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# Durability performance potential and strength of blended Portland limestone cement concrete

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ABSTRACT

This paper describes a study on the durability potential and strength of composite Portland-limestone cement (PLC) concrete mixtures blended with ground granulated blast furnace slag (GGBS) and/or fly ash (FA). Their performance was compared against ordinary Portland cement, plain PLC and Portland-slag cement concrete mixtures. Using the South African Durability Index approach, results indicate reductions in the penetrability of the composite PLC blends compared to the other mixtures. The durability indicators are chloride conductivity, gas (oxygen) permeability and water sorptivity. Compressive strength of the composite PLC mixtures containing both GGBS and FA showed competitive performance with the comparative mixtures, but FA blended PLC mixtures had diminished compressive strength values. The paper also presents considerations on the practical implications of using blended PLC concrete mixtures.


## 1. Introduction

Globally there has been considerable evolutionary research into improving the technical performance of concrete, particularly into ways of optimising the constitution of its binder phase. Such research has further evolved into optimising the environmental and economic benefits achievable in cement production and concrete manufacture. As such, blending the most common binder type, ordinary Portland cement (OPC), with supplementary cementitious materials (SCMs), that are themselves by-products of other industrial processes, is now recommended practice. Common SCMs used are ground granulated blast furnace slag (GGBS), fly ash (FA) and condensed silica fume. Depending on their particular chemical composition, physical characteristics and level of replacement for OPC, SCMs typically densify the concrete microstructure decreasing its penetrability to agents of deterioration. This among other factors increases the durability potential of concrete.

Another material now prominent in today's construction binders is ground limestone, typically introduced to Portland cement (PC) clinker during milling. Limestone particles are much smaller than PC clinker particles; which improves the hydraulic potential of the clinker component by reducing the grinding energy costs and increasing the dispersion of OPC grains in the final product [1]. The South African standard for common cements, SANS 50197-1 [2], allows for four classes of Portland-limestone cement (PLC): CEM II A-L and CEM II A-LL containing 6–20% limestone by mass, and CEM II B-L and CEM II B-LL containing 21–35% limestone by mass. Review of the literature on the technical performance of PLC concretes reveals that hardened PLC concrete mixtures containing between 10% and 20% ground limestone have near-similar to better technical performance properties compared to plain OPC mixtures. Ground limestone in the binder phase of a mixture improves the particle packing efficiency due to its finer particle size, referred to as the filler effect. This results in reducing water demand, improving workability, reducing bleeding and, in hardened concrete, blocking capillary pores thereby reducing penetrability [3–11].

Several researchers [12–18] have also reported that fine limestone particles participate in the hydration reaction by accelerating it. This has the result of improving early age strength gain, which however at later ages often results in diminished strength. This is known as the dilution effect. Limestone particles also act as nucleation sites for calcium silicate hydrate formation and participate in the hydration reaction through the formation of calcium monocarboaluminate compounds indirectly leading to increased ettringite formation [19,20].

Further studies exploring the effect of blending PLC with an SCM show that positive and complementary performance characteristics can be achieved. Menéndez et al. [18], Carrasco et al. [21] and Villagrán-Zaccardi et al. [22] report positive synergy in blended PLC and GGBS binder mixtures. Limestone improves the early age strength and GGBS the later age strength. This effectively counters the dilution effect on the strength performance of PLC mixtures. Ghrici et al. [23], working with natural pozzolana and ground limestone filler, found similar results in addition to better

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chloride penetration resistance and reduced sorption of the pozzolana–limestone blended mixtures at specific replacement levels and water-to-binder (w/b) ratios in comparison to plain OPC mixtures. Positive synergy with regard to early age strength gain and 28 d compressive strength have also been reported by Van Dam et al. [24], De Weerdt et al. [25], and Bentz et al. [26] on ternary blended mixtures of OPC, FA and limestone. In the studies performance was compared to OPC and FA binary blended mixtures. FA blended mixtures are known to sometimes have retarded hydration, delayed setting and low early age strengths. The inclusion of limestone appears to counteract these effects. Van Dam et al. [24] further reports competitive durability performance of such ternary blended mixtures compared to plain PLC mixtures. Such synergies that work towards improving the durability potential and technical performance of PLC mixtures need to be identified and optimised for better application.

To this end, an experimental study was carried out at the University of Cape Town with the aim of identifying the potential positive influences on the durability and strength performance aspects of blending PLC binder mixtures with GGBS and/or FA. The performance of two composite PLC binder mixtures containing Slagmore[1] and FA was tested against three commonly used binders i.e. an OPC mixture (CEM I, 42.5N), a PLC mixture (CEM II A-L, 32.5R) and a blended Portland-slag cement mixture (CEM II A-S, 42.5N). The three were used as reference binder mixtures to gauge performance. The South African Durability Index approach described by Alexander [27] was used to characterise the transport properties of the concrete mixtures. Performance was inferred for carbonating and chloride environments. This paper presents 28 d and 90 d compressive strength and durability characteristics of the range of mixtures studied at the two w/b ratios of 0.40 and 0.55.

## 2. Objectives and research significance

The reported study compares the potential durability and compressive strength performance of composite PLC blended concrete mixtures with other commonly used concrete mixtures. Performance was determined by conducting penetrability and strength tests. The aim was to establish the technical performance viability of further blending PLC binders with GGBS and/or FA. It was anticipated that positive synergy would come into play in such composite binder mixtures, with each binder component, depending on its characteristics, improving performance whilst mitigating the shortcomings of the other binder components. It was hypothesised that limestone on its part would improve the early age strength gain of concrete, in addition to reducing the penetrability of concrete by pore-filling. GGBS would improve the chemical resistance of concrete in addition to increasing the late age strength. FA would also improve chemical resistance and reduce permeability. Such positive synergistic effects offer new options for innovative construction materials from which further economical and environmental gains can be accrued.

## 3. The Durability Index approach used to evaluate potential durability performance

A range of test methods exist in different parts of the world for determining and controlling the potential durability performance indicators of concrete. Key parameters investigated by the test methods are gas permeability, water sorptivity and ion migration by a measure of electrical resistance or conductance [28–31]. Results of the tests, often referred to as durability indicators, quantify the penetrability of a concrete matrix by measuring gaseous, liquid or ionic transport through the penetrable zones of concrete thereby revealing the structure, connectivity and solution chemistry of pores within the concrete matrix [32]. In South Africa, three test methods are used to characterise the transport properties of concrete, collectively referred to as Durability Index (DI) tests, which give rise to the so called DI approach. The DI approach is a performance-based durability design philosophy that is sensitive to concrete making material constituents and proportions. The tests can reliably detect changes in w/b ratio and binder composition of concrete mixtures in addition to being responsive to the influences of construction practices such as curing and compaction [33–35].

DI test specimens are 70 mm diameter, 30 mm thick concrete discs cored from concrete cubes or actual structures [36]. The specimens are preconditioned in a 50 °C drying oven for 7 d before testing to ensure uniform low moisture contents within concrete pores. As reported by Pigeon et al. [37], drying concrete at 50 °C causes less damage than at 100 °C. In addition, tests conducted at the University of Cape Town's Laboratories have shown that mass loss in specimens of the given dimensions is negligible after 7 d oven drying. Two of the DI tests also require the test specimens to be saturated with the test solution, so drying helps to prevent dilution of the saturating solution by pore water [38]. Four specimens are used per test, and the average of the test results determined. The determinations are index values which are indicators of the potential durability of concrete, via measures of its susceptibility to penetration. The test parameters comprise a chloride conductivity index (CCI), an oxygen permeability index (OPI), and a water sorptivity index (WSI).

The CCI test is an accelerated test used to measure the electrical conductance of a concrete's pore system which can in turn be related to resistance to chloride ion penetration. Prior to testing, dry specimens are vacuum saturated in a 5 M NaCl solution for 4 h and left to soak for a further 18 h to achieve steady state conditions [38]. The test apparatus is a two-cell conduction rig in which the specimens are exposed to the same 5 M NaCl solution on either side. A 10 V potential difference is applied across the specimen to accelerate movement of chloride ions, and the current passed is measured. Typical CCI values range from 0.5 mS/cm for highly chloride resistant GGBS blended binder mixtures, to 2.5 mS/cm for penetrable plain OPC mixtures [27,33–35,39].

The OPI test is a gas permeability test that provides an indication of the degree of pore connectivity in a concrete matrix. Specimens are placed in a falling head permeameter and a 100 kPa pressure gradient applied across the test sample. The pressure decay in the pressure cell is subsequently monitored over time and used to determine the D'Arcy coefficient of permeability, $k$ (m/s). There exists a linear relationship between the logarithm of the ratio of pressure drop and time. For practical usefulness, the negative value of $k$ is log transformed to give an OPI value. Typical OPI values range over three orders of magnitude i.e. 8–11, with higher values indicating reduced permeability [27,33–35,39].

The WSI test characterises the rate of movement of a penetrating wetting front through the exposure face of a concrete specimen under capillary suction. The rate of penetration is dependent on pore geometry which is among others a factor of the curing regime used. Test specimens are sealed on the circular sides, to ensure unidirectional absorption, and placed facing downwards in a calcium hydroxide solution. At regular time intervals, the specimens are removed and weighed to determine the change in mass. Measurements are stopped before saturation is reached. The specimens are thereafter vacuum-saturated in the same calcium hydroxide solution to determine porosity [36]. A linear relationship exists between the mass gain of the specimen and the square root of time with the gradient of the line used in an expression to obtain the sorptivity value expressed in $mm/h^{0.5}$. WSI values typically range

[1] Slagmore is a brand name SCM produced by Natal Portland Cement, South Africa. It is a blend of 92% GGBS and 8% FA.

from to 6-7 mm/h$^{0.5}$ for well cured mixtures to 15–20 mm/h$^{0.5}$ for poorly cured mixtures [27,33–35,39].

## 4. Experimental details

### 4.1. Materials

A total of 10 concrete mixtures were prepared, using five different binder combinations at two w/b ratios; 0.40 and 0.55. The w/b ratio of 0.40 was chosen to investigate the performance of low penetrability concrete while the w/b ratio of 0.55 was chosen following the specification of the South African concrete design code of practice [40]. Table 1 presents the binders used and their chemical analyses. The first reference binder was a CEM I 42.5N OPC from the Cape Town region. The second was a CEM II A-L 32.5R PLC from the Durban region containing 20% by mass limestone filler interground with Portland cement clinker during milling. The third reference binder was a CEM II A-S 42.5N Portland-slag cement containing 15% Slagmore also from the Durban region. All the binder types complied with SANS 50197-1 [2]. The SCMs were Slagmore and fly ash (FA) which complied with SANS 1491-1 and -2 respectively [41,42]. Slagmore was blended with the CEM II A-L at a 40% replacement level and with the CEM II A-S at 40% and 30% replacement levels for the 0.40 and 0.55 w/b ratios, respectively. The lower Slagmore content was used in the 0.55 w/b ratio mixture to minimise bleeding and improve workability retention. FA was substituted for the CEM II A-L binder mixture at a 30% replacement level. The aggregates used were 19 mm tillite for the coarse fraction and a blend of river sand with a 10% proportion of pit sand for the fine fraction, all conforming to SANS 1083 [43]. The pit sand was included to improve the fines content of the mixtures as the river sand was a slightly "bunch graded" coarse sand, while the pit sand was extremely fine.

### 4.2. Mixture proportions

Mixture designs were based on typical mixtures supplied by ready mix manufacturers for use in the aggressive marine environments of Durban, South Africa, using the Cement and Concrete Institute volumetric mix design method [44]. Table 2 gives the concrete mixture proportions. A fixed water content of 165 l/m$^3$ was used with the two w/b ratios to give total binder contents of 412 kg/m$^3$ and 300 kg/m$^3$ for the 0.40 w/b and the 0.55 w/b ratios, respectively. The coarse aggregate content for all the mixtures was fixed at 1070 kg/m$^3$. A polycarboxylate superplasticiser was used to achieve workability in the slump range of 65–95 mm. Details of the amount of superplasticiser added and the slump achieved are also given in Table 2. The dosage is given as a percentage of the total binder content by mass.

**Table 1**
Chemical composition of binders (%).

| Oxides | CEM I | CEM II A-S | CEM II A-L | Slagmore | FA |
|---|---|---|---|---|---|
| CaO | 65.29 | 59.08 | 65.75 | 35.03 | 4.40 |
| $SiO_2$ | 21.59 | 24.40 | 20.21 | 35.79 | 52.80 |
| $Al_2O_3$ | 4.54 | 6.00 | 4.26 | 13.67 | 34.10 |
| $Fe_2O_3$ | 3.47 | 2.59 | 2.89 | 0.71 | 3.60 |
| $SO_3$ | 2.21 | 2.50 | 2.89 | N/A | 0.10 |
| MgO | 1.24 | 4.55 | 2.86 | 9.76 | 1.10 |
| $K_2O$ | 0.68 | 0.59 | 0.57 | 0.30 | 0.50 |

### 4.3. Concrete production, preparation and testing of samples

Concrete was produced in 50 kg batch masses using a horizontal forced action pan mixer of 0.05 m$^3$ capacity. The mixer was charged with coarse aggregate, fine aggregate and binder respectively and the constituents dry mixed for approximately 30 s. Water mixed with superplasticiser was slowly added until the mixture was visually consistent. The total mixing time was about 3 min. After testing for slump, 100 mm cube moulds were filled, compacted on a vibrating table, and covered with polythene sheets for 24 h at room temperature before demoulding. The cubes were thereafter placed in a water bath maintained at 23 °C ± 2 °C for continuous water curing until their respective test ages of 28 d and 91 d. The durability tests were executed according to the Durability Index Testing Procedure Manual [36] while the strength tests were performed in compliance with SANS 5863 [45].

## 5. Experimental results and discussion

### 5.1. Chloride conductivity

Fig. 1 illustrates chloride conductivity index (CCI) results for 0.40 w/b and 0.55 w/b ratio concrete specimens tested at 28 d and 91 d. As expected, the results indicate significant reductions in CCI with reducing w/b ratio and increasing curing duration for all mixture types.

Comparing the results for the CEM II A-L and CEM I mixtures, it is noted that the former binder type mixtures have higher chloride conductivity than the latter mixtures. At 28 d, the differences are less than 10% at both w/b ratios. At the 91 d test age, however, the differences in values increases to more than 70% at the 0.40 w/b ratio and 35% at the 0.55 w/b ratio. The higher CCI values of the CEM II A-L mixtures are considered to be a result of the dilution effect of limestone. The reduced comparative performance in age and continued curing is further attributed to the lack of continued hydration in PLC mixtures as reported by Klemm and Adams [46].

**Table 2**
Concrete mixture proportions (kg/m$^3$).

| ID | w/b ratio | Binder content (kg/m$^3$) | | | | | | Fine aggregate content (kg/m$^3$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CEM I | CEM II A-S | CEM II A-L | Slagmore | FA | Total Binder | Umgeni River sand | Durban pit sand | Total | SP* | Slump (mm) |
| (1) | 0.40 | 412 | – | – | – | – | 412 | 708 | 78 | 786 | 0.6 | 90 |
| | 0.55 | 300 | – | – | – | – | 300 | 796 | 87 | 883 | 0.6 | 75 |
| (2) | 0.40 | – | 237 | – | 175 | – | 412 | 708 | 78 | 786 | 0.6 | 65 |
| | 0.55 | – | 210 | – | 90 | – | 300 | 796 | 87 | 883 | 0.6 | 70 |
| (3) | 0.40 | – | – | 412 | – | – | 412 | 708 | 78 | 786 | 0.6 | 70 |
| | 0.55 | – | – | 300 | – | – | 300 | 796 | 87 | 883 | 0.6 | 85 |
| (4) | 0.40 | – | – | 247 | 165 | – | 412 | 708 | 78 | 786 | 0.5 | 80 |
| | 0.55 | – | – | 180 | 120 | – | 300 | 796 | 87 | 883 | 0.5 | 90 |
| (5) | 0.40 | – | – | 288 | – | 124 | 412 | 708 | 78 | 786 | 0.4 | 75 |
| | 0.55 | – | – | 210 | – | 90 | 300 | 796 | 87 | 883 | 0.4 | 95 |

(1) CEM I binder mixture; (2) CEM II A-S: Slagmore mixture; (3) CEM II A-L mixture; (4) CEM II A-L: Slagmore mixture; (5) CEM II A-L: FA mixture.
Water content – 165 l/m$^3$.
Tillite coarse aggregate content – 1070 kg/m$^3$.
SP* Superplasticiser dosage (% mass of binder).

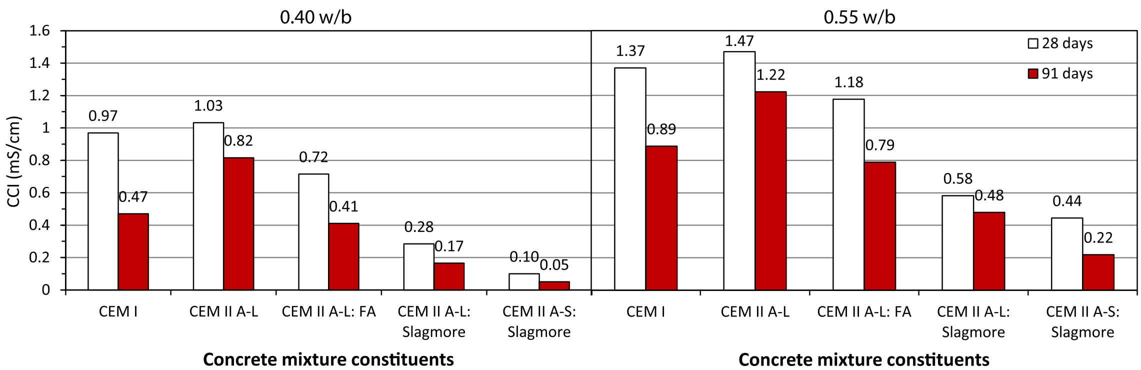


**Fig. 1.** CCI values for 0.40 and 0.55 w/b ratio concrete mixtures at 28 d and 91 d.

The inclusion of Slagmore in the CEM II A-L mixture is seen to lower 28 d chloride conductivity values by more than 70% at the 0.40 w/b ratio and 60% at the 0.55 w/b ratio. A similar percentage difference is also seen at the 91 d test age. The addition of FA to the CEM II A-L mixtures also causes considerable reductions in CCI values, by up to 30% for the 0.40 w/b ratio mixtures and 19% for the 0.55 w/b ratio mixtures. Further reductions in chloride conductivity are seen in the 91 d test results, attesting to continued pore structure improvement through ongoing pozzolanic and hydration reactions. This would potentially result in reduced chloride ion penetration.

Comparing the Slagmore and FA blended CEM II A-L mixtures, the former have lower CCI values and therefore potentially better resistance to chloride ion penetration. Comparing CCI values of the CEM II A-L: Slagmore mixture with the CEM II A-S: Slagmore mixture, the former shows higher chloride conductivity which is considered to be a consequence of the dilution effect of limestone. The improved performance of the blended binder PLC mixtures in comparison to the plain PLC mixtures is attributed to the finer particle size nature of the SCMs in the binder phase of a concrete mixture resulting in improved pore filling, thereby reducing the penetrable zones of the concrete microstructure. It is important to note that at later ages, the higher alumina content of the blended binder mixtures would result in improved chloride binding [47–49].

### 5.2. Oxygen permeability

Figs. 2 and 3 present coefficient of permeability ($k$) and oxygen permeability index (OPI) values respectively for 0.40 and 0.55 w/b ratio concretes tested at 28 d and 91 d. The results show consistent reductions in gas permeability of all the concrete mixtures with reducing w/b ratio and increasing sample age. The only exception is the 91 d result for the 0.55 w/b ratio CEM II A-S: Slagmore

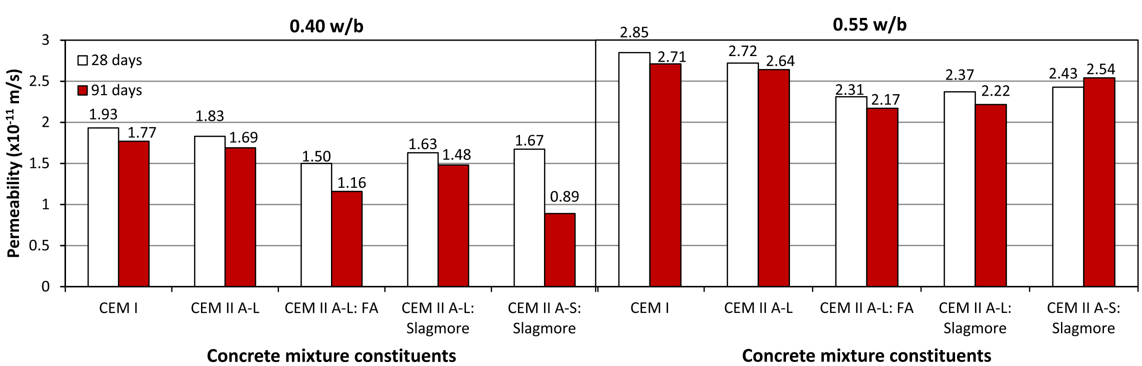


**Fig. 2.** Permeability values for 0.40 and 0.55 w/b ratio concrete mixtures at 28 d and 91 d.

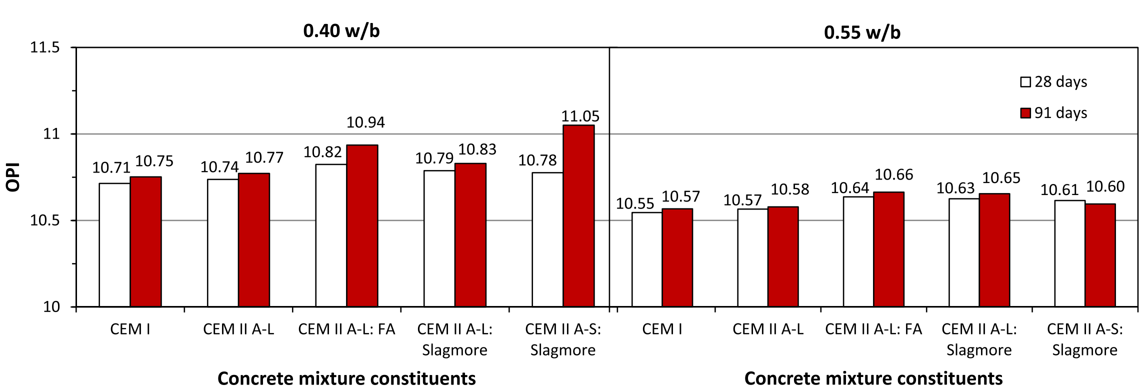


**Fig. 3.** OPI values for 0.40 and 0.55 w/b ratio concrete mixtures at 28 d and 91 d.

mixture which shows an increase in permeability. This result is thought to be anomalous and is subsequently excluded from further discussion.

It is noted that the permeability values of the CEM II A-L mixtures are lower than those for the CEM I mixtures. The differences are however small and average at 5% at both w/b ratios and sample ages. This indicates that ground limestone has no potential detrimental effect on gas permeability despite its dilution effect on the clinker content of CEM I OPC.

The addition of FA to the CEM II A-L binder is seen to significantly decrease the permeability of the PLC binder mixtures. At 28 d and at the 0.40 w/b ratio, the FA blended PLC mixture exhibits an 18% reduction in permeability values. At the 0.55 w/b ratio, the reduction is up to 15%. At the 91 d test age, permeability values for the CEM II A-L: FA blended mixtures decrease by more than 30% and 17% at the two w/b ratios of 0.40 and 0.55, respectively. The improved impermeability with age is attributed to a combination of continued hydration and pozzolanic reactions of the FA component of the binder phase during the extended curing period.

28 d and 91 d values of the CEM II A-L: Slagmore mixture also showed improved impermeability performance in comparison to the CEM II A-L mixture by more than 10% at both w/b ratios. Looking at the permeability results of CEM II A-S: Slagmore mixtures, they are seen to have near-similar values to the CEM II A-L: Slagmore mixtures at 28 d, with the difference between the test results averaging at less than 3%. This suggests that the two would have comparable performance in in-service concrete.

The improved permeability characteristics of the composite blended PLC binder mixtures portend denser concrete microstructures making them more impermeable than the plain OPC and PLC mixtures. This is in addition to the physical effect of the much smaller and finer particles of both the SCMs used and limestone filling the interstitial and capillary pores of the binder phases of such mixtures [50–52].

It can be argued from an engineering perspective that the transformed OPI test results reveal relatively minor differences between the various binders. The values vary over a small range of magnitude with all results indicating a dense concrete microstructure possessing good durability potential [32,39].

### 5.3. Water sorptivity

Note: Water sorptivity test specimens are the same used for the oxygen permeability test.

Fig. 4 illustrates water sorptivity index (WSI) values for 0.40 and 0.55 w/b ratio concrete specimens tested at 28 d and 91 d. Reductions in WSI values are seen with reducing w/b ratio and increasing sample age.

Comparing the 28 d WSI values for the CEM I and CEM II A-L mixtures, the beneficial filler effect of limestone blocking the capillary pores is seen once again, with the values for the latter mixtures being lower at both w/b ratios by more than 15%. This indicates that their capillary pores are smaller and/or the degree of interconnectedness is less. The addition of Slagmore to the CEM II A-L mixture further lowers 28 d sorptivity values by 27% and 18% at the 0.40 and 0.55 w/b ratios, respectively. A marked decrease in sorptivity values is also seen at the 91-d testing age.

The inclusion of FA in the CEM II A-L mixtures however, shows a different picture. At the 28 d test age, the sorptivity values of the CEM II A-L: FA mixtures are slightly higher. It is only at 91 d that a reduction in values of the FA blended mixtures is seen. This could be a result of the slower and extended hydration periods that FA blended binder mixtures require for the pore structure to sufficiently densify, such that capillary suction is reduced [53].

An overall look at the sorptivity results, however, reveals that the differences, though significant, have limited practical impact, since any value less than about 9 mm/h$^{0.5}$ indicates a good quality concrete that has been cured adequately [39]. It should also be noted that the WSI test is not directly related to a reinforced concrete deterioration mechanism. At this stage, the test is used to assess the construction quality as regards the extent of curing and to provide information on the degree of compaction and aggregate particle distribution and orientation [39].

### 5.4. Compressive strength

Fig. 5 illustrates compressive strength for 0.40 and 0.55 w/b ratio concrete specimens tested at 28 d and 91 d. The results indicate the dominant effect of w/b ratio on compressive strength and its increment with continued curing.

Comparing the test results of the CEM I and CEM II A-L mixtures, a marginal decrease in values for the latter mixture is seen; a result of the dilution effect of limestone. Nevertheless, its contribution to hydration and therefore development of the concrete pore structure should not be overlooked as the difference in the test results is less than 3% at 28 d. The addition of Slagmore to the CEM II A-L mixtures however brings out the beneficial effect of this SCM on compressive strength. An improvement in compressive strength values is seen at both w/b ratios and samples ages in the CEM II A-L: Slagmore mixtures compared to the plain CEM II A-L mixtures. Hooton et al. [54] reported a similar strength increase attributing it to an increase in the formation of carboaluminates owing to the higher aluminate content of slag. The FA blended CEM II A-L mixtures, however, do not exhibit a similar trend. A difference in values of more than 15% is seen at both w/b ratios and sample ages. The diminished values could be due to the dual effect of the slow

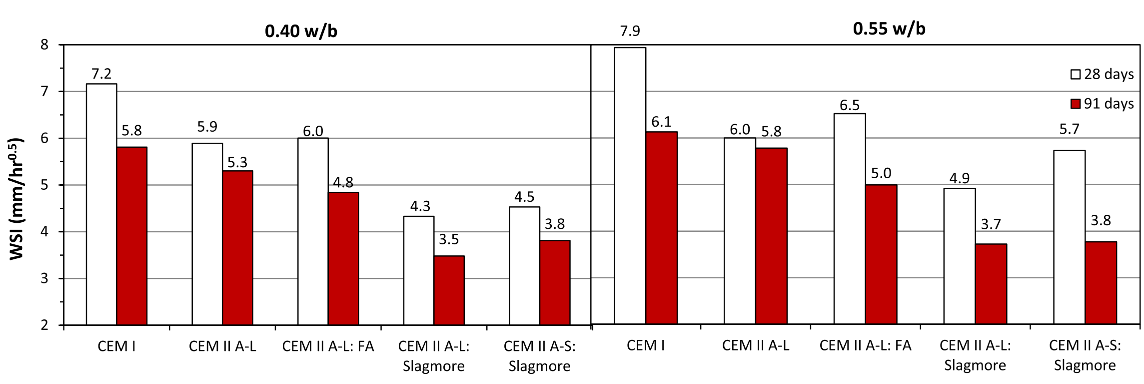


**Fig. 4.** WSI values for 0.40 & 0.55 w/b ratio concrete mixtures at 28 d and 91 d.

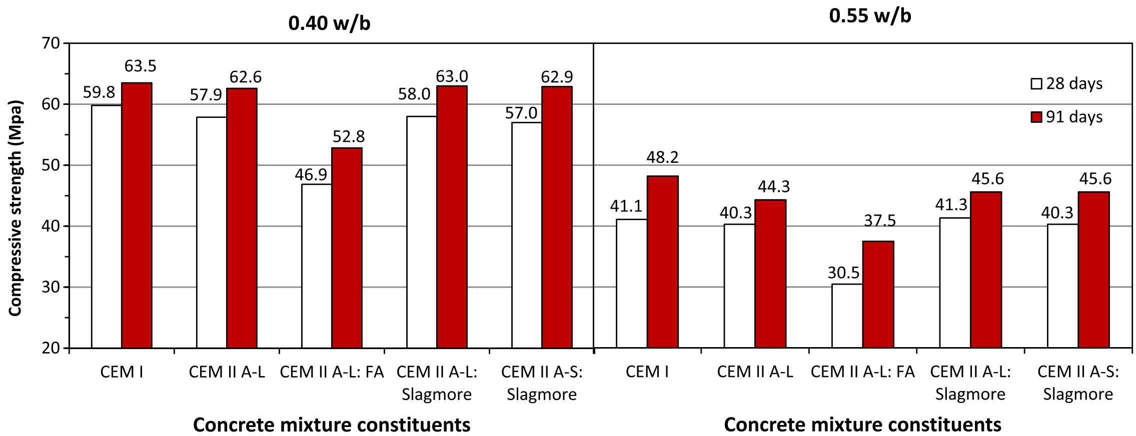


**Fig. 5.** Compressive strength for 0.40 and 0.55 w/b ratio concrete mixtures at 28 d and 91 d.

reacting pozzolanic nature of this FA and the dilution effect of limestone in the binder phase of these mixtures [55,56].

## 6. General discussion and practical implications

The study reported in this paper shows that improved concrete performance can be obtained by blending SCMs with a PLC binder. Performance was compared to three other concrete binder mixtures i.e. plain OPC, plain PLC and Portland-slag cement mixtures. The results provide valuable information to both concrete research and practice.

The inclusion of Slagmore in the CEM II A-L mixtures shows good durability potential, with the effects appearing to be synergistic. The CCI test has shown that such composite binder mixtures have low chloride conductivity values translating to better resistance to chloride ion penetration. Moreover, the higher magnesium oxide and alumina contents of Slagmore blended mixtures would increase the mixtures chloride binding potential [57,58]. The pore structure is also seen to be sufficiently developed, as evidenced by the low gas permeability and water sorptivity and high compressive strength values in comparison to the CEM II A-S: Slagmore binder mixtures. This is attributed to the finer particle size nature of both the Slagmore and ground limestone in the binder phase of the mixture which has the added effect of improving the hydration kinetics and pore filling.

The CEM II A-L: FA mixtures also show good durability performance characteristics. The chloride conductivity of these mixtures is significantly lower than those measured for the CEM I and CEM II A-L mixtures, though not as low as its Slagmore blended counterpart. The mixture type however shows good gas permeability resistance. It is thought that the finer particle size of the FA and limestone work together in filling the space within the interstitial pores of concrete, thus reducing its permeability. This effect would retard gaseous diffusion. Further work by direct carbonation testing is however required to determine if the reduced gas permeability indicated would result in enhanced carbonation resistance. Water sorptivity test values also follow a similar trend though the beneficial effect becomes apparent at 91 d, which is attributed to the extended curing period. Compressive strength values are however suppressed in the FA blended PLC mixtures This is thought to be a result of FA concretes requiring an extended hydration (curing) period for continued pore structure development. In choosing this mixture type, the concrete designer should carefully consider the environment of application and what trade-off is acceptable i.e. reduced strength or durability potential.

## 7. Conclusions

This study has explored the viability of incorporating SCMs in CEM II A-L mixtures from which the following specific conclusions are drawn:

1. Improved durability performance can be achieved by blending CEM II A-L mixtures with SCMs such as Slagmore and FA. Reduced chloride conductivity is seen in addition to reduced gas permeability and water sorptivity. The importance of adequate curing should however not be overlooked in the development of these concrete performance properties.
2. The inclusion of limestone in the binder phase of a concrete mixture has no effect on the gas permeability of concrete.
3. Blending Slagmore with CEM II A-L does not adversely affect the strength properties of a mixture, while blending with FA results in lower strength values.
4. Increased use of composite binder mixtures containing ground limestone and SCMs which are by-products of other industrial processes will lead to a reduction in cement energy production costs and the associated negative environmental effects of increased noxious emissions thus contributing to more sustainable construction.

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