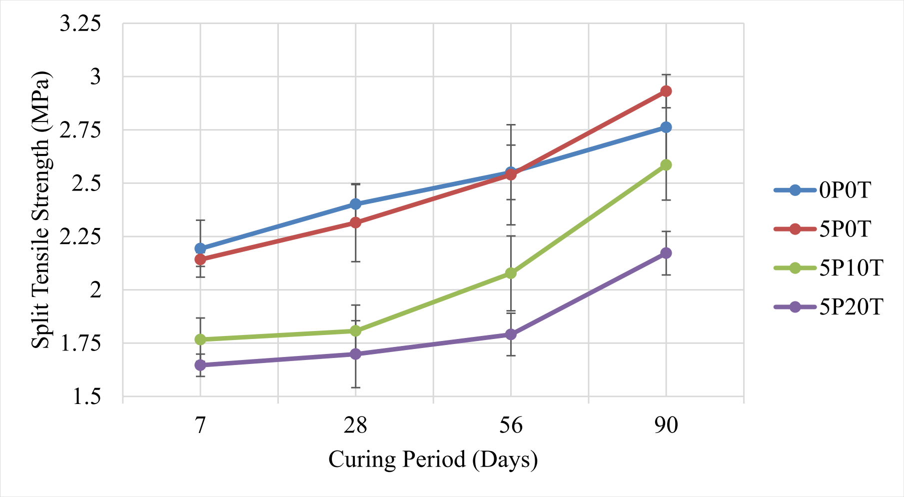


Figure 13. Split tensile strengths of class 20 control and modified concretes. The findings are presented as the mean values for $n_{sample} = 3$. The error bars are also included.

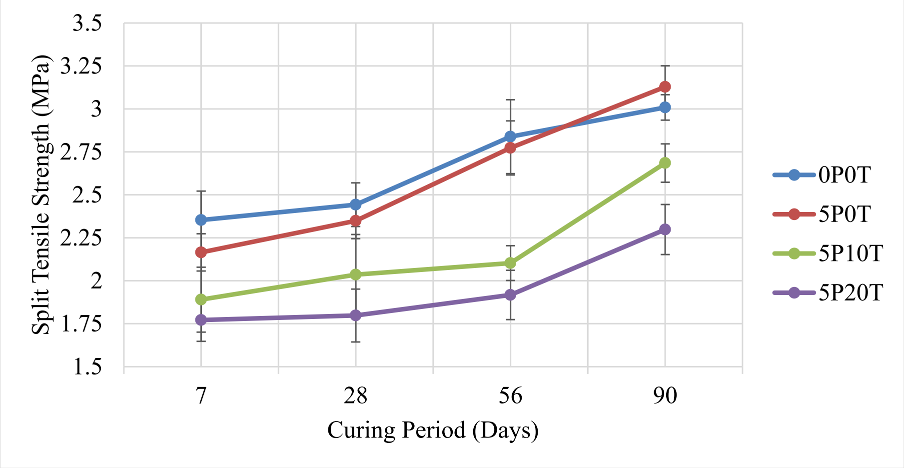


Figure 14. Split tensile strengths of class 25 control and modified concretes. The findings are presented as the mean values for $n_{sample} = 3$. The error bars are also included.

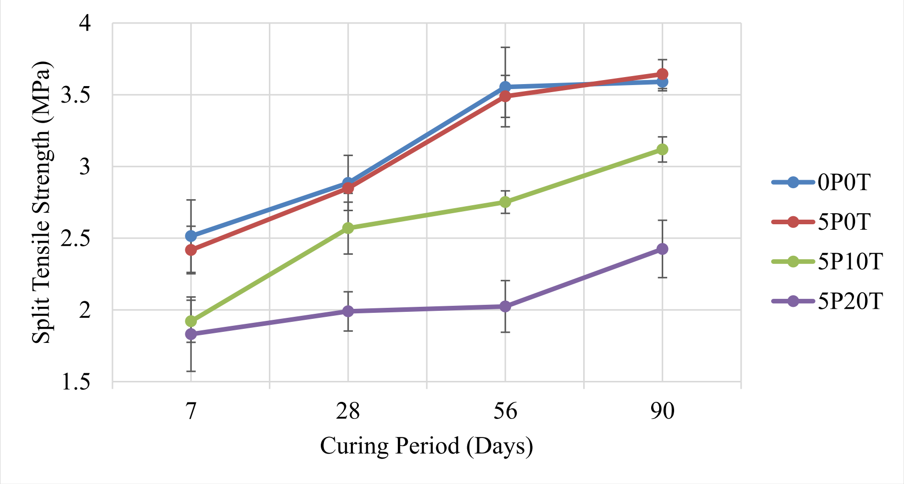


Figure 15. Split tensile strengths of class 30 control and modified concretes. The findings are presented as the mean values for $n_{sample} = 3$. The error bars are also included.

specimens with higher strengths will result in smaller strains before failure leading to a brittle material [72]. Crack widths generally seemed to reduce in number for the specimens without WTR and they increased after introduction of BCP and WTR. Such findings have also been ascertained for beams in another study [73]. Visual observation demonstrates that 5P20T concrete mix shows increased number of cracks with the lowest crack widths.

3.7. Split tensile strengths of control and modified concretes

Figures 13, 14, and 15 show graphs of split tensile strength of rubberised concrete containing BCP for class 20, 25 and 30 concretes respectively. In these figures, the means and error bars of the findings have been shown. It is recognised that error bars are graphical representations of confidence intervals; ranges within which one expects values to fall with certain probabilities provided there is what is currently known [74]. Figure 16 illustrates rubber distribution in concrete matrix after split tensile failure. From Figures 13, 14, and 15, minor split tensile strength reductions were observed as cement was replaced by 5% BCP. 28-days split tensile strengths reduced by 3.61%, 3.87% and 1.25% for class 20, 25 and 30 concretes respectively, for 5P0T mixes compared to control concrete mixes. After 90 days curing period, concrete with 5% BCP showed enhanced split tensile strength compared to control concrete. For 5P20T mixes at 28 days curing duration, 29.30%, 26.40% and 31.13% reductions in split tensile strengths were observed for class 20, 25 and 30 concretes respectively, in comparison with the control concrete mixes. It has been found that tire rubber inclusion in concrete facilitates the decrease in split tensile strength [18].

The incorporation of 5% BCP is seen to decrease the split tensile strength in concrete up to 56 days curing period. Low pozzolanic reaction associated with low curing duration is thought to lead to such behaviour [57]. The increase in split tensile strength for concrete with 5% BCP compared to control concrete at 90 days curing period was due to the previously explained increased pozzolanic reaction of BCP at longer curing periods. However, a minor discrepancy exists between split tensile strength findings for 0P0T and 5P0T. It should be noted that despite the mean split tensile strength values of 5P0T being greater than those of 0P0T, their differences are probably not statistically significant. The decrease in split tensile strength was more pronounced in concrete when tire rubber was added. Breaking of specimens (Figure 16), showed that tire rubber aggregates were clearly visible compared to coarse aggregates. Surface segregation between cement paste and rubber aggregates during crack expansion is speculated to be the reason for this behaviour [75]. Poor bonding between rubber aggregates and cement paste is observed to induce cracking [76]. Also, the zone of interface between cement paste and rubber is reasoned to behave like a micro-crack which is attributed to weak bonding thereby accelerating concrete disintegration [75]. Visual inspection (Figure 16), supported this poor bonding

Figure 16. Rubber distributions in cylinder specimens broken after 28 days curing period.

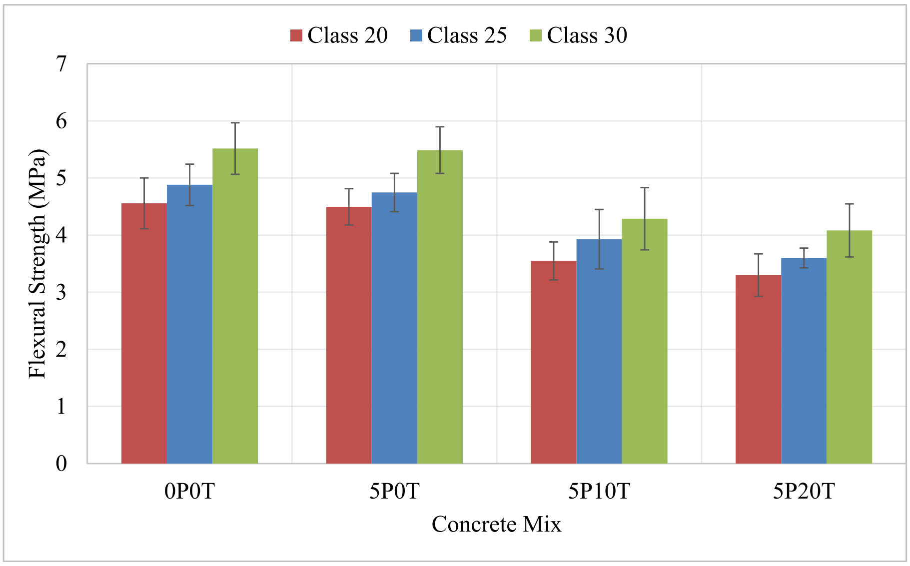


Figure 17. Flexural strength of rubberised concrete containing BCP. The findings are presented as the mean values for $n_{\text{sample}} = 3$. The error bars are also included.

phenomenon as rubber aggregates were easier to remove compared to coarse aggregates after breaking the samples.

3.8. *Flexural strengths of control and modified concretes*

Figure 17 illustrates the flexural strength losses due to BCP and WTR inclusions in concrete. The inclusion of error bars in the figure provides a big statistical advantage by giving details of graphical signals of probabilities existing in the data. The replacements of cement with 5% BCP in class 20, 25 and 30 concrete mixes revealed minor flexural strength losses after 28 days curing period compared to control concrete mixes. Minor flexural strength losses of 1.32%, 2.74% and 0.53% were observed compared to normal concrete mixes for class 20, 25 and 30 concrete mixes respectively. The most significant reductions in flexural strength were noticed with rubberised concrete mixes with 5% BCP compared with control concrete mixes for class 20, 25 and 30 concrete mixes.

It is clear that flexural strength was decreasingly affected by 5% BCP replacement in cement. Together with analysis of error bars, inclusion of 5% BCP replacing cement is seen to slightly reduce the concrete flexural strengths compared to control concrete mixes for all concrete grades. Minor flexural strength losses due to incorporation of BCP are expected with small replacement levels [63]. These replacement levels do not significantly influence the flexural strength [31]. 5% BCP replacing cement can potentially demonstrate comparable flexural strength results compared to normal concrete mixes [77]. WTR inclusion in concrete has been found to reduce concrete flexural strength [13]. Other investigators [23], also reported that decrease in concrete density due to tire rubber addition leads to reduced flexural strength. Agreeing with other researchers' findings [2], the usage of WTR is concluded to result in the flexural strength reduction at 28 days.

4. Conclusions

The following conclusions were established from this study.

1. The compressive and split tensile strengths of concrete mixes with 5% BCP decreased compared to control concrete mixes for 7, 28 and 56 days curing periods. The inclusion of BCP at shorter curing periods may not give rise to increased concrete mechanical properties compared to control concrete.
2. At 90 days, concrete mixes with 5% BCP demonstrated increments in compressive and split tensile strengths in comparison with the control concrete mixes. Available data seem to illustrate possibility of BCP being primarily responsible for such increments. The inclusion of BCP in concrete would tend to govern increased pozzolanic reaction at longer curing periods.
3. The flexural strength of small unreinforced beams decreased due to inclusion of 5% BCP compared to control concrete after 28 days of curing. The introduction of 5% BCP simply dilutes clinker component without significantly increasing pozzolanic reaction at this curing period. The reduction of flexural strength was significantly increased following introduction of WTR.
4. The introduction of WTR resulted in reductions in compressive and split tensile strengths of concrete mixes in comparison with the

control concrete mixes. The existence of WTR is probably responsible for micro-crack formation leading to reduced mechanical properties.

5. The inclusion of BCP has potential in reducing mechanical properties losses of rubberised concrete at longer curing periods because of pozzolanic properties residing in BCP.

Declarations

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 interests statement

The authors declare no conflict of interest.

Additional information

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