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Analysis of the influence of water qualities on the strength of concrete

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Abstract

Concrete is commonly employed in construction for its tremendous compressive strength, despite its low tensile strength. This study aimed at analyzing the strength of concrete when mixed with water of varying qualities. Before concrete is formulated, tests are done on the aggregates to ascertain the right proportions but not on water used. Dreux-Gorrise concrete formulation method was employed. CAMWATER (tap water), rain water and water from a free-flowing river was used to cast concrete samples after which it was crushed to obtain 7 and 28 day resistances. The water qualities varied were pH and hardness. Hydrochloric acid and sodium hydroxide were used to vary the pH of water. Results showed an increase in concrete strength as a function of increase in water pH. Water with a high pH resulted in concrete with an appreciable strength value while acidic water resulted in very low strength values. The usage of hard water for mixing concrete resulted in a strength value lower than with soft water. Conclusively, water quality has an effect on the strength of concrete. Therefore, it is advisable to use water with a high pH value for mixing concrete, preferring rainwater over tap water when mixing concrete due to hardness of water.

Keywords: Concrete, Strength, Water quality, Water pH, Water hardness

Introduction

Concrete, a composite material, comprises cement, coarse and fine aggregates (e.g., sand and stone), water, and various admixtures [1]. Concrete is the second most used substance in the world after water and the most used material in civil engineering [2]. It is used in almost every aspect of civil engineering for example,construction of beams and pillars in buildings, construction of slabs for bridges, construction of pavements for rigid pavements, construction of retaining walls for, etc.

Due to its application in various domains of civil engineering, concrete is needed in various strengths. It is for this reason that concrete has been classified into various classes depending on the its strength. These classes are defined in ascending numbers of 5, starting at 10, and determination of compressive strength of the concrete is done after 28 days. For example, strength of 20 Newtons has been recorded for C20 [2].

Various classes of concrete shows varied strength due to the proportions of the components of concrete thus it is worth noting that the properties of these components play an essential role in the strength of concrete [3].

Concrete is formulated using the properties of the components to be used for that particular concrete. The properties are obtained in the lab by carrying out various test such as sieve analysis, specific gravity and sand equivalence test. With the results of these test and using the Dreux Gorrise method [4] of formulation, the proportion of the various components could be obtained and used to compose concrete of a desired strength [5].

The formulation of concrete involves field collection of aggregates and cement which are then brought to the lab for testing. Studies show that when the concrete has been formulated and tested in the lab there is still a disparity in the strength when the results are applied on the field using the same materials. The only component which is not usually maintained on the field as was done in the lab is water [6]. It is for this reason that this study seeked to investigate the influence of the quality of water on the strength of concrete. This was done using water of various qualities to do a concrete mix and compare on the strengths obtained from each trial.

When concrete is casted under standard conditions it has a very high pH. Fresh concrete has a surprisingly high pH value of around 13 in other words, nearly at the top of the pH scale [7]. This high pH stems from the cement used to bind the concrete together. Cement contains a large amount of alkalis, a highly basic category of minerals. As the cement dissolves and mixes with the water, it imparts its high pH to the concrete as a whole [7].

When concrete has been casted its pH changes over time. Concrete normally has a high pH when it has been casted but due to this, it is more volatile on a chemical level. When it comes in contact with any substance of a lower pH it starts to react with the substance thereby neutralizing its basic nature and in effect reduces the pH of concrete [8].

Concrete is very susceptible of chemical reactions such that when it is in the fresh state it reacts with carbon dioxide in the air. This process is known as carbonation which is a continuous process that occurs even when concrete comes in contact with acidic substances such as acid rain [9].

After concrete has been casted, some negative effects set in when its pH goes below a value of 11. This can alter the chemical nature of the cement such that it no longer binds to the aggregate particles tightly, resulting to the concrete breaking apart [7]. This type of damage begins from the outer layers of the concrete. Patches of flaking, chipping or otherwise damaged concrete is called spalling. As the surface of the concrete shears away, the process of carbonation would easily affect deep portions of the slab which might damage the concrete mat beyond repair [7].

Carbonation poses even more serious problems for concrete that has been reinforced with internal steel supports. The changing pH would leave these structural elements much more prone to corrosion. As rust starts to build up on the outside of the metal, the rust will place large amounts of pressure stress on the surrounding concrete. This stress makes the concrete more prone to developing cracks and potholes [10].

Methods

Nature and source of materials

Source of materials

Cement The cement used for this experimental study was Dangote Cement with grade CEM II 42.5.

Aggregate The various aggregates with their diameters which were used for this research are shown in Table 1 below.

Nature of materials

Before concrete formulation, the sand and gravel were identified by carrying out laboratory test on the samples. These tests included; sieve analysis, specific gravity, apparent density and sand equivalence test.

- Sieve analysis was conducted following the norm NF P94 – 056 [11]. This test helps to give an idea of the gradation of the materials. The apparatus needed for this test include a set of sieves, scale balance, oven and a bowl.
- Sand equivalence test was conducted following the norm NF EN 933 [12]. This test is used to determine the cleanliness of the sand by the percentage of silty material in the sand. The apparatus needed for this test include a transparent measuring cylinder, an agitator tube, a measuring piston.
- Specific gravity test was done following the norm, NF P94 – 054 [13], the value obtained from this test is used to obtain the proportion by mass for the aggregates after formulation. The apparatus needed for this test includes; a pycnometer, a thermometer, a scale balance.
- Apparent density test was done following the norm NF P18 – 558 [14]. The value obtained from this test is used to obtain the proportion by volume for the aggregates after formulation. The apparatus needed for this test include; a cylindrical mould, and a scale balance.

Experimental protocol

Formulation using Dreux Gorrise method

Determination of the quantity of cement and water The concrete we formulated had as target strength after 28-days to be 20 MPa

$$f_{cm} \approx 1.2x20 = 24MPa$$

We used Dangote cement CEM II 42.5 (commercial strength class). The true class is estimated at $F_{CE} = 51$ MPa.

Table 1 Source of aggregates

Aggregate size (diameter)	Aggregate characteristic	Source
0/5	fine aggregate	Mbengwi Sand
5/15	coarse aggregate	Dreamland Quarry
15/25	coarse aggregate	Dreamland Quarry

The granularity of the gravel allows the estimation of the granular coefficient K_{DG} with $D_{max}=25$ mm, and aggregates of average quality, $K_{DG} \approx 0.4$. The granular dimensions of the various aggregates used in the study are presented in Table 2.

The cement dosing/water dosing (C/E) ratio is evaluated with equation:

$$f_{cm} = K_{DG}.F_{CM}.(\frac{C}{E} - 0.5) \quad (1)$$

$$\frac{C}{E} = \frac{f_{cm}}{(K_{DG}.F_{CE})} + 0.5 \quad (2)$$

$$\frac{C}{E} = \frac{24}{(0.4x51)} + 0.5 = 1.68$$

Figure 1 shows the abacus which was used to estimate the quantity of cement required according to the C/E ratio estimated by formula above and the desired workability, which was identified from the slump test and designed in this application to 8 cm.

The quantity of cement required C was estimated at 350 $kg.m^3$ of concrete.

We can therefore evaluate the quantity of water by substituting the quantity of cement obtained from the chart in the C/E formula.

$$E = \frac{350}{(1.68)} = 208Kg$$

The correction is made to the water dosage if the maximum dimension of the aggregates is different from 25 mm.

In this application Dmax = 25 mm, the correction made is 0% on the water dosage E, i.e. $208 \times 1.00 = 208$ $L.m^3$ (Table 3).

This first part of the formulation of a concrete proposes for each of the constituents the quantities and their ratio:

$$\mathrm{C} = 350\mathrm{kg.m}^3, \mathrm{E} = 208\mathrm{L.m}^3\mathrm{andC/E} = 1.68$$

However, concrete is made up of one sand and two gravels, the proportions of which still needs to be determined.

Determination of the quantity of sand and gravel *Reference granular curve:* On the granulometric analysis graph, complying with standard NF-EN-933-1, a reference granular composition OAB is plotted. Point O is placed at the origin of the graph; point B

Table 2 Table of granular coefficient

Quality of aggregates	Dimensions of aggregates		
	Fine (D ≤ 16 mm)	Medium (25 ≤ D ≤ 40 mm)	Coarse (D ≤ 63 mm)
Excellent	0.55	0.60	0.65
Good	0.45	0.50	0.55
Average	0.35	0.40	0.45

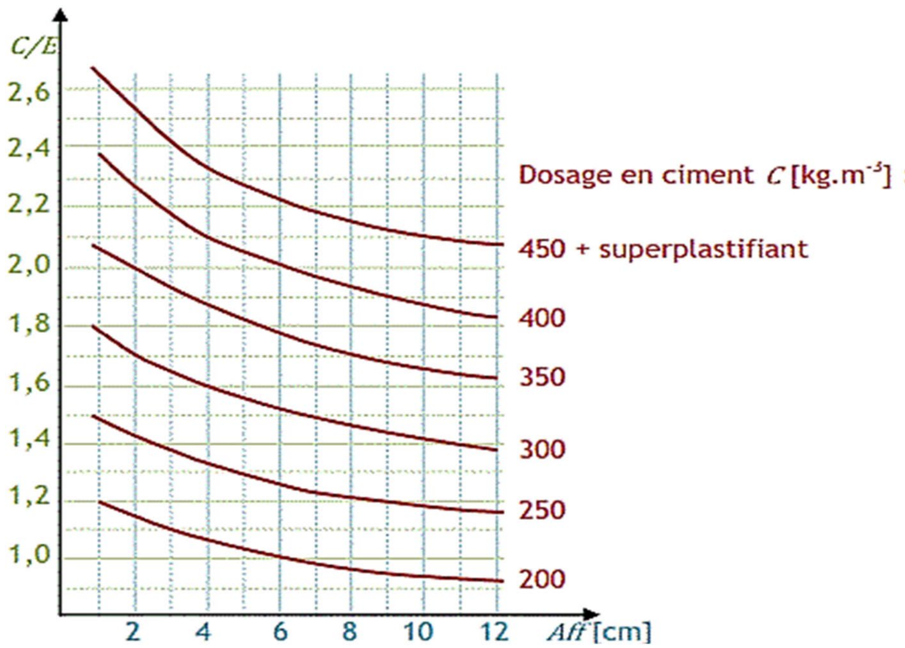

Fig. 1 Chart for estimating amount of cement

Table 3 Table for correction of water dosage

Maximum dimension of aggregates (Dmax)	5	10	16	25	40	63	100
Correction of dosage of water	+15	+9	+4	0	-4	-8	-12

corresponds to the dimension D_{max} of the largest aggregates at the ordinate 100%. The break point A is determined by:

- on the abscissa (from the dimension of the largest aggregates D_{max}) X_A➢ if $D_{max} \leq 20$ mm, the abscissa is D_{max} / 2;
  ➢ if $D_{max} > 20$ mm, the abscissa is located in the middle of the gravel segment limited by module 38 (5 mm) and the module corresponding to D_{max};
- On the y-axis: $Y_A = 50 - \sqrt{D_{max}} + K$ where K is a correcting term obtained by the table below (Table 4).

For this research, the aggregates were crushed; the power of the vibration was normal and the cement dosage C of 350. K was therefore taken as +2.

With the fineness modulus of 2.85 and the fact that the concrete was unpumped, no additional correction was required. Therefore, we had:

$$X_A = (5 + Dmax)/2 = (5 + 25)/2 = 15 \quad (3)$$

$$\mathbf{Y_A} = 50 - \sqrt{25} + 2 = 47\mathbf{mm} \tag{4}$$

Figure 2 below presents the graph of granulometreic analysis of the aggregates which was used for the concrete. The values obtained above were used to plot the granular reference line which is then used to obtain the proportions of the aggregates.

In this application, we are looking for plastic consistency, with normal vibration and Dmax=25mm, therefore $\gamma_{th} = \mathbf{0.822}$

For 1m3 of concrete and with $\gamma_{th} = \mathbf{0.822}$:

$$\gamma_{th} = \frac{V_{cement} + V_{aggregates}}{V_{concrete}} = \frac{V_{cement} + V_{aggregate}}{1} \tag{5}$$

$$V_{aggregates} = \gamma_{th} - V_{cement} = 0.822 - \frac{350[Kg]}{3,100\left[Kg.m^3\right]}$$

$$\boldsymbol{V_{aggregates}} = 709\boldsymbol{L}$$

Calculations of the proportion of aggregates per meter cube

Using the results curve (9% gravel 5/15, 54% gravel 15/25, 37% sand 0/5) it was possible to calculate the quantity of each of the constituents:

- In terms of mass

$$\boldsymbol{mass = totalvolumexaggregate\%xspecificweight} \tag{6}$$

$$\begin{gathered} \mathrm{S}_{0/5} = 0.709\mathrm{x}0.37\mathrm{x}2,470 = 648\mathrm{kg.m}^3 \\ \mathrm{G}_{5/15} = 0.709\mathrm{x}0.09\mathrm{x}2,580 = 165\mathrm{kg.m}^3 \\ \mathrm{G}_{15/25} = 0.709\mathrm{x}0.54\mathrm{x}2,810 = 1076\mathrm{kg.m}^3 \end{gathered}$$

- In terms of Volume

$$\boldsymbol{Volume = totalvolumexaggregate\%} \tag{7}$$

Table 4 Correction value, k

Vibration		Weak		Normal		Powerful	
Forms aggregates (sands in particular)		**Rolled**	**Crushed**	**Rolled**	**Crushed**	**Rolled**	**Crushed**
Dosage in Cement	400 + Adjuvant	- 2	0	- 4	- 2	- 6	- 4
	400	0	+ 2	- 2	0	- 4	- 2
	350	+ 2	+ 4	0	+ 2	- 2	0
	300	+ 4	+ 6	+ 2	+ 4	0	+ 2
	250	+ 6	+ 8	+ 4	+ 6	+ 2	+ 4
	200	+ 8	+ 10	+ 6	+ 8	+ 4	+ 6

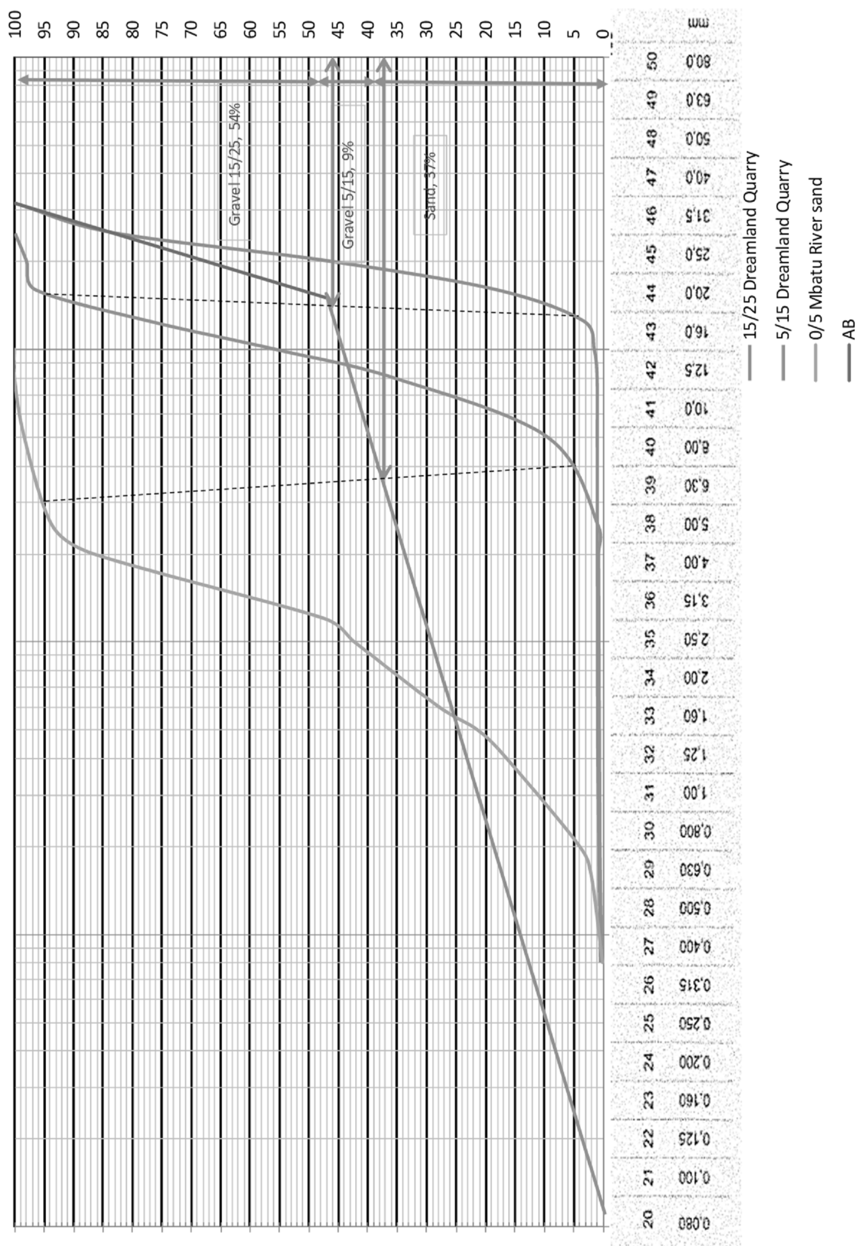

Fig. 2 Reference granular curve

$$S_{0/5} = 0.709x0.37 = 262.33L$$
$$G_{5/15} = 0.709x0.09 = 63.81L$$
$$G_{15/25} = 0.709x0.54 = 382.86L$$

Preparation of water samples

From the objectives of this study, concrete samples were cast using water samples of varying quality. Water was obtained from two sources for this research. Chemicals were added to some of the water samples in order to vary the pH of the water samples. Water was collected from the rain, and from CAMWATER.

To vary the pH of the water samples, hydrochloric acid and Sodium hydroxide pellets were used. These reagents were added to the already measured water samples and the pH was obtained using a pH meter and confirmed using a litmus paper which changes colours depending on the pH value of the water sample.

Slump test (NF EN 12350–2) [15]

Apparatus Slump cone and base, Compacting rod

Test procedure This test was done by filling concrete into the Abrams cone in 3 layers. Every layer was compacted by 25 strokes of a tamping rod. When the mould was filled, it was carefully removed and the depth of depression was measured as the slump value.

Casting of concrete cylinders (NF EN 12350–1) [16]

Apparatus Cylindrical mould (15 × 30 cm), Scale balance, Calibrated measuring cylinder, Engine oil and brush, Spade, Compacting rod.

Test procedure After the slump test was conducted, the concrete was then filled into the already oiled moulds in 3 layers and giving 25 strokes of the tamping rod to each layer. The moulds were then allowed undisturbed for 24 h after which the samples were demolded and kept in a water bath for curing.

Compressive strength test (NF P94-077) [17]

The compressive strength test was done using the HUMBOlDT compression machine (HCM – 4000IHAC.XX, manual 400,000 Ibs/1,780 KN). The crushing machine uses the principles of action and reaction. The machine exerts a force on the surface area of the element and the force at which the elements starts to fail is the maximum force which the element can carry. The machine displays the maximum force exerted and the corresponding strength of concrete in MPa.

On the day of crushing, the concrete samples were removed from the water bath and placed under the sun for the water on its surface to get dry. After that the concrete sample was then weighed. The weight was then used to calculate the density of the concrete after immersion in water.

After weighing the concrete sample, it was taken to the Sulphur room where a mixture of Sulphur and egg shells was used to smoothen the surface of the concrete sample. The essence of this process was to ensure that during crushing the force which is applied on the surface of the concrete element is evenly distributed throughout the element. The concrete element was then taken for crushing.

Results and discussion

Results

Results for formulation

Dreux Gorrise method of formulation was used to obtain the proportions of the various components of concrete. Concrete formulated was done at a batching dosage of 350 kg/m^3 giving a 28-day strength of 20 MPa, a slump value of 8 cm and cement water ratio of 1.68. Table 5 below presents the proportions of the components in terms of mass and volume.

Results of weight and density of concrete samples

After the samples were removed from the water bath and kept for the surface water to drain off, the samples were weighed before being crushed. From the weight, the density of the concrete samples was obtained. Tables 6 and 7 below presents the weight and density of the concrete samples after being cured for 7 and 28 days respectively.

Results for concrete compression test

Varying pH of water The table below presents the concrete compression results obtained after crushing the concrete samples casted with water of varying pH (Table 8).

A plot of variation of concrete strength with varying pH of water was produced as shown in Fig. 3. The chart displays the values of the 7th and 28th day strengths of concrete. From the chart, the strength value of concrete increases with increase pH.

Figure 4 below is a reflection of the chart presented above where the concrete strength was plotted against the corresponding pH of concrete which was obtained from mixing concrete with water of a specific pH value. Also, the compressive strength of concrete increases with increase in pH of concrete mixed with water of a specific pH.

Varying hardness of water Concrete samples were cast using water obtained from the rain and tap water (CAMWATER). These water samples were of different hardness as rain water is soft and tap water is hard.

Table 5 proportion of concrete components

Component	Proportion %	Absolute volume l/m3	Specific weight kg/m^3	Apparent volume l.m^3	Dosage per mould kg
0/5	37	262.33	648	456	3.43
5/15	9	63.81	165	114.82	0.87
15/25	54	382.86	1076	739.52	5.7
Cement CEM II 42.5		113	350	113	1.86
Water		208		208	1.1 L

Table 6 Results of weight and density of concrete samples after 7 days of curing

Sample characteristic	Weight of samples after 7 days	Volume of concrete element	Density of samples after 7 days
pH 3.23	14.26	0.0053	2691
pH 5.45	14.09	0.0053	2658
pH 6.56	14.37	0.0053	2711
pH 8.21	14.43	0.0053	2723
pH 11.82	14.26	0.0053	2691
Rain Water	14.05	0.0053	2651
Tap Water	14.21	0.0053	2681
River Water	14.03	0.0053	2647

Table 7 Results of weight and density of concrete samples after 28 days of curing

Sample Characteristic	Weight of samples after 28 days	Volume of concrete element	Density of samples after 28 days
pH 3.23	14.59	0.0053	2753
pH 5.45	14.72	0.0053	2777
pH 6.56	14.78	0.0053	2789
pH 8.21	14.64	0.0053	2762
pH 11.82	14.74	0.0053	2781
Rain Water	14.58	0.0053	2751
Tap Water	14.71	0.0053	2775
River Water	14.65	0.0053	2764

Table 8 Results for concrete compression test for water samples with varying pH

Sample ID	pH of water	pH of concrete	Compressive strength after 7 days	Compressive strength after 28 days
1	3.23	5.51	10.4	17.17
2	5.45	6.83	9.80	16.67
3	6.56	8.26	11.46	18.15
4	8.21	10.73	13.81	19.40
5	11.82	13.15	14.28	21.37

The table below presents the concrete compression results obtained after crushing the concrete samples were casted with water of varying hardness (Table 9).

Figure 5 below shows the variation of concrete strength with varying hardness of water. From the chart we can see that the concrete mixed with rain water gave a strength of 21.09 MPa which is greater than what was obtained for the concrete mixed with tap water. The colors of the bars represent the concrete ages of 7 and 28 days.

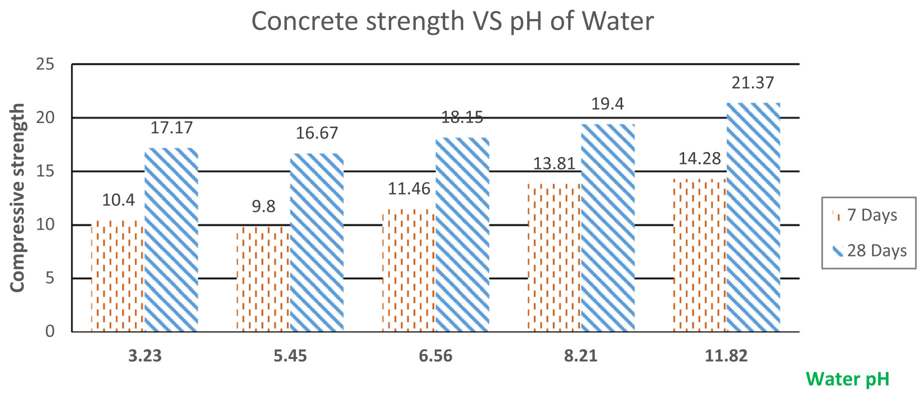

Fig. 3 Chart of concrete compressive strength with varying pH of water

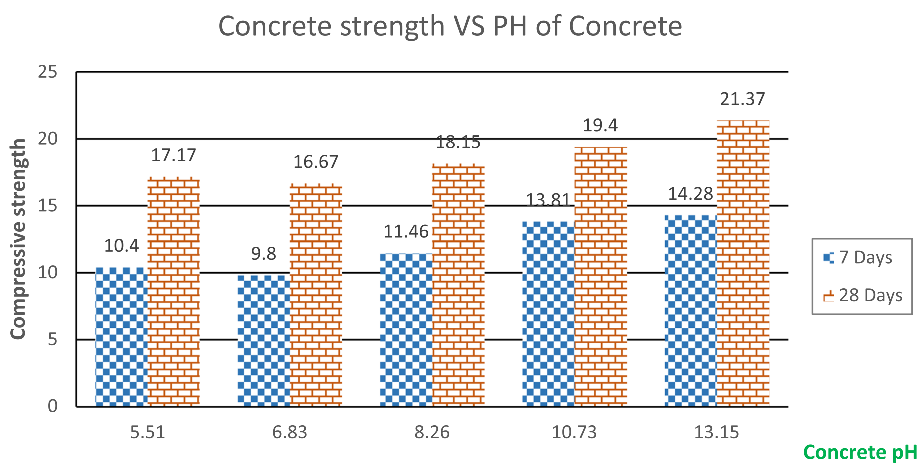

Fig. 4 Chart of concrete compressive strength with varying pH of concrete

Table 9 Results for concrete compression test for water samples with hardness

Sample ID	Water quality	Compressive strength after 7 days	Compressive strength after 28 days
Tap Water	Soft water	12.9	19.28
Rain water	Hard water	13.52	21.09

Discussion

Varying pH of water

- A maximum strength of 21.37 MPa was recorded after the crushing test. This was obtained from a concrete sample which was mixed with water of pH value, 11.82 and resulted in a concrete of pH 13.15. The water sample used and the resulting concrete sample were both in the basic zone of the pH scale. It was therefore confirmed that concrete exhibits high strength properties when mixed with water of a high pH value. This can be explained with the fact that cement has a pH value of 13 as such the alkaline nature of water favoured the reaction between water and cement which is also a factor in the strength of concrete. It was also noted that the 7-day compressive strength of concrete of 14.28 was quite high as compared to the strengths obtained in other samples implying the alkaline nature of water favours the early strength of concrete. This finding is in accordance with the results of some studies on MTA (Mineral Trioxide aggregate) showing that acidic environment had a negative impact on its setting properties, compressive strength and sealing ability [18]. This finding also confirms with the results of another study on some modifications on MTA which showed higher compressive strength in pH value of 10.4 [19]. Two separate studies on the effect of alkaline pH on micro hardness and push out-out bond strength of MTA showed higher surface hardness in the presence of alkaline PH [20, 21]. They also showed significantly lower surface hardness, high porosity and a more non hydrated structure in neutral condition.

- The lowest strength was obtained in concrete sample mixed with water of pH value 5.45 which resulted in the pH of concrete being in the acidic zone with a value of 6.83, almost neutral. From this, it could be inferred that cement does not perform well in the neutral zone of the PH scale as this does not favour the hydration reaction. This aligns with the work of Fereshteh et al [22]. in the Iranian Endodontic journal where he worked with cement enriched materials and also came to conclusion that both acidic and alkaline pH produced better compressive strength of CEM cement compared to the neutral pH.

Varying hardness of water

This study used tap water and rain water. Rain water is naturally soft water unless it has gone through soluble rocks whereby it dissolves the minerals present in the rocks then it becomes hard. Tap water is considered hard water as the chemicals used to treat the water makes it difficult to form lather with soap [23].

After crushing the samples which were cast with these varying qualities of water a higher resistance from rain water was obtained as compared to the strength of concrete samples casted with tap water. This goes ahead to confirm the presence of minerals in tap water which produced whitish efflorescence on the surface the concrete [24].

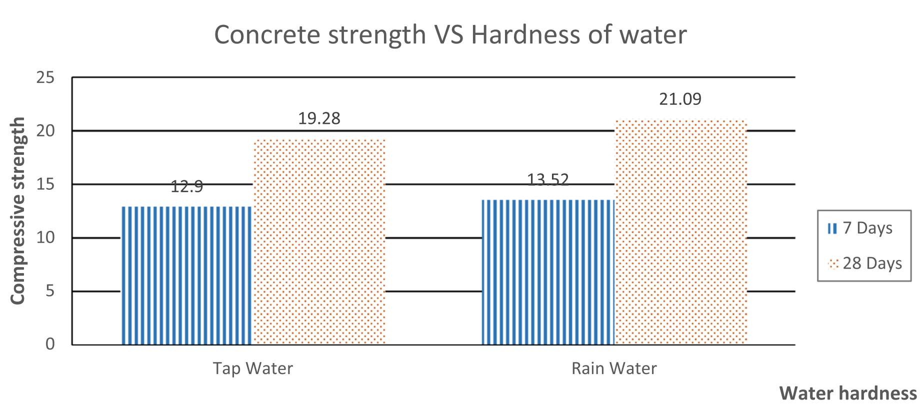

Fig. 5 Chart of concrete compressive strength with varying water hardness

Conclusions

After carrying out test on the various aggregates of concrete and using the obtained results to formulate concrete of 20 MPa, concrete elements were cast using water samples of varying qualities being; pH, water hardness and the source of water. For the preliminary study, two elements were cast for each water sample to be crushed on the 7th and 28th day to enable us access the early strength of the concrete elements and standard strength under these various water qualities.

From the results, it was concluded that water quality affects the strength and quality of concrete. This is evident in the variation of the strength of concrete when mixed with water of varying pH. A maximum strength of 21.37 MPa and a minimum strength of 16.67 MPa was obtained. From the 5 samples caste, an average strength of 18.6 MPa was obtained which gave a deviation of 1.7 MPa. From the deviation obtained it could therefore conclude that varying pH of water has an effect on the strength of concrete.

In addition to strength variation, it was also observed that varying the quality of water used in mixing concrete can as well affect the quality and properties of concrete as efflorescence on the surface of concrete mixed with tap water (hard water) was recorded, giving the concrete a whitish coloration. Thus, hard water is not desirable for concrete as it alters the properties and qualities of the concrete.

In conclusion it is better to increase the pH of tap and rain water for casting concrete as it aids the hydration reaction of cement and gives a high early strength to concrete and consequently its standard strength. Water which is acidic rather neutralizes the pH of cement thereby altering its functionality and reducing its strength thus it is undesirable and in addition acidic water will promote carbonation in concrete. Hard water as well is not desirable for concrete mix as the minerals in hard water could cause cracking in concrete and as well produce a white powdery substance on its surface called efflorescence.

Abbreviations

CAMWATER	Cameroon Water Utilities Corporation
CEM	Portland Cement
EN	European Norm
FM	Fineness Modulus
NF	French Norm
W/C	Water-cement ratio
WHO	World Health Organization

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Authors' contributions

MMK and FPC were the investigators and drafted the manuscript. NLN and PJB designed the study and analyzed the data. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author, [Mbuh Moses Kuma], upon reasonable request.

Declarations

Competing interests

No potential conflict of interest was reported by the author(s).

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