EFFECT OF WOLLASTONITE AND LIME SLUDGE ON STRENGTH, DURABILITY AND ASR OF TERNARY BLENDED CEMENT CONCRETE

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The development of unique and high volume cement replacement concrete with enhanced strength and durability properties is attempted in the present study. In this paper, fresh and hardened state properties of concrete containing wollastonite and limesludge are used as cement replacements to attain a unique composition and several experiments such as determination of compressive strength, flexural strength, split tensile strength, water absorption, sorptivity, ultrasonic pulse velocity, charge passed, alkali silica reaction, scanning electron microscope studies coupled with EDX analysis (Energy Dispersive X-Ray Analysis) were performed. The results show that the size of mineral additions has a pre-dominant role on the reduction of ASR expansion. Among all the ternary blended mixes, the mix containing wollastonite at 15% with 5% LS showed increased strength and durability at all ages. This paper also emphasized the measurement of electrical resistivity behaviour of the series of wollastonite-limesludge mixes thereby showing enhanced bulk resistance of the concrete mixes

Keywords: *wollastonite, lime sludge, durability, mechanical strength, microstructure*

1. Introduction

The high carbon foot print of the cement production increases the usage of development of alternative cement materials to reduce the cement consumption. Ordinary Portland Cement (OPC) can be blended with various supplementary cementitious materials and industrial by-products to enhance the strength behaviour for use in special applications. The blended cement concretes are inexpensive and exhibit better mechanical and strength properties. Wollastonite as a cement replacement material has been focused by several researchers to reduce cement consumption and production [1]. Besides, the strength and hydration behaviour of cement has also shown positive inclination due to wollastonite substitution [2]. The worldwide production of wollastonite is abundant [3] and hence commonly is used in ceramics, paints, plastics and other commercial applications [4]. In addition, the synthetic production of wollastonite using calcium and silicate sources has extended the boundary of usage of wollastonite [5]. The concrete mixes were made by replacing Portland cement with wollastonite at diverse replacement levels ranging from 0–25 percent at various w/b ratios of 0.45, 0.50, and 0.55. The use of wollastonite instead of 10–15 percent cement improved the strength and durability of concrete. The results of SEM and MIP showed that replacing cement with wollastonite reduced porosity and densified the concrete microstructure by up to 15% [6].Concrete and cement applications have recently attempted the utilization of with phosphoric acid [7] and carbonation treatment [8]. Wollastonite in concrete managed to improve early point compressive strength and endorsed pore discontinuity, according to Soliman and Nehdi 2014 [9], way that results in less drying shrinkage of extremely high performance concrete. Ransinchung et al. 2008 [10] studied the microstructure of pavement quality concrete incorporating wollastonite and silica fume. When wollastonite or wollastonite–silica fume were employed instead of cement, the voids and microcracks that were visible in the control concrete with only cement as a binding ingredient were filled with C–S–H gel and CH crystals. Kalla et al. 2013 [11] found that concrete containing a wollastonite–fly ash combination improved in strength, impermeability, resistance to chloride transfer, carbonation, shrinkage, and corrosion.

Wollastonite is needle like calcium silicate minerals that occur naturally due to interaction between silica and limestone at high temperature. Wollastonite as an ingredient in OPC systems were attempted in a number of studies and the significant variation in the strength results were reported [12]. Sand replacement by wollastonite showed improved mechanical strength of the mortar at 20% replacement ratio, beyond which a detrimental effect in the strength was observed [13]. A similar study by Kalla et al., 2015 [6] showed that the strength properties were optimum when 10-15% of cement was replaced by wollastonite with minimal chloride penetration and reduced permeability. The wollastonite micro fibres have a profound effect on the flexural strength of the concrete with improved ductile behaviour and dense microstructure [2]. A study by Soliman and Nehdi 2014 [9] reported reduced shrinkage behaviour of the ultra high performance concrete with wollastonite addition. The needle like structure of wollastonite has been explored and has been reported as the main reason for improving the toughness of the mortar and

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overall behaviour of the high alumina cement [14]. The filler effect of wollastonite also created an acceleration effect on the cement hydration through nucleation and shearing process. The study on the particle size effect of wollastonite suggested the utilization of finer sized wollastonite particles as cement replacement due to their filler effect and dilution effect whereas large sized wollastonite particles showed an inert behaviour in the mixture [15]. Ever growing need of the infrastructure development exponentially increases the cement production raising the need for incorporation of alternative cementitious materials [16]. Construction sector is now thriving to match the demand and supply of construction material by developing solution through waste recycling and reuse into construction industry [17]. Limesludge is one such waste material that is being generated in millions of tonnes from the paper industry and is being disposed off in the landfill without any proper disposal methods [18]. The chemical composition of limesludge and their physical behaviour makes it suitable for use in concrete applications. Limesludge as cement replacement can change the facets of construction by limiting enormous amount of cement production [19]. Limesludge utilization can also address the serious concerns of cement industry such as resource and energy conservation [20].

The high amounts of silica and magnesium contents present in limesludge can make them function similar to the cement properties by enhancing their setting properties [21]. The fresh behaviour of the concrete gets modified significantly due to the addition of limesludge. A significant increase in the viscosity, cohesion and yield stress of the concrete with reduction in the fluidity was observed [22]. Some studies recommended the usage of limesludge upto 30% for use in concrete with a maximum reduction of porosity upto 6% [23]. The porosity reduction and fluidity reduction were mainly attributed to the increased cohesion of the limesludge and the cement particles when mixed with water. The modulus of elasticity increment of the concrete as a function of limesludge increment of the concrete as a function of limesludge increment ratio was presented by Solanki and Pitroda 2013 [24]. Most of the studies reported limesludge as a fluidity retarder due to their smaller size which reduces workability and elasticity behaviour of concrete. Combined effect of limesludge with other pozzolanic and waste materials has also been reported by several authors [25]. Limesludge has been used in combination with flyash [26, 27], metakaolin [18], silica fume [21]. Lime sludge has been mostly recommended for use as alternative for cement whereas few studies tried to utilize limesludge as fine aggregate replacement [21]. Limesludge has been utilized in the past studies without any modification due to the economic constraints. Limestone has also been used mainly as filler and its efficiency with reference to the commercial fillers have been compared [23]. Reduction of particle size of limesludge using ball mill grinding has been done to enhance the filling effect of limesludge in cement concrete. The ball milled limesludge was used as fine aggregate replacement and showed both filing effect and pozzolanic effect in the concrete enhancing the strength behaviour [28].

2. Materials

Ordinary Portland Cement (OPC) of grade 53 which confirm to the technical specification of IS 12269-1987 is used as the binder. The properties of OPC are shown in Table 1. The limesludge was collected from the Elasai Enterprises in India. The particle size distribution for limesludge and wollastonite is shown in Figure 1 and their XRD results are presented in Figure 2a and 2b respectively. The calcite peaks were identified as major peaks with traces of kaolinite. The chemical oxide values of limesludge showed the SiO_2, Fe_2O_3 and Al_2O_3 that summed to attain the value of 2.64 which is satisfiable under IS 1727:1967 to be used as a pozzolanic material in cement. Wollastonite acquired from Wolkem India Limited and the original mean particle size of the wollastonite particles were measured as 9μm. The average particle size of wollastonite was reduced to around 6 μm using a ball mill. The XRD peaks showed wollastonite crystalline phases as its major peaks. The coarse aggregates used in concrete mainly composed of crushed quartzite aggregates with a nominal size of 12 mm and the fine aggregates were natural river sand with a fineness modulus of 1.32. The chemical admixture used is a high range water reducing agent Sika Viscocrete which is naphthalene based high range water reducing agent.

Table 1

Oxide composition of binder materials

Content	OPC	Wollastonite	Limesludge
(%)			
SiO_2	21.25	48.22	1.12
CaO	63.3	41.13	51.5
MgO	1.65	3.1	0.26
Al_2O_3	4.99	1.27	0.98
Fe_2O_3	4.08	1.3	0.54
SO_3	2.7	-	0.58
TiO_2	-	-	0.08
P O	-	-	2.72
MnO	-		0.1
K_2O	0.23	-	0.1
Na_2O	0.51	-	0.08
LOI	1.29	4.98	41.94

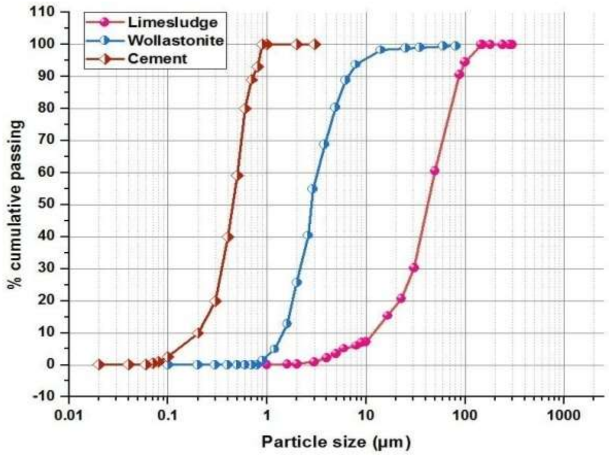

Fig. 1- Particle size distribution curve of binder materials

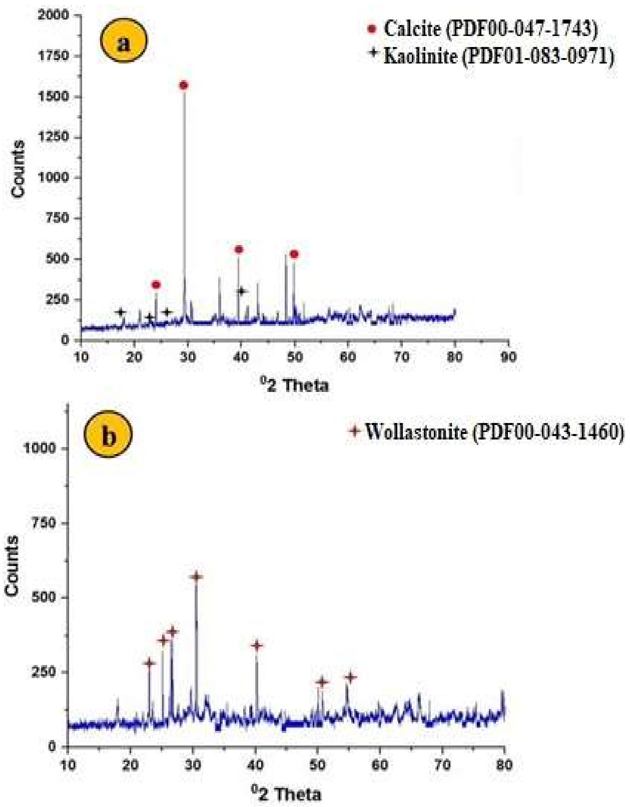

Fig.2- XRD of (a) Limesludge (b) Wollastonite

3. Mix Proportion

The ternary blended concrete mixes were prepared using wollastonite and limesludge as binder materials at various percentage replacements fine aggregate and coarse aggregate were kept at constant weights. The ternary replacement ratio was varied over a range of 0% to 15% and 0% to 20% at 5% intervals of limesludge and wollastonite respectively (by the weight of cement). Nine different ternary blended concrete mixes were produced with different combinations of wollastonite and limesludge replacement ratio as shown in Table 2. The water binder ratio was kept as 0.38 for all the mixes. The superplasticizer dosage was varied depending on the slump value fulfilling the requirement of medium slump values.

Table 2

Mix Proportion details of ternary blended concrete in kg/m^3

Mix Id	Cement	LS	W	FA	CA	SP
REF	324	-	-	785	1093	8.2
5/10	275.4	16.2	32.4	785	1093	8.8
5/15	259.2	16.2	48.6	785	1093	8.9
5/20	243	16.2	64.8	785	1093	9.3
10/10	259.2	32.4	32.4	785	1093	9.4
10/15	243	32.4	48.6	785	1093	9.8
10/20	226.8	32.4	64.8	785	1093	10.1
15/10	243	48.6	32.4	785	1093	10.3
15/15	226.8	48.6	48.6	785	1093	10.4
15/20	210.6	48.6	64.8	785	1093	10.8

Abbreviations: LS-Lime sludge; W-Wollastonite; FA-Fine aggregate; CA-Coarse aggregate; SP-Super-plasticizer

3.1. Mixing Method

After adopting a number of trial mixes, by varying the water/superplasticizer ratio, a series of mixes were finalized to attain medium slump values. The mixing procedure was carefully adopted to prevent segregation and accumulation of ingredients of the concrete. The concrete mixes were prepared in a cylindrical pan mixer, and the ingredients were added.

4. Experimental Methods

The cubical concrete specimens of size 100mmx100mm were tested using compression testing machine of 2000 kN capacity to determine the compressive strength of concrete in accordance with procedure as stated in IS 516:2002. The flexural and split tensile strength of the concrete is obtained by testing the concrete prisms (100mmx100mmx500mm) and cylinders (150mmx300mm) as per IS 516:2002. The machine and specimen axes are aligned for the test. The specimen of flexural strength is loaded without force or progressively at 0.7 N/mm^2 or 4000 N/min. By applying compressive force to the cylinder's axially opposed lines, the cylindrical specimens were loaded for split tensile strength. As suggested by ASTM C642, the water absorption test was carried over 100 mm x 50 mm cylindrical concrete specimens at various ages and the values were recorded at different intervals such as 30 min, 60 min and 72 hours. In order to assess the rate of absorption, the 28 days sorptivity test was performed as per ASTM C1585 on 100 mm x 50 mm cylindrical specimens. The chloride ion penetration resistance of concrete was evaluated using RCPT performed as per ASTM C1202 over 100 mm x 50 mm cylindrical concrete specimens. The concrete samples are sandwiched between two reservoirs, one containing a 0.3M NaOH solution and the other a 3.5% NaCl solution, with their respective terminals attached to a direct current supply. Every sample at a different stage of curing is given a 60 V DC current through steel electrodes. The current that passed through the samples was recorded at 30-minute intervals throughout the roughly 6-hour procedure. The electric current resisting power of the concrete was measured using a four point Wenner Probe tester on cylindrical specimens of size 100 mm x 200 mm. The voltage potential is measured at the inner points, while the current is delivered at the equally spaced outer points. The scanning electron microscopy experiments were carried out in order to better understand the morphological changes in concrete and the SEM pictures were taken using a SEM, ZEISS EVO device in secondary electron mode with a 40 kV accelerating voltage. Through line analysis methodology, the EDAX analysis was used to determine the chemical elements present in the concrete mixes.

5. Results and Discussions

5.1. Workability measurements

The fresh state behavior of the concrete containing limesludge and wollastonite as measured through slump flow test is shown in Figure 3. It can be seen that the workability mainly depended on the proportion of wollastonite and decreased significantly with increasing wollastonite contents in the concrete mix. The slump value of control concrete showed 72 mm indicating the medium slump value. The higher specific surface area of the wollastonite particles (and finer) decreased the slump value of the concrete. The results were higher to the previous studies conducted on wollastonite with similar proportions due to the effect of limesludge addition. Studies conducted by Soliman & Nehdi, 2012 [9] provided results that expressed the effect of aspect ratio of the microfibers of wollastonite in workability. According to their conclusion, aspect ratio of 10 decreased the workability of concrete. Herein, the results showed similar trends and the amount of water required to attain the slump of 72mm increased with increasing wollastonite contents. The size effect of the wollastonite also significantly minimizes the slump value and the wollastonite particle addition has been found to influence workability leading to two opposite conclusions as follows: i) the reduction in workability due to the smaller size and higher specific area that demands high water content for wetting the surface. ii) Smaller size particles with less aspect ratio increases workability by providing lubricating effect as the cement grains can ef fectively flow in its fresh state. Apart from this, the interlocking effects of the wollastonite particles also highly influence the workability by restricting the flow and increasing the slump value of the concrete.

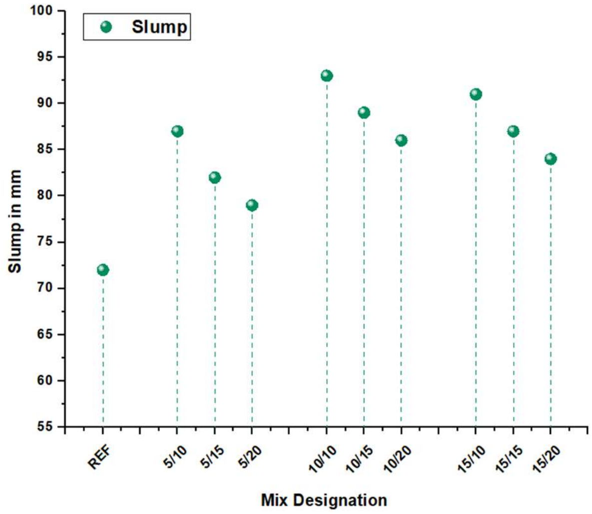

Fig. 3- Workability of wollastonite-lime sludge blended concrete

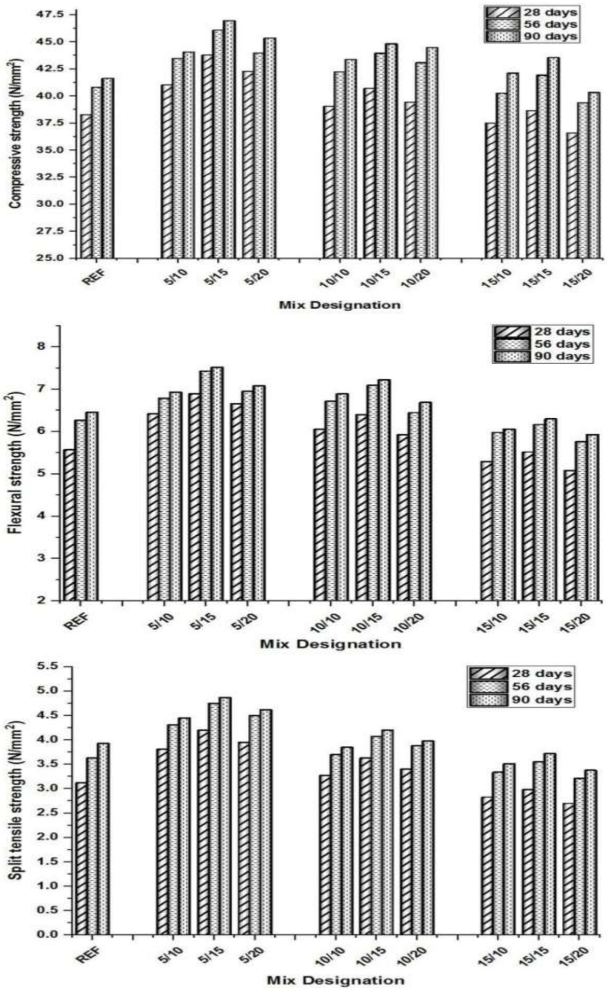

Fig. 4 - Mechanical strength of wollastonite-lime sludge blended concrete

5.2. Mechanical strength

The compressive strength, flexural strength and split tensile strength of the concrete tested at various curing ages are presented as a function of wollastonite/limesludge proportion as shown in Figure 4. The results clearly show that the wollastonite content significantly influence the increment of the mechanical strength and negative influence on the mechanical strength was observed in the concrete with increasing limesludge contents. A significant reduction in the mechanical strength results were observed when the limesludge content exceeded 10% and wollastonite additions proved to be much more beneficial in enhancing the mechanical strength of the concrete at various ages. Beyond 28 days, the strength values increased with the limesludge contents indicating the consumption of CH indicating the secondary formation of CSH gels. Only 5.1% reduction in the compressive strength were observed when cement was replaced by 15% limesludge and 20% wollastonite which is much lower than the studies by Mona Abdel Wahab et. al 2017 [13] that presented a strength reduction of 12% at 28 days when 20% wollastonite used as cement replacement. Comparing the results of the concrete containing wollastonite and limesludge with plain concrete the later age strength of concrete was much improved indicating the bridging effect of the wollastonite with the CSH gels formed by the early age. The flexural strength of the concrete at different ages is presented in Figure 4. The flexural strength of the concrete increased linearly with increase in the curing ages irrespective of the limesludge and wollastonite additions. The relationship between flexural strength and compressive strength as observed using linear regression lines is presented in equation (1):

$$y = 0.266x - 4.011 \qquad (1)$$

The ratio of the 28 days flexural strength of the concrete to the compressive strength expressed as a strength ratio is also presented in Figure 5. The increment in the flexural strength for all the mixes in comparison to control concrete clearly showed enhanced value for the mix L5W15 and declined gradually when the limesludge content increased in the concrete mix. The increased flexural strength was obtained as 6.15 MPa, 6.69 MPa and 6.78 MPa at 28, 56 and 90 days respectively for the mix containing 10% wollastonite with 5% limesludge. The wollastonite particles exhibited flat and elongated fibrous structure that enhanced the bonding of the equi-dimensional lime sludge powder with the cement particles. Similar results were reported by the Yucel & Ozcan, 2019 [29] where wollastonite were used as cement replacement that exhibited higher interlocking with the cement particles leading to higher tolerance and enhanced stability at higher flexural loads.

The split tensile strength development in the concrete at various ages is presented in Figure 4. The Figure 4 showed an increment in the split tensile strength that ranged from 2.31 to 4.48 MPa for the mixes containing varying proportions of wollastonite and limesludge. The increment in the split tensile strength was also uniform and steady as

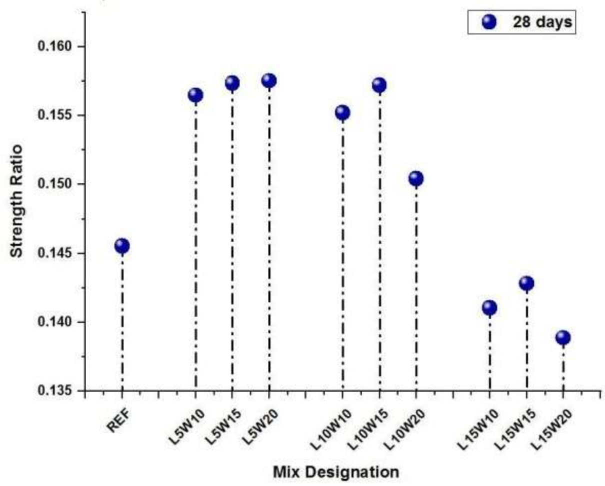

Fig. 5 - Strength ratio of flexural strength to the compressive strength of the concrete at 28 days

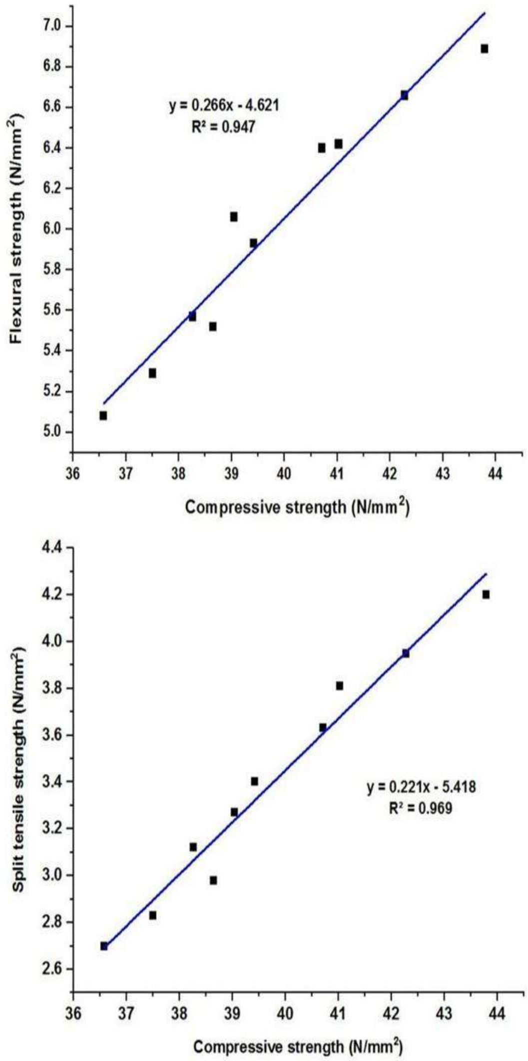

Fig. 6 - Correlation between mechanical strength of wollastonite-lime sludge blended concrete

the curing time increased. Some mixes showed a reduction in the split tensile strength and the reduction was more prominent in the increased limesludge contents and the strength reduction was about 5.1 and 15.4% for the mixes L15W15 and

L15W20 respectively at 28 days. The split tensile strength variation was almost similar to the compressive strength results with minor deviations. This may be due to the increased contribution of wollastonite in bridging the gaps formed during the splitting load increments. The relationship between the compressive and split tensile strength as obtained through linear regression analysis is presented in Figure 6. The early age split tensile strength increment was much higher in the concrete with less limesludge proportion indicating the enhanced dilution effect of cement that minimized the pores in the concrete. The relationship between compressive and split tensile strength observed using linear regression lines is presented in equation (2):

$$y = 0.221x - 4.686 \qquad (2)$$

On comparing the obtained results, the 5% limesludge content in combination with various percentage of wollastonite exhibited better strength than the 10% and 15% limesludge series. In all the limesludge combinations, the strength characteristics were greater when 15% wollastonite content is substituted. The extra fineness developed due to the filling effect of wollastonite is the main reason for achieving better strength behavior.

5.3. Water absorption

Figure 7 shows the water absorption of the concrete containing wollastonite and limesludge at various proportions in comparison to plain concrete. The water absorption values decreased with increase in wollastonite content upto 15% beyond which a slight increase in the water absorption was observed. As the limesludge proportion increased beyond 10%, the water absorption values increased significantly and the values indicate the porosity increment with the limesludge content increment. The water absorption values indicate the pore volume in the concrete and thus show that wollastonite addition decreased the pores in the concrete. The filling effect of limesludge can be seen effectively in the lower proportions of additions upto 10% beyond which the deterioration effect of cement is disrupted leading to reduced CSH gel formation and increased porosity. Moreover, the effect of increased additions of wollastonite and limesludge can be seen in the increased water absorption values indicating the separation of the ingredients of concrete due to the less adhesion coupled with less CSH gel formations. The optimum level of limesludge substitution is found to be 5% in all the combinations of wollastonite content. The higher substitution of wollastonite results in greater water absorption values and this is due to the more fineness created.

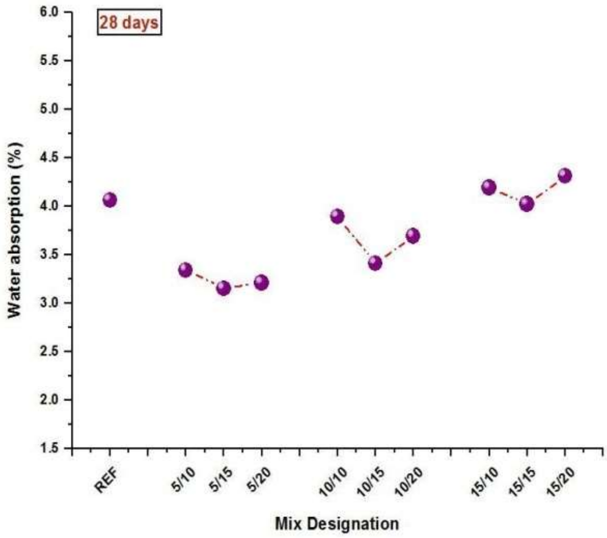

Fig. 7 - Water absorption of wollastonite-lime sludge blended concrete

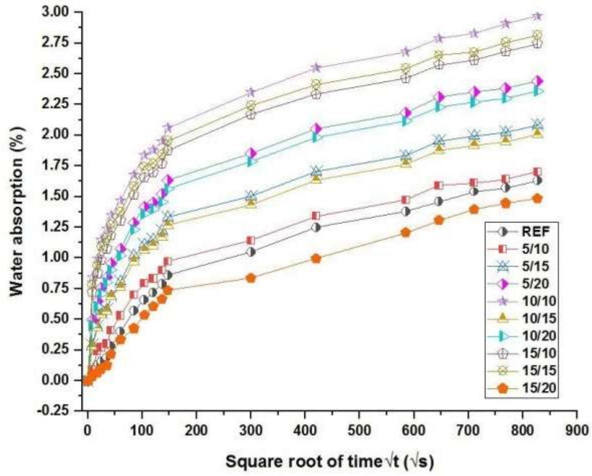

Fig. 8 - Capillary absorption of wollastonite-lime sludge blended concrete

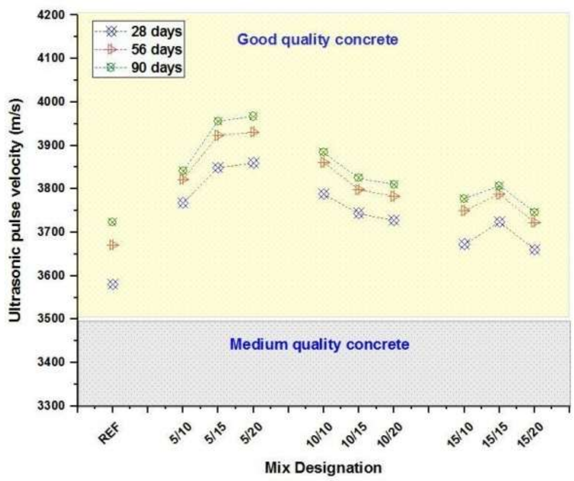

Fig. 9 - UPV values of wollastonite-lime sludge blended concrete

5.4. Sorptivity

The rate of water absorption by the surface of concrete can effectively be visualized through the capillary water absorption test. The water absorption of the concrete through the capillary pores as a function of time is presented in Figure 8. The curves obtained through capillary absorption clearly presented two different stages confirming to the model predicted by in previous studies. The initial curve showed lesser values for the concretes containing lime sludge and wollastonite upto 10% beyond which a sudden increase in the initial water absorption curve of 15 and 30 minutes is also presented in Figure 8. The sorptivity values however reduced significantly for the concrete containing limesludge at 10% and wollastonite at 15% matching the results obtained through the mechanical strength results. The higher sorptivity values with increasing limesludge content may be due to the bonding of the cement grains and higher limesludge content. The decrement in the capillary water absorption is due to the synergistic effect of high specific surface area of limesludge and bridging effect of the wollastonite. The stronger pozzolanic reaction that exhibited between the cement particles also enhanced the interfacial transition zone between the aggregates and cement phase. The reaction between the calcium hydroxide present in the cement phase and silicates present in wollastonite can also form CSH gels as evident from the studies presented by Khan & Ashraf, 2019 [15]. Refinement in the pore structure reduced the pores in the concrete and limesludge acted as fillers interrupting the flow of water through the capillary channels

5.5. Ultrasound Pulse Velocity

As observed in Figure 9, the use of limesludge and wollastonite in the concrete reduced the ultrasonic velocity and the time taken was significantly reduced in the concretes indicating refined pore structure in the concrete. The UPV values clearly show the impermeable nature of the concrete with fewer amounts of voids and pores with limesludge and wollastonite substitution. The UPV values agree well with the mechanical strength results. The UPV values of the concrete ranged from 3580 m/s to 3967 m/s indicating ‘good’ quality concrete as per IS 13311 Part I 1992 classification. Although, the UPV values slightly reduced with increasing limesludge contents in the concrete, the wollastonite addition exhibited higher contribution to the porosity reduction and micro crack reduction. The UPV values increased at all curing ages and were pronounced in the early ages of curing showing the cement reaction with hydration product formation. The wollastonite substitution also reduced the penetration of chlorides into the concrete due to their micro crystalline nature that can relieve the concentration of stresses in the cement matrix leading to well developed hydration product formation. The UPV values obtained are in agreement with the strength results in achieving good quality concrete.

5.6. Electrical Resistivity

The lower porosity and dense microstructure of the concrete aided by the wollastonite and limesludge additions have increased the electrical resistivity of concrete as shown in Figure 10. The electrical resistivity indicates the rate of entry of deleterious ions and correlates the size and amount of pores present in concrete. The wollastonite addition in concrete reduced the permeability of concrete by reducing the continuity of pores in concrete and restricting the micro crack development. The high electrical resistivity of the concrete is mainly due to their denser nature and filling ability of limesludge that enhanced the integrity of the concrete. The concrete containing wollastonite exhibited better electrical resistivity than the plain concrete. The better compaction of the concrete aided by finer limesludge and wollastonite substitution explains the reason for the increased resistance to electrical resistivity.

5.7. Rapid Chloride Penetration Test

The use of wollastonite and limesludge in concrete significantly improved the chloride penetration of the concrete and the values decreased significantly for the concrete containing 10% limesludge and 10% wollastonite by nearly half the chloride penetration value of the concrete at 28 days as shown in Figure 11. This is mainly due to the smaller sized particles of wollastonite and limesludge that reduced the permeability of the concrete by providing a compact structure. As shown in Figure 11, the chloride penetration values as measured through charge passed remains almost similar to the control concrete in early ages and became much reduced at later ages [30, 31]. Alternatively, it can be stated that permeability of concrete was much reduced due to the filling effect of limesludge and the concretes containing limesludge upto 10% with 15% wollastonite can be graded as ‘low’ permeability. The increased resistance towards chloride penetration with increasing ages indicates the development of increased amounts of CSH that filled the concrete pores. Increased limesludge content with wollastonite showed higher charge passed values that showed the weaker interfacial transition zone due to the loss in the binding capacity of the mortar phase of the concrete.

5.8. Alkali Silica Reaction

The experimental values of accelerated mortar bar test results at various ages are shown in Figure 12. The 7 days and 14 days expansion results were much higher in the concrete containing wollastonite and limesludge which reduced linearly as the age progressed. The reduction in expansion indicates the less alkalinity in the pore solution. As expected, the expansion of the mortar prism was much higher in the concretes exposed to NaOH solutions. However the values were lower than the values obtained previously in the similar studies [32, 33] indicating the impermeability of the produced concretes. The expansion of the mortar prisms mainly depend on the quantity of alkalis present in pore solution and the amount of alkalis that can penetrate through the pores in the concrete. Similar to the results obtained through porosity studies, the expansion values slightly increased at increasing limesludge values indicating the interrelationship between porosity and the level of expansion.

5.9. Microstructural study

To corroborate the results obtained through mechanical and durability testing, microstructural investigation on the concrete was done and the crystalline hydration phases present in the concrete containing wollastonite and limesludge was observed. The SEM images as shown in Figure 13 clearly showed compactness of the concrete samples with increasing wollastonite content in the concrete. The strengthening effect of the wollastonite microfibers can be seen through the dense and compact structure of the concrete with minimal number of pores. The enhanced dense phase of the concrete significantly inhibited the penetration of deleterious substances thereby enhancing the durability. The increasing wollastonite content beyond certain level provided a fibrous reinforcing effect and the sheathing effect of the CSH gels can be seen effectively due to the formation of secondary hydration products.

6. Conclusions

The detailed analysis of the experimental results has provided an insight into behavior of concrete incorporating limesludge and wollastonite. The following points can be drawn as conclusions:

1) Incorporation of limesludge and wollastonite as cement replacement has decreased the concrete workability due to their finer nature and higher surface area.

2) The compressive strength of the concrete was increased by as much as 16.6% and 14.6% at 28 and 90 days respectively for the mix 5/15 due to the ultra filling nature and reinforcing effect of the micro fibrils of wollastonite. About 27.3% increase in flexural strength at 28 days for the mix containing 15% wollastonite with 5% limesludge was reported indicating the higher bonding and bridging characteristics of wollastonite with the cement particles.

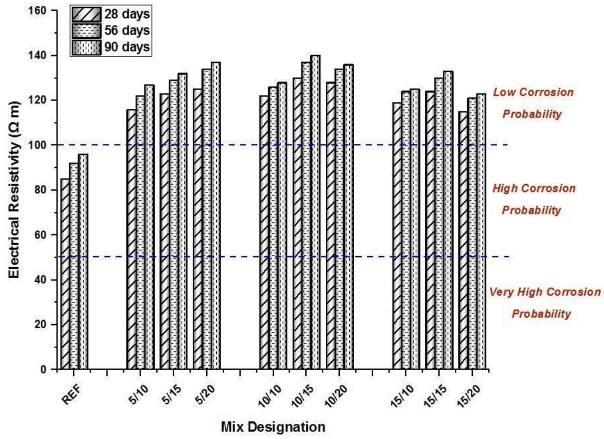

Fig. 10 - Electrical Resistivity of wollastonite-lime sludge blended concrete

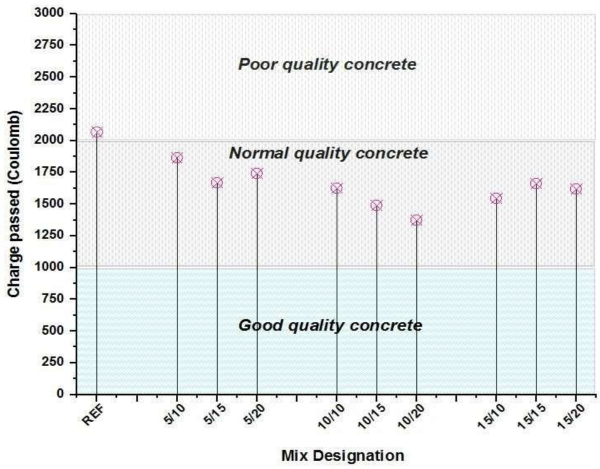

Fig. 11- RCPT of wollastonite-lime sludge blended concrete

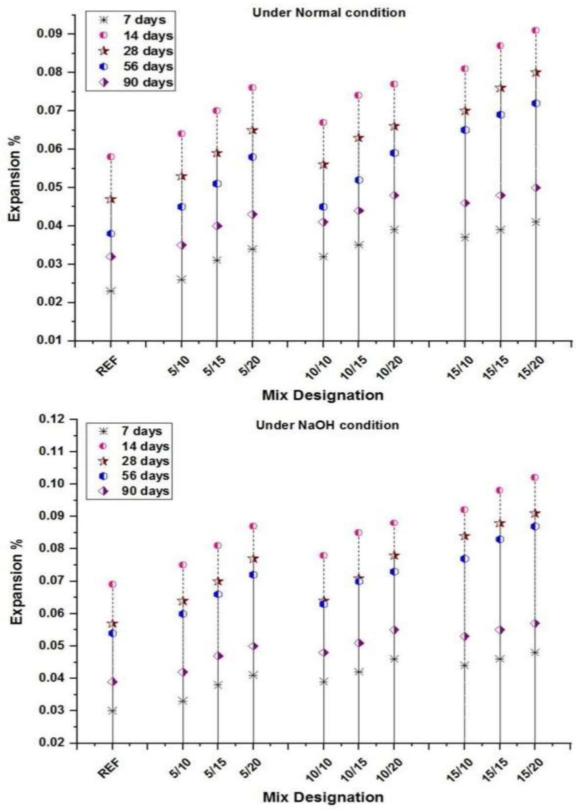

Fig. 12 - Percentage expansion of wollastonite-lime sludge blended concrete under both normal and NaOH conditioned

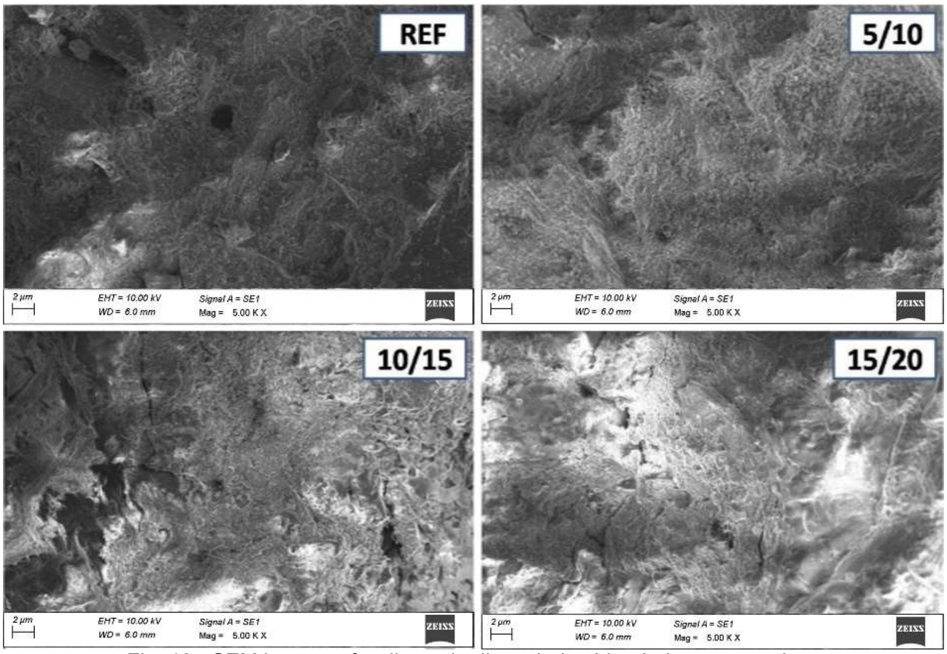

Fig. 13 - SEM images of wollastonite-lime sludge blended concrete mixes

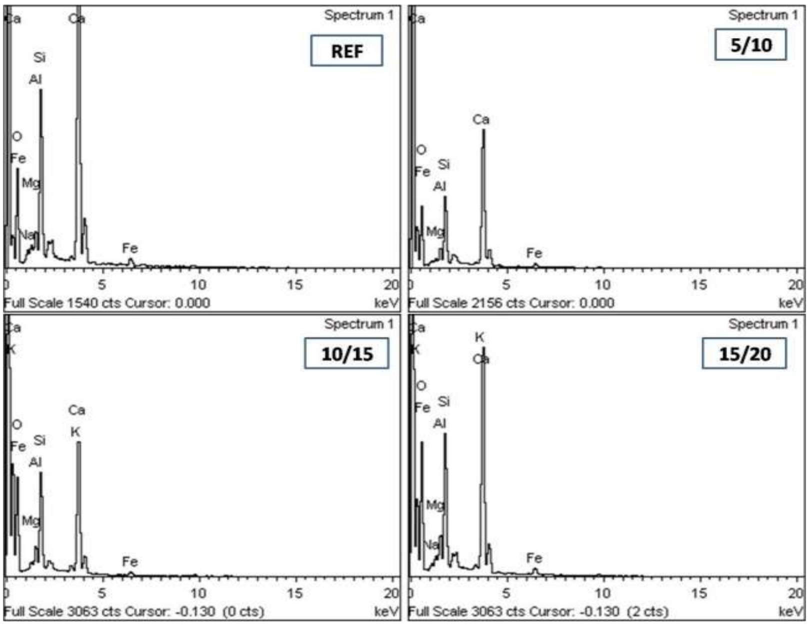

Fig. 14- EDAX spectrum of wollastonite-lime sludge blended concrete mixes

3) By substituting wollastonite and limesludge, the permeability and porosity of the concrete was reduced significantly through reduction in water absorption and sorptivity values.

4) The UPV values and chloride penetration resistance of the concrete were also higher than that of control concrete and as the proportion of wollastonite and limesludge increased beyond 15% a slight reduction in UPV values were observed and the values were very close to the control concrete.

5) The maximum variation can be seen in the concrete expansion at normal condition and NaOH curing indicating the contribution of wollastonite in the reduction of alkalinity of the concrete pore solution. The expansion of the concrete prisms was much reduced indicating the non-reactive characteristics of the wollastonite and limesludge with increased secondary CSH gel formations.

6) The micro images at the paste/mortar level of the concrete showed increased CSH gel formations that contributed to the better compactness of the concrete mix.

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