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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.