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Influence of Lime and Coal Bottom Ash as Partial Cement Replacement Material on Mechanical Properties of Concrete

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Abstract: Coal bottom ash (CBA) is a waste product collected at the bottom of the furnace from the coal operated power plants. However, its huge production becomes a major environmental issue that will bring a negative impact on the environment as it will lead to a higher risk of groundwater contamination. In this study selected 10% of CBA based on previous studies, but various percentages (5% to 15%) of lime content were used in this study by weight method. The compressive, tensile, and flexural strength tests were performed at 7 and 28days. Based on the results, the workability of concrete showed a reduction when the cement replacement level increased. The compressive, splitting tensile, and flexural strengths were reduced when cement replacement level increase, but the strength was improved with the increase in curing age. However, the concrete with10% CBA indicated higher splitting tensile strength than the control.

Keywords: Coal bottom ash, lime, compressive strength, concrete, tensile strength, flexural strength

1. Introduction

Concrete is the key construction material utilized in the construction since the early 1800s century. It was the main construction material that used broadly in buildings, bridges, roads, and other construction (Kadam et al., 2013). The demand for concrete is increasing each year which leads to reduction in natural assets (Rafieizonooz et al., 2016). Concrete is mixture of cement, aggregates, and water (Nwofor et al., 2015). Concrete was formed when the cement makes a paste with water that binds with aggregates to solidify (Nwofor et al., 2015). However, the increasing cement production has various toxic impacts on the environment (Mohd Kamal et al., 2016). The manufactures of cement release a huge amount of greenhouse gases such as carbon dioxide (CO_2) into the atmosphere and thus causing global warming. Globally, around 3300 million tons of cement being generated annually (Acharya et al., 2015a). It is predicted that the CO_2 emissions resulting from the cement production added to around 1.35 billion tons per annum. Thus, there is a need to find alternative material in replacing cement in concrete to lessen the problem of environment (Aydin, 2016). The supplementary cementitious material in concrete not only increases the performance of concrete but

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*Corresponding author: haziman@uthm.edu.my also lead to the sustainable concrete production. Coal Bottom Ash (CBA) and Fly Ash (FA) can be used to replace cement in the production of concrete (Rafieizonooz et al., 2016). However, CBA can be collected at the bottom of the furnace which is coarser in size as compared to FA. The annual worldwide production of coal ash is estimated at six hundred million tons with CBA forming around one hundred million tons (Argiz et al., 2018). CBA is waste product that generated from the combustion of pulverized coal in the thermal power plant that constitutes about 10% to 20% of the total coal ash. The amount of coal combustion production is increasing every year and they face the problem of managing waste (Muhardi et al., 2010). In the long term, this will harm the environment and human health (Aydin, 2016). It can irritate eyes, skin, and respiratory system (Muhardi et al., 2010). Direct disposal of FA and CBA could contaminate the groundwater with heavy metals which affect the soil quality (Marto et al., 2016). CBA has manifest to have constructability benefits and hence it was declared as an economical material for construction (Wongkeo et al., 2010). It was earlier declared that the CBA can be employed as cementitious material but after proper grinding process (Cheriaf et al., 1999). It could help to reduce the dead weight of the structure due to its less specific gravity compared to cement in addition to the mitigation of environmental threats. The usage of CBA as a cementitious material could reduce energy and raw material consumption (Argiz et al., 2018). The use of CBA could increase the workability of the concrete mix and could enhances the strength and durability of concrete (Khan et al., 2016).

Literature review indicated that the compressive strength of concrete was reduced with the more replacement level of CBA. The decrease of strength is notable at lower curing age such as at 7days. The reduction in strength of concrete with the increased in CBA quantity may be due to the reason that CBA delay the cement hydration (Mangi et al., 2019). However, the compressive strength of concrete comprising CBA is improved with the increase in curing age. Perhaps, CBA concrete attains strength at a faster rate beyond 28days, which may be due to the pozzolanic response of CBA (Aggarwal et al., 2007). Next, when the substitute level of CBA is increased, the tensile strength of concrete is decreased, because pozzolanic response not yet started at 28days (Aggarwal et al., 2007 and Singh et al., 2013). Moreover, the rise in tensile strength of CBA concrete with increase in the curing period, it could be due to the expansion of C-S-H gel. Moreover, the strength of concrete decreases when the addition of CBA is more than 10% (Mangi et al., 2019). Hence, 10% of CBA replacement in cement could improve the properties of concrete (Torkittikul et al., 2017).

Moreover, the flexural strength of concrete with 10% replacement is higher compared to other concrete mixes for all water-cement ratio (Cheriaf et al., 1999). But the flexural strength starts to decrease when the replacement of CBA with sand in concrete exceed 15%. There was a test on the replacement of different percentages of CBA with cement to study its influence on the flexural strength of concrete (Kurama et al., 2008). The flexural strength of concrete at 56 days increases significantly when 10% of cement is replaced with cement when compared with other mixture of cement. The flexural strength of concrete starts to decrease when 10% of cement is replaced by CBA. As a result of high CBA, the content will decrease the rate of reaction activity in concrete. Besides, it also causes a slow gain of strength at the early ages of concrete when a higher amount of CBA is replaced to the cement.

Lime ($CaCO_3$) is a raw material that is cheap and sufficiently available in nature. Lime has been utilized as binding agent for construction works around the world since the earliest age (Acharya et al., 2016b). However, cement was replaced with lime to balance $CaCO_3$ content in blended cement which containing CBA, OPC and lime. Therefore, replacement of cement with lime and CBA (Siddique, 2014). Compressive strength of concrete including lime as cement replacement was found to decrease with a higher percentage of lime (Ramezanianpour et al., 2009). Previous research reported that, with 5% and 7% of lime in PSC concrete, the compressive strength is found to increase (Acharya et al., 2016b). However, compressive strength started to decrease with the addition of 10% of lime at all curing age. Furthermore, the decrease in compressive strength is due to the clinker dilution effect which is a result of replacing partial cement by lime (Ramezanianpour et al., 2009). Besides that, the compressive strength of concrete with lime as replacement of OPC was found to increase with the increase in curing age. The increase in strength with curing age may be due to the creation of more C-S-H gel on the usage of excess SiO_2 and Al_2O_3 in the occurrence of lime (Acharya et al., 2016b). Next, splitting tensile strength of concrete containing lime is also found to decrease with the increase of lime percentage due to the consequences from the translation of gelatinous C_3S hydrate to crystalline C_3AH_6 (Siddique, 2014). Moreover, the translation of rapid hydration of C_4AF to C_3AH_6 and CFH also contributed to the lower compressive and tensile strength of concrete.

Another research discovered that maximum flexural strength was documented at 7% lime (Acharya et al., 2016b) and noticed that the flexural strength was found to rise with age on the addition of lime in concrete. Hence, the reason for the improvement in the flexural strength of lime in concrete is because of the filling effect of the pore in the pore structure. On the other hand, the practice of lime in concrete has increased drastically over the past few years (Acharya et al., 2016b). The addition of lime increases the rate of hydration, decrease the setting time and total porosity. This research shows that the substitution of 60% of cement with lime improves the rate of hydration at an early age up to 28 days. Therefore, the addition of lime into the cement will enhance the workability of concrete. Several investigations on the use of CBA have been subjected to its use in cement and concrete in recent years. However, this study considered lime as cement substitute material in concrete in presence of CBA.

2. Materials and Experimental Works

2.1 Materials

The Portland cement (OPC), the coarse aggregates that retained on 5mm sieve and sand which passed through 5mm sieve were used. The CBA used was collected from Sultan Salahuddin Abdul Aziz Power Plant Selangor, Malaysia. For CBA preparation, it was oven-dried at a temperature of 110 ± 5 °C for 24 hours. Next, it was ground in Los Angeles (LA) grinder machine for 2hours. The ground CBA was sieved and the passing 300μm CBA was ground again using Ball mill for 20hours. The hydrated lime manufactured by Lhoist Pg Sdn. Bhd was used. The chemical composition of CBA and PC were evaluated through XRF test and results are provided in Table 1, which showed that CBA has good pozzolanic characteristics as per ASTM C618 it is classified as Class-F pozzolanic ash.

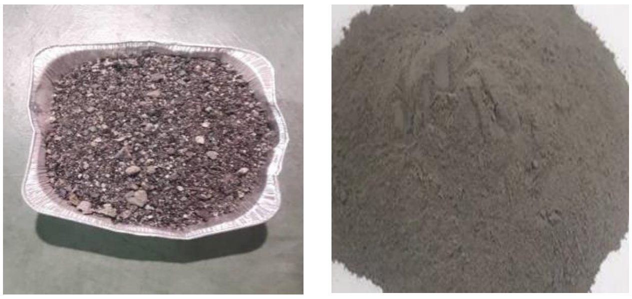
(a) (b)

Fig. 1 - (a) Raw CBA; (b) Ground CBA

Table 1 - Chemical composition of CBA and OPC

Oxides (%)	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**LOI**
CBA	52.5	17.6	8.3	4.7	0.6	0.8	**4.0**
OPC	20.6	3.9	3.5	64.0	1.9	3.6	**2.2**

2.2 Mix Proportion

The control mix designed for M35 with a 0.5% cement ratio was carried based on the Building Research Establishment (BRE); Design of Experiment (DOE) method. Based on the earlier studies, 10% of the cement was replaced with CBA that passed through 63μm sieve (Mangi et al., 2019 and Aggarwal et al., 2007). The cement was replaced with hydrated lime at 5%, 10% and 15% by weight. Table 2 shows the detail of concrete mix.

Table 2 - Concrete mix design detail

Design Sample	**OPC (kg)**	**CBA (kg)**	**Lime (kg)**	**Fine Aggregates (kg)**	**Coarse Aggregates (kg)**	**Water (kg)**
Control Mix	18.22	-	-	33.33	34.28	9.11
CBA10	16.40	1.82	-	33.33	34.28	9.11
CBA 10% + Lime 5%	15.49	1.82	0.91	33.33	34.28	9.11
CBA 10% + Lime 10%	14.58	1.82	1.82	33.33	34.28	9.11
CBA 10% + Lime 15%	13.67	1.82	2.73	33.33	34.28	9.11

2.3 Experimental Works

Physical properties of CBA, cement, and lime were tested using particle size analyzer. Moreover, the slump test was performed as per BS EN 12350-2:2019 (British Standard Institution, 2019a) to measure the slump of fresh concrete. The compressive strength was performed as per BS EN 12390-3:2019 (British Standard Institution, 2019b) with cubes size of 100mm, the splitting tensile strength test was performed as per BS EN 12390-6:2009 (British Standard Institution, 2019c) with cylindrical shapes of 100mm in diameter and 200mm in length. The concrete beam of size 100mm × 100mm × 500mm was prepared for the flexural test under four-point loading as per BS EN 12390-

5:2019 (British Standard Institution, 2019d). The specimens were tested for compressive, tensile, and flexural strength after 7 and 28 days of water curing.

3. Results and Discussions

Particle Size Analyser (PSA) was performed through liquid mode (0.04 µm – 2500.00 µm) to determine the particle size of OPC, CBA, and lime. Based on Figure 2, the size distribution curve for OPC, CBA, and lime indicated a similar trend. The results showed that the finest particle was lime and followed by CBA. Moreover, the particle size distribution curve of cement demonstrated that it had the least of the finest among CBA and lime.

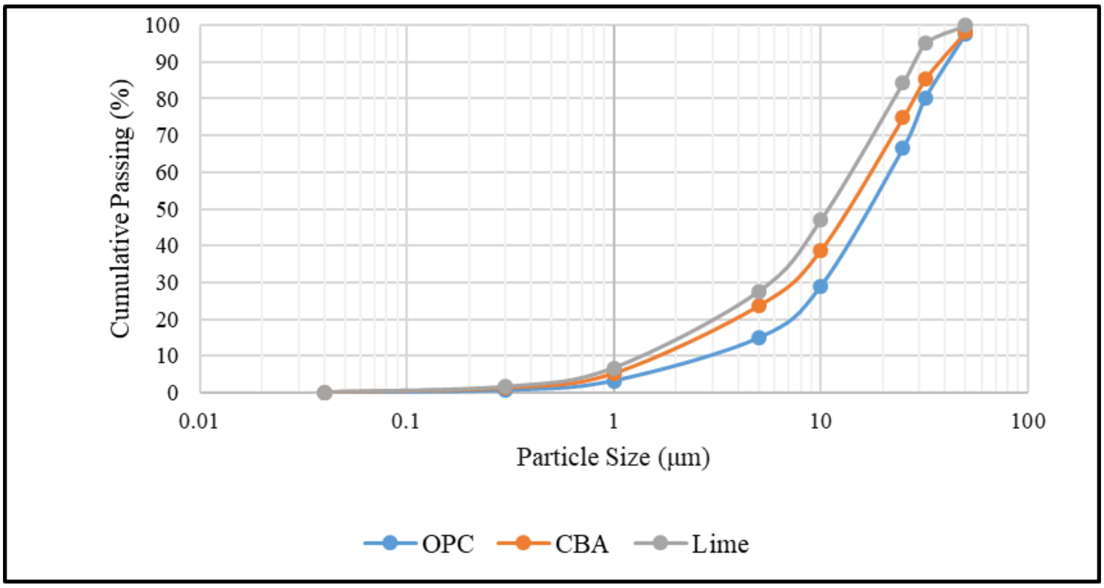

Fig. 2 - Particle size distribution

Table 3 displayed the passing percentage and specific surface of cement, CBA and lime. The results showed that at 60% of passing, the particle size of PC, CBA, and lime was 22.00µm, 17.96 µm and 13.63 µm respectively. These values indicated that lime was the finest particle as it had the lowest D_{60}. Besides that, specific surface was found to be increased with the decrease in particle size, which also infulences the specific gravity of OPC, CBA and lime.

Table 3 - Passing percentages and specific surface area

Description	D_{10} (µm)	D_{30} (µm)	D_{60} (µm)	Specific surface area (cm^2/g)	Specific gravity
OPC	3.19	10.36	22.00	4335.87	3.10
CBA	1.67	1.07	17.96	7036.76	2.41
Lime	1.37	5.62	13.63	8561.18	2.25

The slump values of control mix and concrete with 10%CBA and concrete containing 10%CBA with different percentages of lime are presented in Figure 3. The results were found declined with the increment of lime proportion. The decrease in workability with the addition of CBA and lime can be explained by the presence of lime leads to a rapid hydration process and extra water demand of CBA (Acharya et al., 2015a). In addition, the porosity of CBA which absorbs more water is also the reason for the decrease in workability (Mangi et al., 2019, Aggarwal et al., 2007, Flatt et al., 2012).

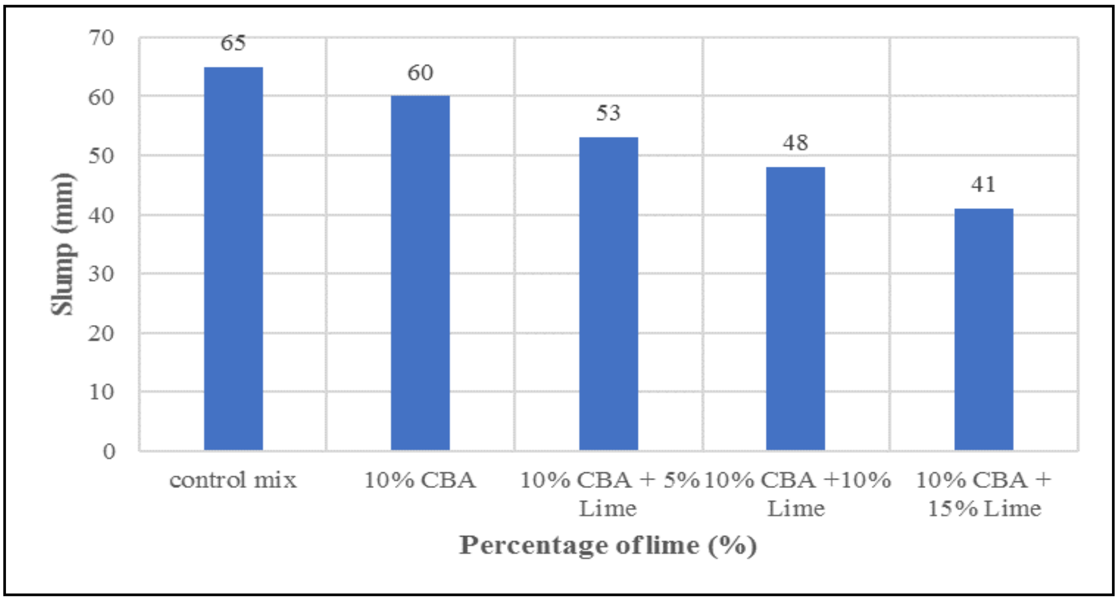

Fig. 3 - Slump of concrete containing CBA with different proportions of lime

Figure 4 demonstrated the compressive strength of concrete at various proportions of lime. The results indicated that the compressive strength was reduced due to inclusion of CBA and lime. It was clearly shown that control mix concrete created the highest compressive strength and continue to decrease with the inclusion of CBA and lime accordingly. However, the compressive strength was improved with respect to curing age. The conservation of C_3H hydrate to crystalline C_3AH_6 is the factor contributed to the decrease in compressive strength (Siddique, 2014). Rapid hydration of C_4AF to C_3AH_6 and CFH also leads to a reduction in compressive strength.

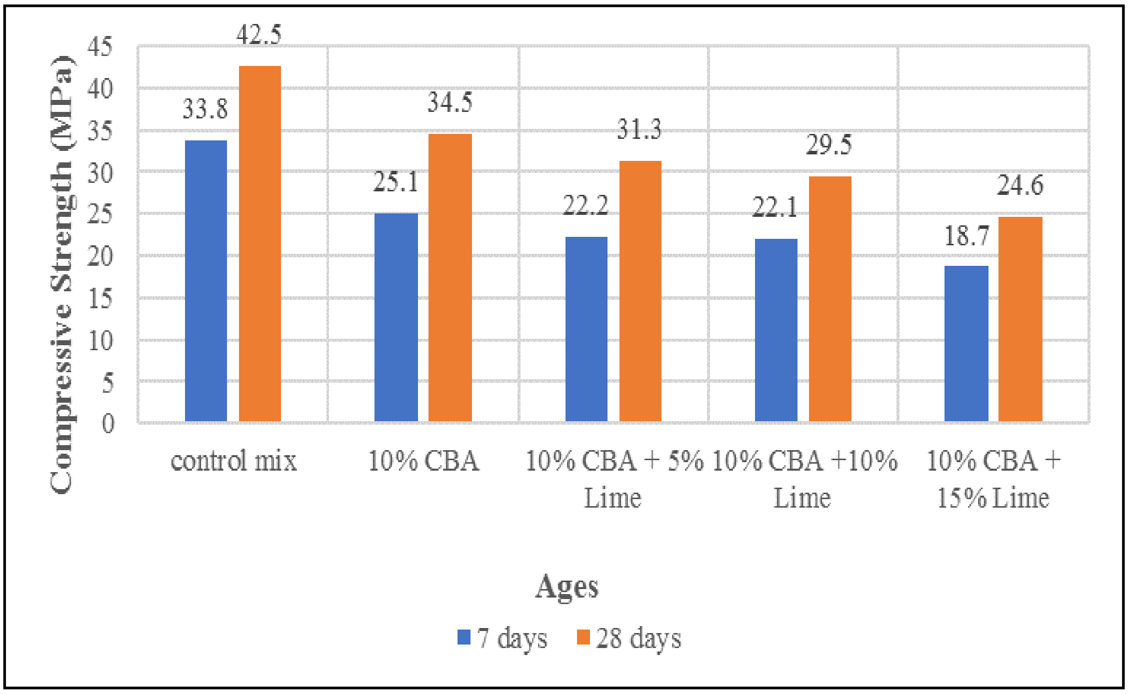

Fig. 4 - Concrete compressive strength with different proportions of lime

Figure 5 shows that concrete specimen tested at 7 and 28days having different trend of splitting tensile strength. The splitting tensile strength at 7days, showed the lower trend among the concrete samples. Whereas, at 28days of curing, splitting tensile strength was decreased. The highest splitting tensile strength of concrete at 7days of curing was observed with 10% of CBA concrete that was 2.09 MPa. Also, 10% of CBA concrete mixtures created the highest splitting tensile strength which was 2.69 MPa for 28days of curing. However, splitting tensile strength was also showed an improvement with the increase in curing age. Moreover, the decrease in tensile strength may be due to the increase in the porosity and distribution of pores in the concrete (Singh et al., 2013).

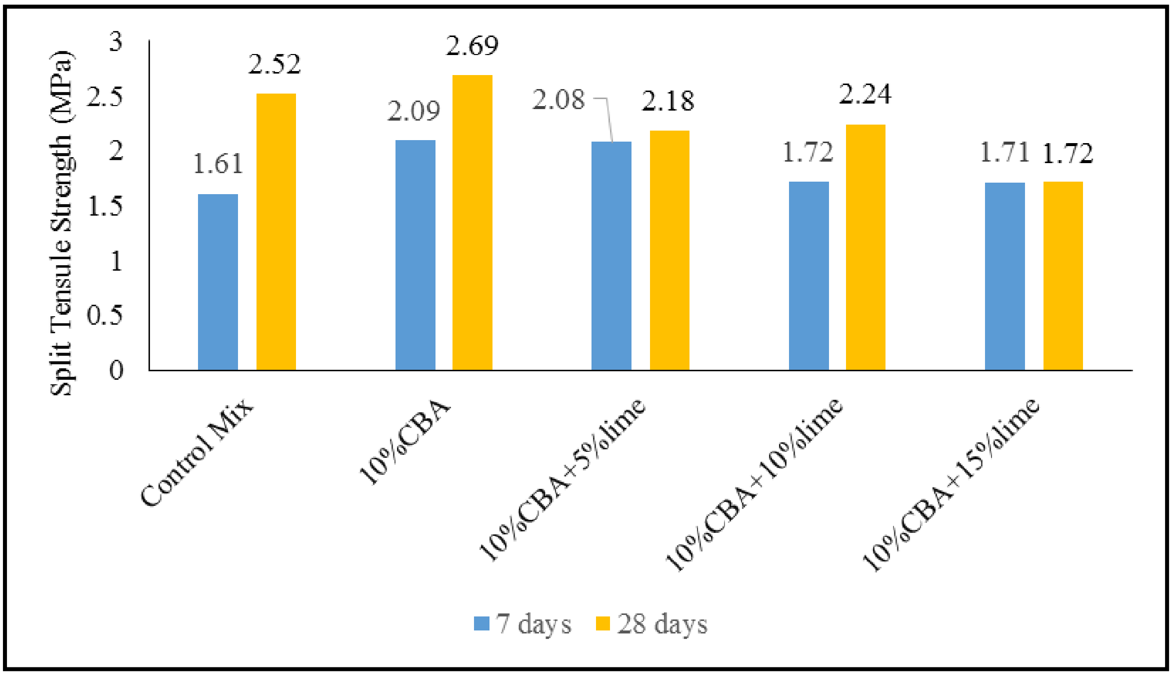

Fig. 5 - Concrete splitting tensile strength with different proportions of lime

Figure 6 indicates the results of flexural strength of the concrete at 7 and 28days. it was observed that the 28days flexural strength was greater than the 7days. However, the control mix samples gained the flexural strength of 3.9 MPa and 5.5 MPa at 7 and 28days, respectively. Then, the concrete containing 10% of CBA achieved the flexural strength of 3.6 MPa and 4.7 MPa at 7 and 28days, respectively. On the other hand, the flexural strength of concrete containing 10% of CBA and 5% of lime increased to 4.5 MPa at 7days and remain at 4.7 MPa on 28days of curing. Additionally, the flexural strength of concrete with 10% of CBA and 15% of lime continued to increase which was 5.1 MPa. However, the concrete containing 10% CBA with 15% of lime decreased to 4.1 MPa at 28days of curing. It was observed that the poor joining of CBA and lime between aggregates caused the decrease in flexural strength of concrete when partial cement was substituted with CBA and lime.

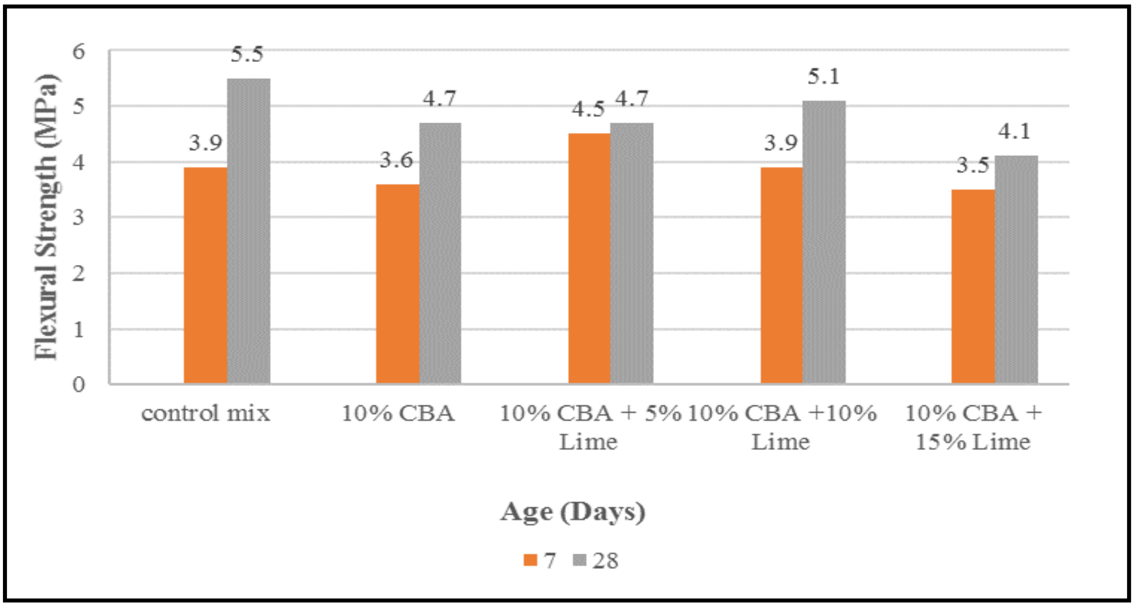

Fig. 6 - Concrete flexural strength with different proportions of lime

4. Conclusions

The folowing conclusions have been made:

i. The particle size of CBA and lime were finer than OPC. Thus, both CBA and lime can be adopted as cementitious material.
ii. The workability of concrete was found to be decreased due to more cement replacement. However, the presence of CBA and lime in concrete leads to increase in surface area and needed more water while mixing concrete.
iii. The reduction in compressive strength of concrete was found when more lime was added. The highest compressive strength of concrete containing 10% CBA was noticed as 25.1 MPa at 7 days and achieved the strength of 34.5 MPa at 28days. The concrete with 10%CBA achieved the highest splitting tensile strength at 7 and 28days which was 2.09 MPa and 2.69 MPa respectively.
iv. Compressive and tensile strength was found to be decaresed with more cement replacement but the strength was increased with the increase in curing age.
v. The average compressive and flexural strength of concrete gradually decrease with the increment percentages of lime in concrete.
vi. This study declared that the 10% of CBA was suitable even without addition of lime as cement replacement material as it was achieved the target strength for compressive and it created the highest split tensile strength among others.

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