Study on Partial Replacement of Cement with Limonite in Mechanical Strength of Mortar

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Abstract With the increasing population worldwide, main concerns are not limited to accessing sustainable living spaces but also managing waste disposal and greenhouse emissions. The supplementary cementitious materials (SCM) therefore play a vital role in providing an economical solution towards a greener environment, especially in the developing countries. The pozzolanic properties of limonite are studied in this paper to identify its potential to be used as an SCM. This study is aimed at utilizing limonite as a partial replacement of cement in the mortar by 5%, 10%, 15% and 20% of its weight. The pozzolanic properties of the limonite are traced through the results of compressive strength and the physical properties are also investigated in the form of specific gravity, setting time, consistency and fineness. Conventional cement mortar is also included for comparison. The results indicate that up to 10% replacement of cement by limonite allows an increase in the compressive strength of the mortar by 27% at 28 days. However, upon further increasing the percentage replacement, limonite had a significant effect in the mortar specimens. Lastly, this paper suggests that a reliable design guideline can be developed which will promote the use of limonite in wider implementations.

Keywords Limonite · Cement replacement · Mortar · Compressive strength

1 Introduction

Affordable building construction practice in the developing nations is increasing its popularity since the cost of construction materials is on the rise every day. Among

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the constituents of traditional concrete, cement is the most expensive one and so reducing the demand of cement eventually reduces the cost of producing concrete. Converting waste products into useful ones through substitution of the conventional raw materials in cement composition plays a vital role in increasing the affordability of building construction. In this way the non-renewable resources are saved leading to reduced environmental degradation. Portland cement production is responsible for emitting an estimated amount of 5% of the global CO_2 emission which is why even a small percentage of reduction in the cement consumption significantly reduces the greenhouse effect [1]. Pozzolans, as defined by ASTM C125 [2], are siliceous materials which obtain binding properties when they are added to Portland cement in finely divided form. Adding mineral in optimum quantity can work as filler material to reduce the voids in concrete mixtures and improve the mechanical strength of mortar.

Widely known industrial wastes used as alternative raw materials in binders are ceramic wastes, steel slag and sludge ash [3–6]. Such an industrial waste is also the iron ore tailings (IOT) which is produced from the extraction of iron ore. With the ever increasing industries worldwide, there are over 300 million tons of IOT released per year as the solid waste generated during the processing of iron and steel. Luo et al. [7] investigated the likelihood of utilizing iron ore tailing as raw material for producing Portland cement clinker. The results showed that using iron ore in producing clinker can improve the reactivity and burn ability of cement clinker. This has led to a considerable perturbation in environmental stability as the waste are dumped in on the landfills and with a recycling rate of merely 10% [8, 9]. With a view to minimize the problem of waste disposal and secondary pollution Chen et al. [9] tried to prepare an eco-friendly construction brick using hematite tailing from western Hubei province of China. The produced bricks were conformed well to the Chinese standard. Utilization of IOTs in building materials offer cost effective solution of the resource recovery and waste management problems [10, 11]. Researches in the past were made on the utilization of IOT as additives in clinker [12], high strength construction materials [13]. Substitution of aggregates in concrete with ferrous mill tailing was investigated by Cai et al. [14]. The result showed that concrete workability and strength can be increased by replacing fine or coarse aggregates with ferrous mill tailing. The chemical and minerals present in iron ore has made it applicable as raw material to prepare environment friendly composite ceramics [15]. Various iron ore derived products such as hematite (Fe_2O_3) and magnetite (Fe_3O_4) can be used to make different types of high strength concrete that can be used in special purposes [16, 17]. Abo-El-Enein et al. [16] revealed that high performance heavy density concrete made from ilmenite and air-cooled slag was suitable for gamma-ray shielding purpose. Adding 10% silica fume with cement and using ilmenite as coarse aggregate can give better physical and mechanical properties of concrete. Similar study was conducted by Ouda [17] to obtain heavy density high performance concrete using magnetite, goethite, barite and serpentine as coarse and fine aggregates. The concrete mixture with magnetite as fine aggregate was found to be efficient and suitable to protect against gamma-ray. Another product is the limonite ($2Fe_2O_3 \cdot 3H_2O$), a hydrous iron ore formed after weathering of hematite and magnetite, also used as aggregates in heavy weight concrete to shield nuclear radiation [18]. Past studies indicate the suitability of limonite as aggregates in concrete [19–21]. In radiation shielding limonite mixed concrete perform well but concrete compressive and flexural strength decreases with an increase in water absorption capacity [20]. Iron ore tailing can be used as partial replacement of cement in mortar with satisfactory compressive strength [22]. Huang et al. [23] used powder formed iron ore tailing as partial replacement of cement to develop greener engineered cementitious composites. The studies done on IOT signify its potential to be used as additives in cement blend to produce effective binders [22–24]. To the authors knowledge, no studies has yet been performed on the use of limonite as cement replacement in mortar or concrete.

This study investigates the pozzolanic characteristics of limonite by replacing Portland cement partially in the amounts of 5%, 10%, 15% and 20% respectively in mortar specimens. Previous researches on pozzolanic materials have been concluded that cement replacements of 10% to 20% with alternative binders provide good results which is why such replacement levels by limonite are undertaken by the authors in the current study [22, 25, 26]. In this paper, the physical and chemical properties are determined accordingly and the short and long term mechanical properties determined are also discussed in the subsequent sections. This utilization of waste limonite would reduce the burden on the waste management authorities as well as provide a sustainable solution to the costly methods of building constructions in the less developed nations.

2 Experimental Investigation

The experimental study constitutes the determination of physical properties of limonite, cement and sand in terms of chemical composition, normal consistency, initial and final setting time, fineness, specific gravity, workability and mechanical properties of the mortar mixtures like compressive strength and strength activity index.

2.1 Materials

The materials used for mortar specimens in this paper are Portland Composite Cement (PCC), limonite, natural fine aggregate (NFA) and water. PCC is used in this study as it is cheaper than Ordinary Portland Cement and it is more readily available in developing countries. The limonite used in the investigation as shown in Fig. 1 is collected from Congo. This limonite was dried in air for about three weeks, ground manually and sieved through 75 μm sieve at the laboratory. The chemical composition of limonite determined through X-Ray Fluorescence and the physical properties are shown in Table 1. The chemical analysis shows that limonite is primarily

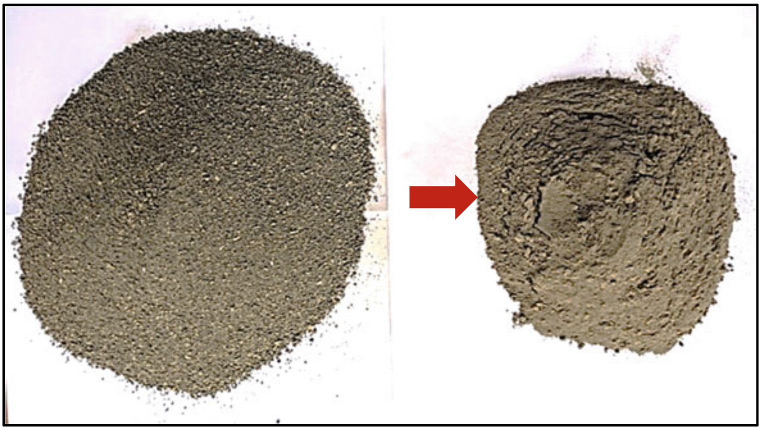


Fig. 1 Limonite sample collected and ground for the current study

Table 1 Chemical and physical properties of limonite and Portland Composite Cement

Component	Limonite (%)	PCC (%)
Chemical Composition		
SiO_2	22.58	19.8
Al_2O_3	12.59	3.98
Fe_2O_3	41.08	4.67
CaO	10.89	64.79
MgO	5.63	2.32
K_2O	0.31	0.4
Na_2O	1.13	0.35
P_2O_5		0.19
TiO_2	0.49	0.2
MnO		
Loss on ignition (LOI)	2.21	1.31
Physical Properties		
Specific Gravity	2.66	3.13
Fineness (m^2/kg)	219.18	320
Bulk Density (kg/m^3) (Oven-Dry Basis)	2120	–

composed of silica which is unlike Portland cement where major component is CaO. The amounts of silicon oxide (SiO_2), aluminum oxide ($A12O_3$) and ferric oxide (Fe_2O_3) compounds in limonite sample used sums upto 75% hence it can be denoted as a class N-type ash material according to ASTM C618 [27]. The alkali present in the limonite sample is less than 2.6% which is the maximum limit in Portland cement [28]. Limonite (fineness of 219 m^2/kg) is found to be much coarser than Portland

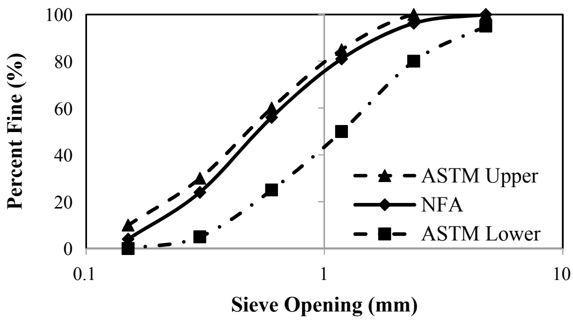


Fig. 2 Gradation curve of natural fine aggregate

Table 2 Physical properties of NFA

Variables	NFA
Apparent Specific Gravity	2.47
Bulk Specific Gravity (SSD)	2.41
Bulk Specific Gravity (OD)	2.36
Absorption Capacity (%)	1.8
Fineness Modulus	2.39
Loose Condition Unit Weight (kg/m^3)	1455.44
Compact Condition Unit Weight (kg/m^3)	1579.25
Loose Condition % of Voids	38.3
Compact Condition % of Voids	33.0

cement whose fineness is 320 m^2/kg, which may lead to an increase in setting time. The NFA used in this study is locally available well graded natural sand with a nominal maximum grain size of 4.75 mm. The gradation curve of NFA, presented in Fig. 2, shows a well-fitting curve within the ASTM range which is determined according to the ASTM C136 [29] standard. Besides, all the physical properties of NFA are also determined according to the ASTM standard presented in Table 2.

2.2 Mixture Proportions

The cement used in this investigation is replaced by 5, 10, 15 and 20% with limonite by weight basis and thus there are four different mixtures of limonite and one control mix (with no limonite). The water to cement and cement to sand ratios in the mixes are 0.48 and 1:2.75 respectively without using any admixtures. A target strength of 35 MPa at 28 days for the control mix was set for this study. The mix proportions of materials per cubic meter can be seen in Table 3. For aid in referencing within this paper, the samples are denoted as CC for control mix, L5, L10, L15 and L20 where the number refers to the percentage replacement and the preceding letter as limonite.

Table 3 Mix proportions of materials per cubic meter

Sample designation	w/c ratio	Water (kg)	Cement (kg)	Limonite (kg)	Fine aggregate (kg)
CC	0.48	234.1	482.5	–	1326.7
L5	0.48	234.1	458.3	24.1	1326.7
L10	0.48	234.1	434.2	48.2	1326.7
L15	0.48	234.1	410.1	72.4	1326.7
L20	0.48	234.1	386.0	96.5	1326.7

For example, L10 means that 10% cement is replaced by limonite and the rest 90% is the percentage of cement content.

2.3 Specimens

A total of 75 mortar cube specimens of 50 mm length are prepared according to ASTM C305 [30]. The specimens are initially cured for 24 h within the mold in a moist room and cured at a controlled temperature in a constant condition under fresh water for 28 days after demolding.

2.4 Testing Procedure

The normal consistency along with the initial and final setting times are determined following the ASTM C187 [31] and ASTM C191 [32] standards respectively. Workability of the mortar specimens were determined through flow table test as described in ASTM C1437 [33]. The compressive strength at different ages (3, 7, 28, 56 and 120 days) is determined according to ASTM C109 [34] standard. The test set up for compressive strength of mortar is shown in Fig. 3 where a constant loading rate of 1.80 KN/s is used. The mortar specimens are tested for their strength activity indices (SAI) following a slightly modified version of the ASTM C311 [35]. The control mixture is prepared with 500 g of ASTM Type 1 Portland cement, 1375 g of standard sand and 242 ml of water. For the purpose of comparison, all the percentage levels as used in the study (5, 10, 15 and 20%) for the SAI test and the resulting cube specimens are cured in saturated lime water until the day of testing.

Fig. 3 Test set up for compressive strength of mortar

3 Results and Discussion

3.1 Normal Consistency and Setting Times

It is necessary to determine consistency of binder materials because the amount of water used in mortar or concrete affects the setting time of the cement. So, correct proportion of water to binder materials is required to be known to achieve proper strength while using it in structure. This can be found out knowing standard consistency of binder paste. As depicted in Fig. 4, the normal consistency decreases with increase in replacement levels. This trend is similar to the behavior of mortar samples containing other cementitious binders such as volcanic ash and blast furnace slag [36]. The setting times indicated in the same figure shows that as the percentage levels increase so does the initial and final setting times. These two phenomenon observed in the test samples might be due to the lower specific gravity and fineness than those of Portland cement. The lower surface area of the limonite particles elongates the time required for hydration reaction thus leading to longer setting times. This can be regarded as advantageous as higher setting times allow lower heat of hydration consequently.

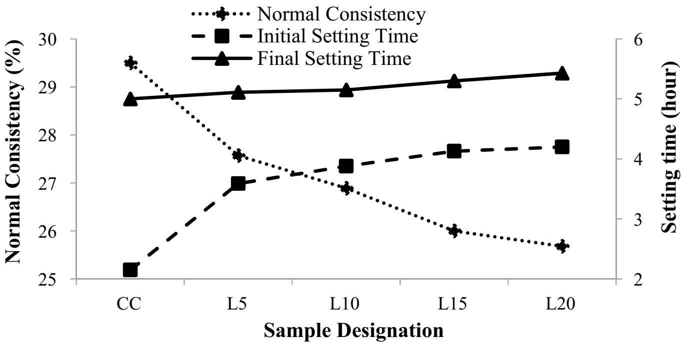


Fig. 4 Effect of limonite on normal consistency and setting time

3.2 Workability

One of the most important property of a mortar mixture is its workability. It must be free flowing without the segregation of water or other constituents in the mix. But too much water in mortar impairs its strength. So it is important to know the right amount water so that proper workability can be ensured. Workability of the mortar mixes were measured following the ASTM C1437 standard [33]. From the results as shown in Fig. 5, the control mix was superior to that of the mixes containing limonite. It is seen that the flow value decreased with increase in percentage replacement by limonite, with L20 having the lowest by 44.4% less than that obtained in sample CC. This suggests that limonite might have higher water absorption capacity than that of the Portland cement.

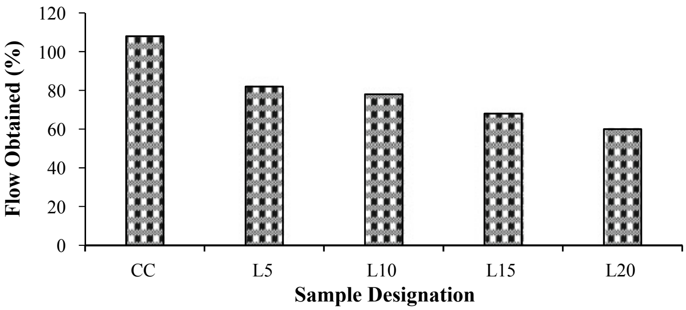


Fig. 5 Flow table test results

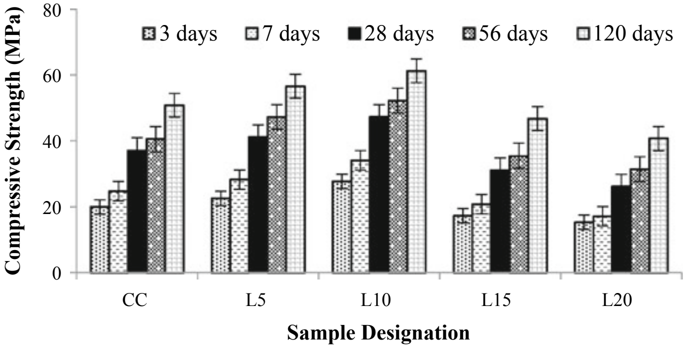


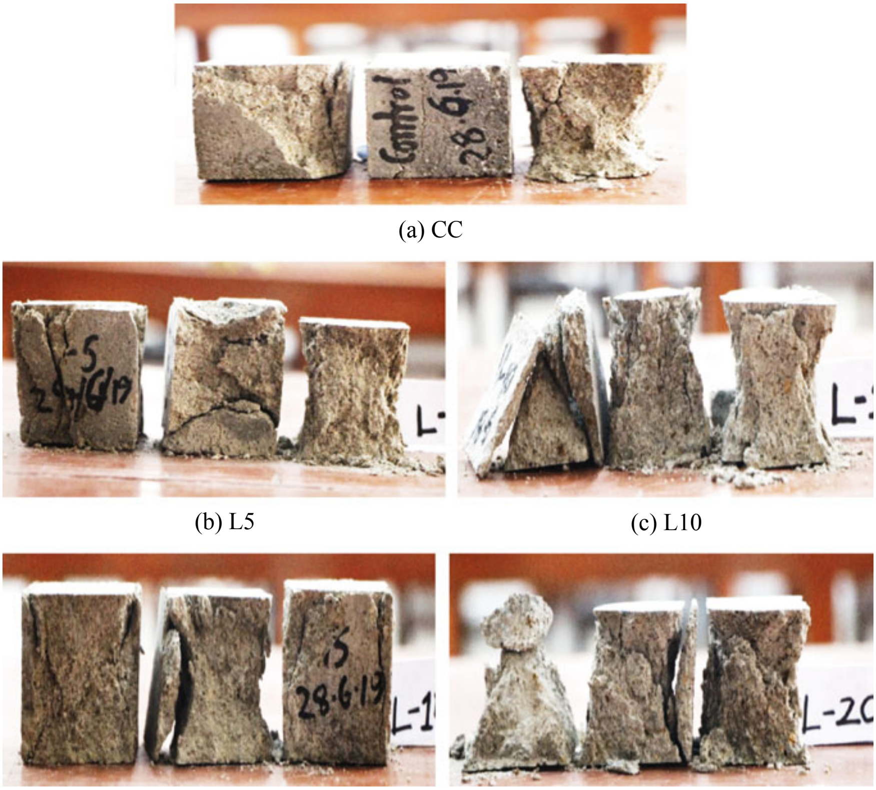
Fig. 6 Effect of limonite on compressive strength of the mortar samples

3.3 Compressive Strength

Compressive strength is one of the most important properties of concrete and mortar. The strength of the binder therefore has a significant effect on the performance characteristics of the mixture and ensures the overall quality of the finished product. The compressive strength at different batches is shown in Fig. 6, where the results are the average of three test specimens. It is observed that the compressive strength of all the samples in general increased with the age. The mortar specimens with 5% and 10% limonite replacement present greater compressive strength than the control samples. This increment might due to the fact that the silica present in the limonite in finely divided to react with the calcium to form calcium silicates in the presence of water, results a higher value of compressive strength. However, it is seen that for all ages the compressive strength starts to decrease for 15% and 20% limonite specimens. The compressive strength at 28 days increased by 10.5% and 27% when the amount of limonite increased from 5 to 10% respectively. On the other hand, the compressive strength at 28 days decreased by 16.2% and 29.5% when the percentage of limonite are 15% and 20%, respectively. This might be due to the fact that the cement content has been reduced thus lowering the binding capacity of the mortar. Similar trend is also observed for 3, 7, 56 and 120 days compressive strength. Thus in terms of short and long term durability the substitution by limonite more than 10% is not suggested so that the compressive strength is not compromised. The failure pattern of different mortar mixtures is shown in Fig. 7. The specimens containing limonite shows a brittle failure compared to control specimens.

3.4 Strength Activity Index (SAI)

The strength activity index is the ratio of the strength of the limonite–cement mortar to the strength of the reference mortar (purely cement based mortar) at each specific



(a) CC

(b) L5

(c) L10

(d) L15

(e) L20

Fig. 7 Mortar cube specimens after crushing

curing time under a special curing process. A separate mix is used for this test and the results are shown in Table 4 which reveals the average value of SAI of three test samples each. According to the specifications by ASTM C618 [27], a natural

Table 4 Effect on SAI due to limonite content in mortar cubes

Sample designation	Percentage replacement by limonite	Average Compressive strength (MPa)		SAI (%)	
		7 days	28 days	7 days	28 days
CC	0	25.40	39.20	100	100
L5	5	29.50	43.40	116	111
L10	10	33.20	48.30	131	123
L15	15	18.50	29.10	73	74
L20	20	15.20	25.30	60	65

pozzolanic material must have an SAI value of a minimum of 75%. The corresponding values at 7 and 28 days for the 5% and 10% replacement levels are more than the minimum requirement. However, the SAI value for 15% and 20% limonite is less than 75% for both 7 and 28 days. Therefore, it is safe to suggest that limonite can perform as a natural pozzolan when their content in the mortar mixes are up to 10% of the weight of Portland cement.

4 Conclusion

This study investigates the effect of partial replacement of cement by limonite on both fresh and hardened properties of mortar. The normal consistency, setting times and workability are taken into consideration at the fresh state whereas compressive strength and SAI are considered as the hardened state properties of the specimens under this investigation. Based on the experimental findings, the following conclusions can be drawn:

1. With the increasing percentage of limonite, the value of normal consistency decreases but the setting time increases thus providing scope for the possible advantages of lower heat of hydration during construction.
2. The compressive strength increases as the replacement of cement by limonite as an alternative binder is up to 10% of the weight of cement and then starts to decrease.
3. Up to 10% replacement of cement by limonite, the SAI value is greater than 75% which is within the specified limit. Thus up to 10% limonite can be used as a replacement of Portland cement without having any discrepancies. Therefore, this study suggests that a cement blend having 10% limonite content can be used for mortar mixes with a target strength of 35 MPa.

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