



Workability and strengths of ternary cementitious concrete incorporating calcined clay and limestone powder

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ABSTRACT

Problems associated with the production and utilization of Portland cement have necessitated the use of alternative or supplementary binders in concrete production. This study investigated the use of two supplementary binders; calcined clay (CC) and limestone powder (LP) as substitutes for cement in the production of concrete. Both the calcined clay and limestone powder were characterized using X-ray diffraction (XRD), X-ray Fluorescence (XRF) and Scanning Electron Microscope (SEM). Blended concrete mix proportions containing calcined clay and limestone powder were prepared and tested for fresh and hardened concrete properties including workability, compressive and splitting tensile strengths. The outcomes of this research showed that calcined clay is majorly amorphous with traces of crystal particles while limestone is all crystal particles. Based on oxides composition, calcined clay can be used as pozzolan while limestone powder can be best utilized as pore fillers. The addition of both calcined clay and limestone powder resulted in the loss of slump, although the effect is more pronounced in concrete blends containing calcined clay. While the inclusion of limestone powder caused a slight loss of strength in the blended concrete, it can still be utilized to achieve reasonably high strengths. Only concrete mix incorporating 10% of calcined clay gives a slight increase in strength, hence calcined clay can be utilized to a limited volume in concrete production.

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1. Introduction

Cement is the most important and widely used constituent of concrete and thus has a wide utilization in the construction industry. Challenges such as CO₂ emission and depletion of natural resources posed by the production and utilization of cement [1–3] have led to several types of research into alternative binders such as alkaline activated binders/geopolymer concrete or the use of supplementary cementitious materials (SCM) as a partial replacement of cement in order to reduce utilization of cement. Several admixtures such as Rice husk ash (RHA) [4–6], Silica Fume (SF) [7–9], Metakaolin (MK) [10–12], Fly Ash (FA) [13–15], Ground Granulated Blast Furnace Slag (GGBFS), Palm Oil Fuel Ash (POFA) [3,16–18], Bagasse Ash (BA) [19,20], Cassava Peel Ash (CPA), Corn Cob Ash (CCA), Wood Waste Ash (WWA), Bamboo Leaf Ash (BLA), Wheat Straw Ash (WSA), Glass Powder (GP), Perlite Powder (PP) etc. [1,21–24,50–53] had successfully been used as SCMs in the

production of different kinds of concrete. All the admixtures have been found to have positively affected the compressive, flexural, and tensile strength as well as durability properties of concrete when utilized as a partial substitute for cement.

There have been extensive research studies on the binary use of calcined clay or limestone powder/filler with cement. The studies include the effects on fresh, mechanical and durability properties of concrete. Different scholars had reported different effects of the addition of limestone powder and calcined clay on workability, strength and durability. Some researchers reported an increase in the flow-ability of concrete containing limestone powder [25,26] while others reported a decrement in flow-ability [27,28]. Some researchers also reported an increase in strengths and improved durability properties of concrete containing a certain percentage of limestone filler/powder [28,29] while others' reports are contrary to it [26,30,31]. In concrete containing calcined clay, the addition of the calcined clay has been reported to be responsible for the increase in water demand [32,33]. A positive influence of a certain percentage of calcined clay on the mechanical and durability properties of concrete had also been established [33,34]. Previous

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research works had also indicated possibilities of using cement and multiple supplementary binders (i.e. ternary or quaternary cementitious binders) in order to enhance the strength and durability indexes of concrete [35–38]. Dhinakaran and Sreekanth [39] utilized ternary blends of 30% GGBFS, 5% RHA and 65% cement to produce concrete samples which exhibited better performance in terms of mechanical and durability compared to control samples. Ternary blends of GP, SF and GGBFS were also used to reduce the effects of alkali-silica reaction (ASR) in concrete samples [40]. Quaternary blends of fly ash and alccofine in the presence of different percentages of nano-silica were also used to improve resistance to acidic attacks [41]. Binary and ternary utilization of ground dune sand and blast furnace slag in mortar productions was also found to have had considerable compressive strength in comparison with that of control mortar [42]. Quaternary and ternary blends are used to improve both the mechanical and resistance to acidic attack by concrete produced from recycled concrete aggregate [43,44]. Ternary cementitious mixtures containing 2.5% nano-silica and 2.5% micro-silica had also been used to achieve the highest compressive strength in high-performance self-compacting concrete [45]. Kathirvel et al. [46] investigated the strength and durability properties of quaternary blended concrete made of FA, RHA and LP. The researchers observed that quaternary mixes were effective means of enhancing the strengths and durability properties of blended concretes. In a ternary blended mortar of Portland Cement-Limestone Powder-Silica Fume, it was observed that the addition of limestone powder caused a diminution in strength and increment in total porosity of mortars, however, additions of SF to mortars containing limestone partially reversed both conditions [47]. Additions of limestone filler were found to increase early strength but at a later age, there was strength lost in ternary concrete containing more limestone filler in comparison with ternary concrete without or with little limestone filler due to dilution effects [48]. There was also noticeable resistance to sulphate attack and improved compressive strength by some quaternary blended mortars made of calcined clay, limestone powder and Portland cement [49]. Simultaneously adding limestone filler, natural pozzolana and blast furnace slag played an assisting role in the compressive strength development of mortars and resistance to sulphuric acid attack [50]. According to Antoni et al. [51], ternary blends containing 30% MK and 15% LP were found to have exhibited better performance in terms of mechanical properties and porosity as compared to the control.

Therefore, the objectives of this study are to evaluate the binary and ternary effects of both calcined clay and limestone powder on the workability and strength properties of concrete.

2. Materials and methods

2.1. Materials

Materials used to achieve our set out objectives are Portland cement (CEM I), Fine aggregate (F.A), Coarse aggregate (C.A), Limestone powder (LP), Calcined clay (CC) and Potable water.

Portland cement: Popular locally produced cement brand called Dangote 42.5R with a strength grade of 42.5Mpa was used for this research. It was purchased from a local vendor around the Tanke area of Ilorin. The chemical properties or the Oxides composition

and physical properties of the cement are shown in Tables 1 and 2 respectively.

Fine Aggregate (F.A): Sharp sand sourced from Oyun river, Ilorin was used for this research. The sharp sand was ensured to be dried and clean of any deleterious materials before being used for the purpose. It was sifted with a BS sieve size of 2.36 mm before being used. Table 2 presents the physical of fine aggregate.

Coarse aggregate (C.A): Granite of a maximum size of 12.5 mm, purchased from a local vendor, was used. The granite was sundried and kept clean in order to remove unwanted materials. Table 2 presents the physical of coarse aggregate while Fig. 1 shows the particle sizes diagram for both fine and coarse aggregates.

Calcined clay (CC): The clay used in preparing the calcined clay was sourced from Lakiri village located at Obafemi-Owode local government in Ogun State. Lakiri is located at latitude $7^{\circ} 19' 25''$ N and longitude $3^{\circ} 28' 44''$ E. The clay was calcined with a Carbolite furnace (Carbolite CWF 1200) at a temperature of 800°C for a duration of 2 h at the Institute of Agricultural research and training (IAR&T), Moor Plantation, Apata, Ibadan in Oyo state and allowed to cool at normal room temperature. The choice of calcination temperature and calcination duration was based on previous works which suggested a calcination temperature of $500\text{--}900^{\circ}\text{C}$ and a duration period of up to 5 h [32,53–56]. Preliminary investigations were carried out on samples calcined at 600°C , 700°C , 800°C and 900°C for 2 h by the authors to determine the optimal calcination temperature and duration for the clay source. The outcome of the preliminary study revealed that 800°C for 2 h was optimum which conforms with previous research [57–59]. The calcined clay was then sifted with BS 212- μm sieve size before being used. Calcined clay was characterized using X-ray diffraction (XRD), X-ray Fluorescence (XRF) and scanning Electron Microscope (SEM).

Limestone Powder (LP): Limestone powder was collected in bags from a limestone quarry in Ibese, Ogun state, southwestern Nigeria. Limestone powder was brought in dry and, pulverized form and it was further sifted with a BS 212- μm sieve size. The fine limestone powder particles that passed through the sieve were used for this research. Characterization of limestone powder using X-ray diffraction (XRD), X-ray Fluorescence (XRF) and Scanning Electron Microscope (SEM) was carried out to determine crystallinity or otherwise, oxide compositions as well as the morphology of the limestone powder.

Potable Water: Available potable water in the concrete laboratory of the University of Ilorin was used both for concrete mixing and curing.

2.2. Methods

2.2.1. Characterization of Metakaolin and limestone powder

To characterize calcined clay and limestone powder, X-ray diffraction (XRD), X-ray Fluorescence (XRF) and scanning electron microscopy (SEM) were employed.

XRD: X-ray diffraction was carried out on samples to determine the crystallinity or amorphousness of their particles. Representative samples were collected from calcined clay and, limestone powder and they were transported to Nigeria Geological Survey Agency in Zaria, Kaduna state where EMPYREAN DIFFRACTOMETER was used for data collection along with a computing machine connected with it, graphs of intensity versus 2θ were plotted for

Table 1
Chemical properties/Oxides compositions of Portland cement.

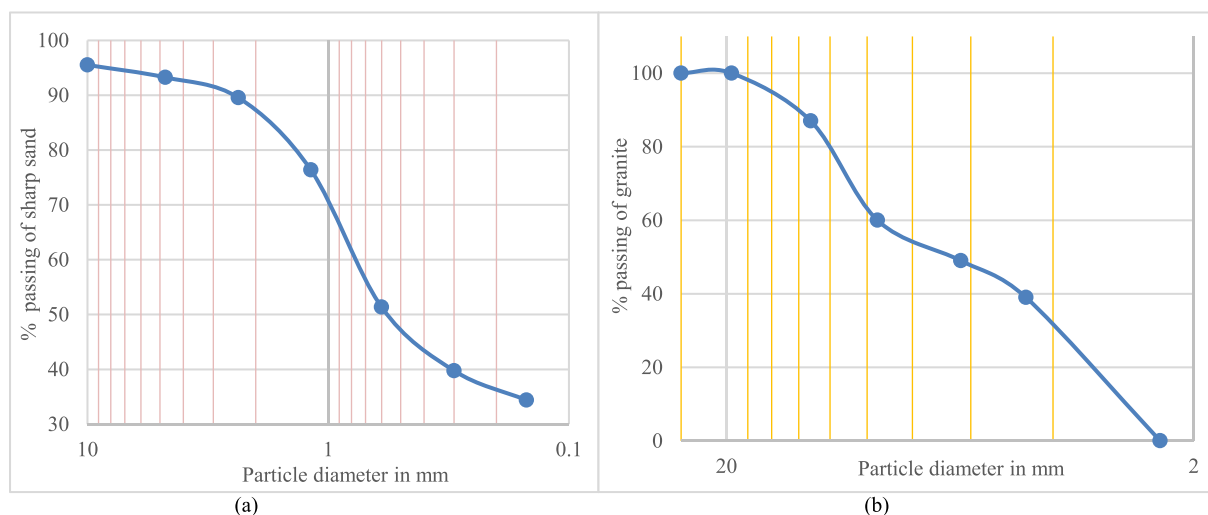
Oxides (%)	CaO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	Na ₂ O	MnO	TiO ₂	MgO	LOI
CEM I	61.79	20.62	3.07	5.35	0.2	0.06	0.12	1.93	3.47

Salman et al. [52].

Table 2

Physical properties of used materials.

	CEM I	CC	LP	FA	CA
Specific gravity	2.83	2.11	2.38	2.44	2.03
Moisture content (%)	–	–	–	2.92%	0.40%
Fineness Modulus	–	–	–	2.2	2.65
Fineness (%)	0.79%	–	–	–	–
Normal Consistency (%)	29%	–	–	–	–
Initial Setting times (mins)	103	–	–	–	–
Final setting times (mins)	349	–	–	–	–

**Fig. 1.** Particle size distributions graph (a) Sharp sand (b) Granite.

calcined clay and Limestone Powder. The outcome of XRD analyses is fully discussed under results and discussion.

XRF: X-ray fluorescence is widely used to identify chemical/oxides composition in minerals. XRF along with ASTM C618 [60] is used to classify minerals or particles as either pozzolana (supplementary cementitious materials) or non-pozzolana. Representative samples were collected and sent to Umaru Musa Yar'adua University, Katsina. The oxides/compound compositions of the representative samples were obtained with the help of thermo Scientific ARL QUANT'X EDXRF Spectrometer. The outcome of the analysis will be discussed in a later section.

SEM: Scanning Electron Microscopy is used to view the size, shape and arrangement of fine particles i.e. morphology of particles. The samples were taken to a private research laboratory named Rolab research and diagnostic laboratory located in Challenge, Ibadan, Oyo state. A JOEL-JSM 7600F provided field emission SEM (FE-SEM) with a semi-in-lens and this is equipped with a gentle beam which helps to deliver an image with high resolution. The result of the SEM analysis will be discussed in a later section.

2.2.2. Workability

Plastic properties of freshly prepared concrete are determined by many methods such as slump cone test, flow test, compacting factor test, Vee Bee consistometer, K-Slump tester and Kelly ball test [61]. For this research, the most commonly used workability test; the slump test was employed. The procedure used for the determination of workability in this research was as per BS EN 12350–2:2010 [62]. The test was carried out on each of the concrete mixes containing cement, calcined clay or/and limestone powder. The mix proportion used for the research is shown in Table 3.

2.2.3. Hardened

2.2.3.1. Compressive Strength. Compressive strength is the most used and acceptable strength test used in assessing concrete strength by concrete engineers and technologists [61]. The compressive strength test was carried out in conformity with the procedure in BS EN 12390-3:2010 [63]. The mix proportion shown in Table 3 was employed in preparing concrete samples. The freshly prepared concrete samples were filled up in three layers and each layer received 25 equally distributed strokes in 100 mm concrete cube moulds. The concrete samples were demoulded after 24 h of casting and cured in water for 56 days. Concrete samples were tested for compressive strength at 7, 14, 28 and 56 days for each of the concrete mixes. Compressive strength is therefore calculated from the recorded maximum load sustained by specimens and surface areas of the concrete specimens.

2.2.3.2. Split tensile strength. The test is also known as the Brazilian test and is an indirect method of measuring the tensile strength of concrete specimens. Cylindrical moulds of 100 mm in diameter and 200 mm in height were used. The test was carried out as per the provision of BS EN 12390-6:2010 [64]. The cylindrical moulds were filled with freshly prepared concrete samples in three layers with each layer receiving 25 equally distributed strokes. Batching by weight was employed as shown in Table 3 and concrete samples were cured for 56 days. Splitting Tensile strength was determined at 7, 14, 28 and 56 days.

CTL stands for control samples. C10LP0 and COP10 stand for concrete samples made with 10% of CC and 10% LP respectively while C20P0, COLP20 and C10LP10 are concrete specimens containing 20% of CC, 20% of LP, and 10% of CC and 10% of LP respectively.

Table 3Concrete mix design (kg/m³).

Mix Codes	Percent	CEM I	CC	LP	F. A	C.A	Water	w/c
CTL	0	470	0	0	595	1100	235	0.5
C10LP0	10	423	47	0	595	1100	235	0.5
COLP10		423	0	47	595	1100	235	0.5
C20LP0	20	376	94	0	595	1100	235	0.5
COLP20		376	0	94	595	1100	235	0.5
C10LP10		376	47	47	595	1100	235	0.5

3. Results and discussion

3.1. Characterization of calcined clay and limestone powder

XRD provides useful information about the crystallinity or amorphousness of calcined clay and limestone powder. Fig. 2 shows plotted diffractograms for calcined clay and limestone powder. It shows that major parts of the calcined clay are in an amorphous state with noticeable Anatase crystals at a few sharp peaks. The presence of a broad hump between when 2theta is 20° and 30° is an indication of amorphousness while Anatase is a crystal and mineral form of Titanium dioxide (TiO₂). The XRD pattern obtained in this research is also similar to the pattern observed in previous research work [65,66].

Limestone powder is a crystalline material. Major minerals phase noticed in limestone powder are Quartz and calcite. Quartz is a silica oxide while calcite is a calcium carbonate (CaCO₃). The absence of a broad hump at any point in the diffractogram indicates the crystallinity of Limestone powder as limestone powder is a by-product of limestone rock.

XRF was carried out to determine the chemical composition present in calcined clay and limestone powder. Table 4 presents the chemical composition majorly in oxide forms. ASTM C618 [60] sets a minimum of 70% for the sum of SiO₃, Al₂O₃ and Fe₂O₃ for a pozzolana. It is also stipulated that SO₃ and loss on ignition (LOI) should not exceed 4% and 10% respectively.

The summation of SiO₃, Al₂O₃ and Fe₂O₃ in calcined clay and Limestone powder is 82.69% and 10.54%. SO₃ is considerably low in calcined clay compared with ASTM 618 requirement and it is not detected in LP while LOI is way too high in LP. Both CC and LP have a moisture content of 2.56% and 1.63% which are considered low compared to ASTM C618 specification of 3%. With the above explanation, CC meets the requirement of pozzolana while LP did not. The outcome reported in this research is similar to what was reported in previous papers [49,67,68].

SEM shows micrographs of CC and LP at the magnification of 6000 and 7000 respectively. Fig. 3 shows both micrographs for

CC and LP. It can be observed that CC (Fig. 3a) are closely packed together with a few noticeable micropores. CC have regular shapes arranged in a regular pattern while Fig. 3b shows LP arranged in layers showing many pores and the LP particles seem to be loosely arranged.

3.2. Workability

A slump cone test was used to determine the fresh properties of concrete specimens. Fig. 4 shows slump values for different mix proportions. As can be seen in the Figure, the continued substitution of CC with cement leads to less workable concrete. This observation is similar to what was reported by Salau and Osemeke [32] and Jaskulski et al. [33].

A partial substitute of LP with cement was also observed to have had some effect on the fresh properties of concrete samples, especially at 20%, there was no noticeable effect at 10%, and this may be due to the fact that enough particles of LP may not have been mobilized for this reaction that negatively affects the workability. Similar outcomes had also been reported in previous research studies [27,28]. Concrete samples containing 10% of CC and 10% of LP provide credence to this argument where slump value is between concrete containing only 10% of CC and only 10% of LP was recorded.

3.3. Hardened properties of concrete

3.3.1. Compressive Strength

Fig. 5 presents the compressive strength of concrete samples containing CC and LP. An increase in compressive strength is observed across all curing ages. It is worthy of note that C10LP0 has the highest compressive strength compared to other concrete mixes, but its early-day compressive strength (especially 7-day) was lower compared to that of control and C20LP0. For every other curing age, its compressive strength soars higher than others, the lower early age compressive strength may be due to the reaction (pozzolanic or secondary hydration) leading to the formation of

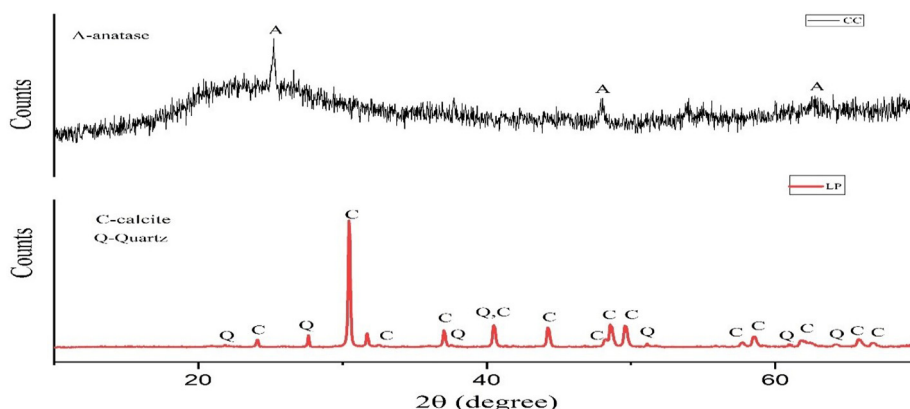
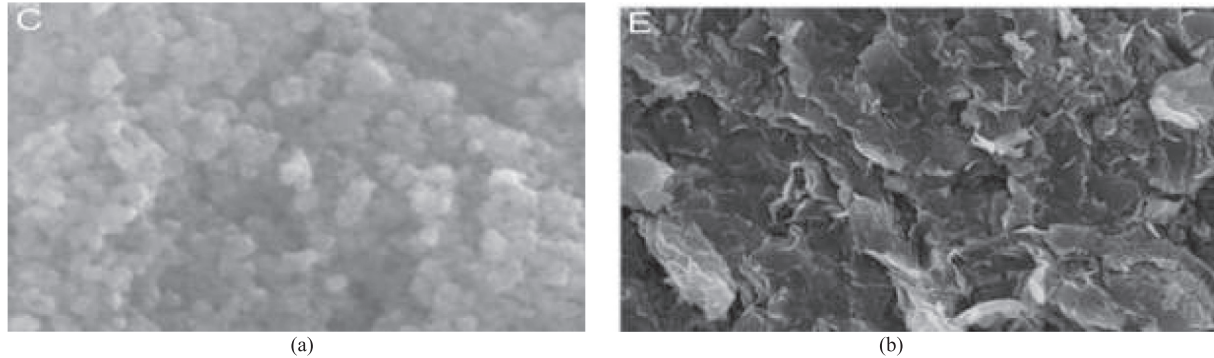
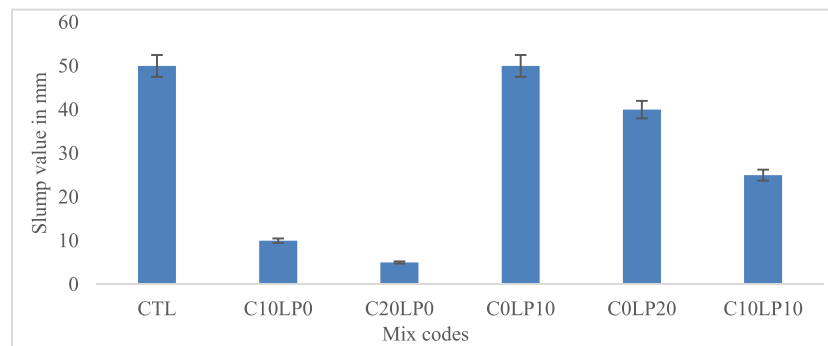
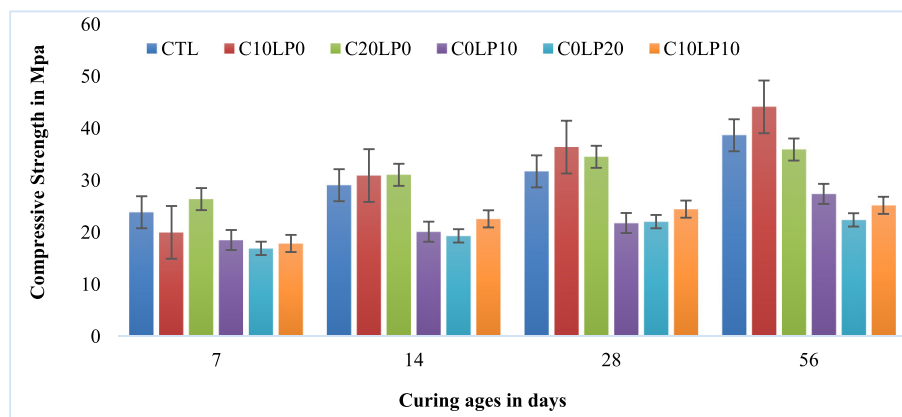
**Fig. 2.** Diffractogram for calcined clay and Limestone powder.

Table 4

Chemical/oxide composition of CC and LP.

Oxides (%)	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	MnO	SO ₃	LOI
CC	45.00	37.14	0.55	0.02	3.35	0.1	–	1.738	0.01	0.11	–
LP	0.85	8.46	1.23	56.1	1.16	0.47	0.04	1.06	0.04	–	30.27

**Fig. 3.** (a) SEM image for CC (b) SEM image for LP.**Fig. 4.** Slump values in mm.**Fig. 5.** Compressive strength of concrete specimens in Mpa.

secondary strength which is very slow as it relied solely on released CH (Calcium hydroxide) from cement (or primary) hydration and interaction between CH and amorphous silica from pozzolan are itself very slow [69].

Similar results were reported by Salau and Osemeke [32] when a certain percentage of calcined clay was used as a partial replacement for cement. Partial substitution of cement with LP did not improve the strength of concrete even in the presence of calcined

clay which is known to improve compressive strength. The reason behind this negative contribution may be due to the non-pozzolanic characteristics of LP. Another contributory factor to the loss of compressive strength is the higher LOI from LP, an increase in the supply of LOI by LP will lead to a reduction in compressive strength. The negative impact of the LP substitution with cement on the mechanical properties of concrete samples had also been reported in previous work [26,30,31]. C10LP10 performed

better in terms of compressive strength compared to other concrete containing various percentages of LP except at 56 days. This may be due to the presence of calcined clay. All-in-all concrete samples containing various percentages of LP have lower compressive strength compared to control samples.

3.3.2. Split tensile strength

Fig. 6 presents the split tensile properties of concrete samples. Split tensile strength increases as concrete samples stay more in curing water except for concrete sample C10LP10 whose split tensile strength only increases slightly after 7 days. All other samples witnessed an increase in split tensile strength from 7 days up to 56 days. There was no major strength gain for C10LP10 beyond 7 days, this may be due to the poor synergistic relationship between CC and LP as well as the sensitivity of split tensile strength to materials composition [69]. As shown in Figure 6, C10LP0 performed better in terms of split tensile strength and the strength at 7 days for C10LP0 was also small compared to the control, C20LP0 and COLP10. The reason behind the smaller split tensile strength for C10LP0 at 7 days (early age) is a result of slow pozzolanic (or secondary) reaction credited for later age strength gain and late release of $\text{Ca}(\text{OH})_2$ from cement (or primary) hydration. The positive influence of CC had also been reported by Salau and Osemeke [32]. Although, the negative impact of the addition of LP had been established for the compressive strength of concrete containing various percent of LP [70,71] but there was no significant effect of LP on the split tensile strength of concrete containing LP as compared to the control. This assertion also agreed with previous work by Klathae et. al [70], where the use of high-volume ground bagasse ash (HVGBA) with different LOIs (i.e 10.9, 16.1 and 22.0%) were used as partial substitutes for cement in concrete production. There was no major strength gain in the substitution of cement with LP [26,30,31].

4. Conclusions

In conclusion, the following can be extrapolated based on the outcomes of this research study:

- XRD analyses showed that CC particles are majorly amorphous while LP particles are crystal in nature and identified crystal structures for LP include Quartz and calcite.
- Based on the results of analyses from XRF and the requirement of ASTM C618, CC can be classified as a pozzolan while LP cannot be classified as a pozzolan.

- Results of SEM also showed that CC is closely packed with few micropores. CC particles are regular shapes arranged in a regular pattern while LP particles are arranged in layers with the presence of many micropores loosely packed together.
- It can also be deduced from this research study that slump value falls with an increase in the substitution of CC with cement, C20LP0 has the lowest slump value while the substitution of LP with cement also contributed to the loss of slump value but the loss of slump is more pronounced in concrete samples containing CC than that of LP. C10LP10 has a slump value that is not greater than the slump value for COLP10 and not lesser than the slump value for the C10LP0 mix.
- Compressive strength results showed that concrete mix C10LP0 has the highest compressive strength compared to control and other concrete mixes containing LP and CC except at 7 days. Concrete samples containing LP either as a binary blend with cement only or as ternary blenders with cement and CC have lower compressive strength compared to control and concrete samples containing only binary blends of CC.
- As in the case of compressive strength, C10LP0 has the highest split tensile strength compared to other concrete mixes except at 7 days. C10LP10 (ternary blends of CC and LP) has the lowest split tensile strength compared to other concrete mixes and there was no major strength gain after 7-day crushing.

CRedit authorship contribution statement

A.M. Salman: Conceptualization, Methodology, Formal analysis, Supervision, Writing – original draft. **M.A Akinpelu:** Writing – review & editing, Visualization, Validation. **I.T Yahaya:** Investigation, Supervision, Data curation, Resources. **H.M Salami:** Investigation, Software, Resources.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

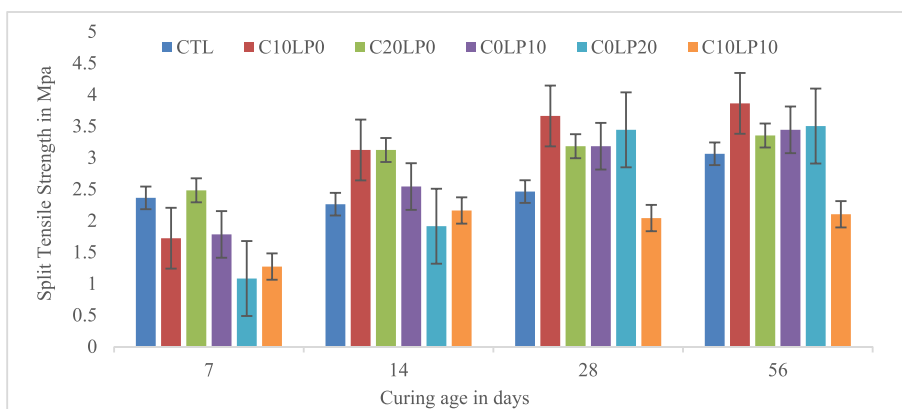


Fig. 6. Split Tensile Strength of concrete specimens in Mpa.

References

- [1] M.N. Amin, T. Murtaza, K. Shahzada, K. Khan, Pozzolanic Potential and Mechanical Performance of Wheat Straw Ash Incorporated Sustainable Concrete, *Sust.* 519 (2019) 1–20, <https://doi.org/10.3390/su11020519>.
- [2] V. Charitha, V.S. Athira, V. Jittin, A. Bahurudeen, P. Nanthagopalan, Use of different agro-waste ashes in concrete for effective upcycling of locally available resources, *Constr. Build. Mater.* 285 (2021) 1–17, <https://doi.org/10.1016/j.conbuildmat.2021.122851>.
- [3] A.A. Raheem B.D. Ikotun Incorporation of agricultural residues as partial substitution for cement in concrete and mortar – A review, *J. Build. Eng.*, (31) 2020: 1–10. Doi: <https://doi.org/10.1016/j.jobe.2020.101428>.
- [4] M. Fouad, U.J. Alengaram, M. Zamin, B. Alsubari, M.A. Alqedra, K. Hung, Effect of aggressive chemicals on durability and microstructure properties of concrete containing crushed new concrete aggregate and non-traditional supplementary cementitious materials, *Constr. Build. Mater.* 163 (2018) 482–495, <https://doi.org/10.1016/j.conbuildmat.2017.12.106>.
- [5] V. Kannan, Strength and durability performance of self-compacting concrete containing self-combusted rice husk ash and Metakaolin, *Constr. Build. Mater.* 160 (2018) 169–179, <https://doi.org/10.1016/j.conbuildmat.2017.11.043>.
- [6] S.A. Zareei, F. Ameri, F. Dorostkar, M. Ahmadi, Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica : Evaluating durability and mechanical properties, *Case Stud. Constr. Mater.* (2017) 73–81, <https://doi.org/10.1016/j.cscm.2017.05.001>.
- [7] M. Sandemir, Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete, *Constr. Build. Mater.* 49 (2013) 484–489, <https://doi.org/10.1016/j.conbuildmat.2013.08.091>.
- [8] M. Oltulu, R. Şahin, Pore structure analysis of hardened cement mortars containing silica fume and different nano-powders, *Constr. Build. Mater.* 53 (2014) 658–664, <https://doi.org/10.1016/j.conbuildmat.2013.11.105>.
- [9] H.W. Song, S.W. Pack, S.H. Nam, J.C. Jang, V. Saraswathy, Estimation of the permeability of silica fume cement concrete, *Constr. Build. Mater.* 24 (2010) 315–321, <https://doi.org/10.1016/j.conbuildmat.2009.08.033>.
- [10] N. Shafiq, M.F. Nuruddin, S.U. Khan, T. Ayub, Calcined kaolin as cement replacing material and its use in high strength concrete, *Constr. Build. Mater.* 81 (2015) 313–323, <https://doi.org/10.1016/j.conbuildmat.2015.02.050>.
- [11] N.M. Al-Akhras, Durability of Metakaolin concrete to sulfate attack, *Cem. Concr. Res.* 36 (2006) 1727–1734, <https://doi.org/10.1016/j.cemconres.2006.03.026>.
- [12] R. Singh, R.A. Khan, Mechanical and Durability Characteristics of High Performance Concrete Using Copper Slag as Fine Aggregate, *J. Mater. Eng. Struct.* 7 (2020) 277–291.
- [13] X. Cai, Z. He, S. Tang, X. Chen, Abrasion erosion characteristics of concrete made with moderate heat Portland cement, fly ash and silica fume using sandblasting test, *Constr. Build. Mater.* 127 (2016) 804–814, <https://doi.org/10.1016/j.conbuildmat.2016.09.117>.
- [14] I. Xinhua Cai, M. Vahdani, K. Amini, M. Shekarchi, Linking stability characteristics to material performance of self-consolidating concrete-equivalent-mortar incorporating fly ash and metakaolin, *Constr. Build. Mater.* 105 (2016) 206–217, <https://doi.org/10.1016/j.conbuildmat.2015.12.090>.
- [15] P. Dinakar, K.G. Babu, M. Santhanam, Durability properties of high-volume fly ash self-compacting concretes, *Cem. Concr. Compos.* 30 (2008) 880–886, <https://doi.org/10.1016/j.cemconcomp.2008.06.011>.
- [16] B.H. Nagaratnam, M.A. Mannan, M.E. Rahman, A.K. Mirasa, A. Richardson, O. Nabinejad, Strength and microstructural characteristics of palm oil fuel ash and fly ash as binary and ternary blends in Self-Compacting concrete, *Constr. Build. Mater.* 202 (2019) 103–120, <https://doi.org/10.1016/j.conbuildmat.2018.12.139>.
- [17] A.M. Zeyad, M.A. Megat, B.A. Tayeh, M.O. Yusuf, Pozzolanic reactivity of ultrafine palm oil fuel ash waste on strength and durability performances of high strength concrete, *J. Clean. Prod.* 144 (2017) 511–522, <https://doi.org/10.1016/j.jclepro.2016.12.121>.
- [18] K. Wi, H. Lee, S. Lim, H. Song, M. Warid, Use of an agricultural by-product, nano sized Palm Oil Fuel Ash as a supplementary cementitious material, *Constr. Build. Mater.* 183 (2018) 139–149, <https://doi.org/10.1016/j.conbuildmat.2018.06.156>.
- [19] F.C.R. Almeida, A. Sales, J.P. Moretti, P.C.D. Mendes, Sugarcane bagasse ash sand (SBAS): Brazilian agroindustrial by-product for use in mortar before, *Constr. Build. Mater.* 82 (2015) 31–38, <https://doi.org/10.1016/j.conbuildmat.2015.02.039>.
- [20] G. Sua-iam, N. Makul, Effect of incinerated sugarcane filter cake on the properties of self-compacting concrete, *Constr. Build. Mater.* 130 (2016) 32–40, <https://doi.org/10.1016/j.conbuildmat.2016.11.033>.
- [21] E. Aprianti, P. Shafiqh, S. Bahri, J.N. Farahani, Supplementary cementitious materials origin from agricultural wastes – A review, *Constr. Build. Mater.*, (74) 2015: 176–187. Doi: <https://doi.org/10.1016/j.conbuildmat.2014.10.010>.
- [22] A.M.D. Higuchi, M. Goretti, L. Farias, R. Pereira, D. Vasconcelos, Use of glass powder residue as an eco-efficient supplementary cementitious material, *Constr. Build. Mater.* 304 (2021) 1–12, <https://doi.org/10.1016/j.conbuildmat.2021.124640>.
- [23] S.M. Motahari, A. Joshaghani, A.A. Ramezani-pour, S. Isapour, M. Karakouzian, Effects of the mechanical milling method on transport properties of self-compacting concrete containing perlite powder as a supplementary cementitious material, *Constr. Build. Mater.* 172 (2018) 677–684, <https://doi.org/10.1016/j.conbuildmat.2018.03.205>.
- [24] A. Siddika, A. Al, R. Alyousef, H. Mohammadhosseini, State-of-the-art-review on rice husk ash : A supplementary cementitious material in concrete, *J. King Saud Univ. - Eng. Sci.* 33 (2021) 294–307, <https://doi.org/10.1016/j.jksues.2020.10.006>.
- [25] G. Sua-iam, N. Makul, Use of limestone powder during incorporation of Pb-containing cathode ray tube waste in self-compacting concrete, *J. Environ. Manage.* 128 (2013) 931–940, <https://doi.org/10.1016/j.jenvman.2013.06.031>.
- [26] J.F. Burroughs, J. Shannon, T.S. Rushing, K. Yi, Q.B. Gutierrez, D.W. Harrelson, Potential of finely ground limestone powder to benefit ultra-high performance concrete mixtures, *Constr. Build. Mater.* 141 (2017) 335–342, <https://doi.org/10.1016/j.conbuildmat.2017.02.073>.
- [27] S.A. Rizwan, T.A. Bier, Blends of limestone powder and fly-ash enhance the response of self-compacting mortars, *Constr. Build. Mater.* 27 (2012) 398–403, <https://doi.org/10.1016/j.conbuildmat.2011.07.030>.
- [28] L.G. Li, A.K.H. Kwan, Adding limestone fines as cementitious paste replacement to improve tensile strength, stiffness and durability of concrete, *Cem. Concr. Compos.* 60 (2015) 17–24, <https://doi.org/10.1016/j.cemconcomp.2015.02.006>.
- [29] Z. Skender, A. Bali, R. Kettab, Self-compacting concrete (SCC) behaviour incorporating limestone fines as cement and sand replacement, *Eur. J. Environ. Civ. Eng.* 25 (2021) 1852–1873, <https://doi.org/10.1080/19648189.2019.1607564>.
- [30] R.K. Dhir, M.C. Limbachiya, M.J. McCarthy, A. Chaipanich, Evaluation of Portland limestone cements for use in concrete construction, *Mater. Struct. Constr.* 40 (2007) 459–473, <https://doi.org/10.1617/s11527-006-9143-7>.
- [31] N. Ghafoori, R. Spitek, M. Najimi, Influence of limestone size and content on transport properties of self-consolidating concrete, *Constr. Build. Mater.* 127 (2016) 588–595, <https://doi.org/10.1016/j.conbuildmat.2016.10.051>.
- [32] M.A. Salau, O.J. Osemeke, Effects of Temperature on the Pozzolanic Characteristics of Metakaolin-Concrete, *Physical Science International Journal* 6 (2015) 131–143, <https://doi.org/10.9734/PSIJ/2015/13146>.
- [33] R. Jaskulski, J. Daria, Calcined Clay as Supplementary Cementitious Material, *Materials (Basel)* 13 (2020) 1–36, <https://doi.org/10.3390/ma13214734>.
- [34] P. Zhan, Z. He, Z. Ma, C. Liang, X. Zhang, Utilization of nano-metakaolin in concrete : A review, *J. Build. Eng.* 30 (2020) 1–14, <https://doi.org/10.1016/j.jobe.2020.101259>.
- [35] A.R. Bagheri, H. Zanganeh, M.M. Moalemi, Mechanical and durability properties of ternary concretes containing silica fume and low reactivity blast furnace slag, *Cem. Concr. Compos.* 34 (2012) 663–670, <https://doi.org/10.1016/j.cemconcomp.2012.01.007>.
- [36] C. Medina, I.F. Sáez del Bosque, M. Frías, M.I. Sánchez de Rojas, Design and characterisation of ternary cements containing rice husk ash and fly ash, *Constr. Build. Mater.* 187 (2018) 65–76, <https://doi.org/10.1016/j.conbuildmat.2018.07.174>.
- [37] E. Güneysi, M. Gesog, Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume, *Constr. Build. Mater.* 23 (2009) 1847–1854, <https://doi.org/10.1016/j.conbuildmat.2008.09.015>.
- [38] J. Bai, S. Wild, B.B. Sabir, Chloride ingress and strength loss in concrete with different PC-PFA-MK binder compositions exposed to synthetic seawater, *Cem. Concr. Res.* 33 (2003) 353–362, [https://doi.org/10.1016/S0008-8846\(02\)00961-4](https://doi.org/10.1016/S0008-8846(02)00961-4).
- [39] G. Dhinakaran, B. Sreekanth, Physical, mechanical, and durability properties of ternary blend concrete, *Sci. Iran.* 25 (2018) 2440–2450, <https://doi.org/10.24200/sci.2017.4210>.
- [40] E.O. Fanijo, E. Kassem, A. Ibrahim, ASR mitigation using binary and ternary blends with waste glass powder, *Constr. Build. Mater.* 280 (2021) 1–16, <https://doi.org/10.1016/j.conbuildmat.2021.122425>.
- [41] A.N. Reddy, T. Meena, Acid Resistance of Ternary Blended Nanosilica Concrete Incorporating Fly Ash and Alccofine, *Civ. Eng. Archit.* 9 (2021) 500–506, <https://doi.org/10.13189/cea.2021.090222>.
- [42] A. Alhozaimey, A. Al-negheimish, O.A. Alawad, M.S. Jaafar, J. Noorzaei, Binary and ternary effects of ground dune sand and blast furnace slag on the compressive strength of mortar, *Cem. Concr. Compos.* 34 (2012) 734–738, <https://doi.org/10.1016/j.cemconcomp.2012.03.002>.
- [43] K.J. Rao, K. Keerthi, S. Vasam, Acid resistance of quaternary blended recycled aggregate concrete, *Case Stud. Constr. Mater.* 8 (2018) 423–433, <https://doi.org/10.1016/j.cscm.2018.03.005>.
- [44] F.U.A. Shaikh, Mechanical properties of recycled aggregate concrete containing ternary blended cementitious materials, *Int. J. Sustain. Built Environ.* 6 (2017) 536–543, <https://doi.org/10.1016/j.ijsbe.2017.10.005>.
- [45] J. Massana, E. Reyes, J. Bernal, N. León, E. Sánchez-Espinosa, Influence of nano- and micro-silica additions on the durability of a high-performance self-compacting concrete, *Constr. Build. Mater.* 165 (2018) 93–103, <https://doi.org/10.1016/j.conbuildmat.2017.12.100>.
- [46] P. Kathirvel, V. Saraswathy, S.P. Karthik, A.S.S. Sekar, Strength and Durability Properties of Quaternary Cement Concrete Made with Fly Ash, Rice Husk Ash and Limestone Powder, *Arab. J. Sci. Eng.* 38 (2013) 589–598, <https://doi.org/10.1007/s13369-012-0331-1>.
- [47] J. Zelic, R. Krstulovic, E. Tkalcic, P. Krolo, The properties of Portland cement-limestone-silica fume mortars, *Cem. Concr. Res.* 30 (2000) 145–152.
- [48] G. Menendez, V. Bonavetti, E.F. Irassar, Strength development of ternary blended cement with limestone filler and blast-furnace slag, *Cem. Concr. Compos.* 25 (2003) 61–67.

- [49] Z. Shi, S. Ferreiro, B. Lothenbach, M.R. Geiker, W. Kunther, J. Kaufmann, D. Herfort, J. Skibsted, Sulfate resistance of calcined clay – Limestone – Portland cements, *Cem. Concr. Res.* 116 (2019) 238–251, <https://doi.org/10.1016/j.cemconres.2018.11.003>.
- [50] Z. Makhloufi, E.H. Kadri, M. Bouhicha, A. Benaissa, Resistance of limestone mortars with quaternary binders to sulfuric acid solution, *Constr. Build. Mater.* 26 (2012) 497–504, <https://doi.org/10.1016/j.conbuildmat.2011.06.050>.
- [51] M. Antoni, J. Rossen, F. Martirena, K. Scrivener, Cement substitution by a combination of metakaolin and limestone, *Cem. Concr. Res.* 42 (2012) 1579–1589, <https://doi.org/10.1016/j.cemconres.2012.09.006>.
- [52] A.M. Salman, M.A. Akinpelu, G.A. Ahmed, A.I. Raheem, Evaluation of Variations of Coarse Aggregate types on Hardened Properties of Concrete, *J. Mater. Eng. Struct.* 8 (2021) 301–311.
- [53] D.K. Ashish, Concrete made with waste marble powder and supplementary cementitious material for sustainable development, *J. Clean. Prod.* 211 (2019) 716–729, <https://doi.org/10.1016/j.jclepro.2018.11.245>.
- [54] R. Siddique, J. Klaus, Influence of metakaolin on the properties of mortar and concrete: A review, *Appl. Clay Sci.* 43 (2009) 392–400, <https://doi.org/10.1016/j.clay.2008.11.007>.
- [55] A. Shvarzman, K. Kovler, G.S. Grader, G.E. Shter, The effect of dehydroxylation/ amorphization degree on pozzolanic activity of kaolinite, *Cem. Concr. Res.* 33 (2003) 405–416.
- [56] M. Singh, M. Garg, Reactive pozzolana from Indian clays-their use in cement mortars, *Cem. Concr. Res.* 36 (2006) 1903–1907, <https://doi.org/10.1016/j.cemconres.2004.12.002>.
- [57] Y.M. Liew, H. Kamarudin, A.M. Mustafa Al Bakri, M. Luqman, I. Khairul Nizar, C. M. Ruzaidi, C.Y. Heah, Processing and characterization of calcined kaolin cement powder, *Constr. Build. Mater.* 30 (2012) 794–802, <https://doi.org/10.1016/j.conbuildmat.2011.12.079>.
- [58] F. Pelisser, E.L. Guerrino, M. Menger, M.D. Michel, J.A. Labrincha, Micromechanical characterization of metakaolin-based geopolymers, *Constr. Build. Mater.* 49 (2013) 547–553, <https://doi.org/10.1016/j.conbuildmat.2013.08.081>.
- [59] D. Ren, C. Yan, P. Duan, Z. Zhang, L. Li, Z. Yan, Durability performances of wollastonite, tremolite and basalt fiber-reinforced metakaolin geopolymer composites under sulfate and chloride attack, *Constr. Build. Mater.* 134 (2017) 56–66, <https://doi.org/10.1016/j.conbuildmat.2016.12.103>.
- [60] ASTM C618-12a, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use, 2014. <https://doi.org/10.1520/C0618>.
- [61] A.M. Salman, M.A. Akinpelu, A. Abdulrasaq, E.A. Adetoro, Influence of Locally Sourced Waste Foundry Sand on Workability and Compressive Strength of Normal-Strength Concrete, *ABUAD J. Eng. Res. Dev.* 5 (2022) 65–75.
- [62] BS EN 12350-2: Testing fresh concrete: Slump test, British Standard Institute, 2010.
- [63] BS EN 1239-3: Testing Hardened concrete: Compressive Strength test, British Standard Institute, 2010.
- [64] BS EN 12390-6: Testing hardened concrete: Split Tensile Strength test, British Standard Institute, 2010.
- [65] H.T. Kouamo, A. Elimbi, J.A. Mbey, C.J.N. Sabouang, D. Njopwouo, The effect of adding alumina-oxide to metakaolin and volcanic ash on geopolymer products : A comparative study, *Constr. Build. Mater.* 35 (2012) 960–969, <https://doi.org/10.1016/j.conbuildmat.2012.04.023>.
- [66] Y. Wang, Z. Shui, T. Sun, Y. Huang, G. Wang, Effect of Fly Ash, Sinking Beads and Metakaolin on the Workability, Strength, Free Shrinkage and Chloride Resistance of Concretes: A Comparative Study, *Arab. J. Sci. Eng.* 43 (2018) 5243–5254, <https://doi.org/10.1007/s13369-018-3068-7>.
- [67] A.Y. Atta, B.Y. Jibril, B.O. Aderemi, S.S. Ade, Preparation of analcime from local kaolin and rice husk ash, *Appl. Clay Sci.* 61 (2012) 8–13, <https://doi.org/10.1016/j.clay.2012.02.018>.
- [68] Å. Frö, J. Cabrera, Influence of MK on the reaction kinetics in MK / lime and MK-blended cement systems at 20° C, *Cem. Concr. Res.* 31 (2001) 519–527.
- [69] M.S. Shetty, *Concrete Technology: Theory and Practice*, seventh ed., S. Chand and Company Ltd, New Delhi, India, 2017.
- [70] T. Klathae, N. Tanawuttiphong, W. Tangchirapat, P. Chindaprasirt, P. Sukontasukkul, C. Jaturapitakkul, Heat evolution, strengths, and drying shrinkage of concrete containing high volume ground bagasse ash with different LOIs, *Constr. Build. Mater.* 258 (2020) 1–11, <https://doi.org/10.1016/j.conbuildmat.2020.119443>.
- [71] M.A. Salih, M.R. Aldikheeli, K.A. Shaalan, Evaluation of factors influencing the compressive strength of Portland cement statistically, in: *Proceedings, IOP Conf. Ser.: Mater. Sci. Eng.*, 4th International Conference on Buildings, Construction and Environment Engineering (BCEE4) , Istanbul Technical University, Ayazaga Campus, Istanbul, Turkey, 7–9 th October, 2020; pp. 1–10, <https://doi.org/10.1088/1757-899X/737/1/012059>.