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Transport Properties of Pozzolanic Concrete Based on the South African Durability Indexes

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Abstract **-** Engineers and designers often incorporate pozzolans in concrete to enhance specific properties, most notably, its resistance to ionic penetration that directly depends on the cover concrete's transport properties, which are a function of the microstructure. This paper describes the influence of pozzolans on concrete microstructure and durability-related transport properties measured according to the South African durability indexes. The resistance of pozzolanic concrete to oxygen permeation, water absorption and chloride diffusion was evaluated. The pozzolanic materials considered were fly ash, blast-furnace slag, silica fume and metakaolin. These materials were used as partial replacement for the Portland cement in binary mixes. At the ages tested, the metakaolin mix displayed excellent performance in strength development, microstructure enhancement and durability. The results also show that the mixture incorporating metakaolin exhibited the highest resistance to oxygen permeation, chloride conduction, and the lowest porosity, followed by the blast-furnace slag mix. The silica fume mix displayed the highest resistance to water absorption, while the fly ash mix exhibited the most moderate resistance to water absorption and chloride conduction.

Keywords**:** Pozzolans, South African Durability Indexes, Transport properties, Penetrability

1. Introduction

Most deteriorations of concrete are often due to the ingress of deleterious substances into the concrete substrate and the inability of the cover concrete to offer adequate resistance against the penetrating species. Therefore, the measure of concrete transport properties serves as indicators of durability since the durability of concrete directly depends on its penetrability [1].

In the effort to design durable concrete, various durability testing methods have been developed to assist engineers with performance-based design and service life prediction, and one such technique is the South African Durability Indexes, developed to promote performance-based thinking in concrete technology. The durability indexes evaluate the penetrability of the cover concrete and provide valuable information for durability assessments and service-life prediction.

This method yields three indexes that describe the main transport mechanisms associated with concrete deterioration [2] and are sensitive to material, mix proportions and curing conditions [3]. Each index is associated with a test which measures a specific transport parameter. Hence, the durability indexes consist of oxygen permeability index test, water sorptivity index and porosity test, and chloride conductivity index test. The oxygen permeability index test directly assesses the interconnectivity of the concrete's pore structure by evaluating the concrete's resistance to gaseous ingress. This test measures the pressure decay of oxygen passed through the test specimen in a falling head permeameter [2]. The water sorptivity index and porosity test also provides an indication of the pore structure of concrete and its ability to absorb moisture. This test evaluates the resistance of unsaturated concrete to water absorption under capillary suction as well as its porosity. The chloride conductivity index test is a rapid chloride conduction test that assesses concrete's resistance to chloride penetration [4].

Apart from reducing the carbon footprint of concrete, pozzolans are often incorporated in concrete to optimise performance in terms of strength, microstructure, and durability enhancements [5]. However, the degree of optimisation depends on the type of pozzolans and its inherent properties. Though appreciable studies have been done on the use of pozzolans in concrete, very few are concerned with the penetration resistance of pozzolanic concrete using the South African standard. Therefore, this paper presents the results of the durability performance of various concrete mixtures containing pozzolans, based on the South African Durability Indexes, and the trend of strength development.

2. Materials and Methods

2.1. Materials

The pozzolanic materials considered in this investigation were fly Ash (FA), ground granulated blast-furnace slag (GGBS), silica fume (SF) and metakaolin (MK). These materials were sourced from South Africa and used as partial replacement of the Portland cement by mass, adopting the optimum replacement levels available in the literature. The cement used was Rapid Hardening Portland Cement (RHPC), CEM-I, 52.5R. Table 1 presents the primary oxide composition for the cementitious materials, and Fig. 1 shows the particle size distribution of the pozzolans. The fine aggregates were natural river sand with a fineness modulus of 3.20 and a specific gravity of 2.61. The coarse aggregates were crushed granite stones, which were angular in shape with the maximum particle size and the specific gravity of 13.2 mm and 2.65, respectively.

Table 1: Major Oxide Composition (%).

OXIDE	RHPC	FA	GGBS	SF	MK
SiO_2	20.79	56.01	37.11	87.8	54.02
Al_2O_3	4.64	31.74	14.34	1.45	42.65
Fe_2O_3	2.69	3.31	0.52	2.46	0.41
CaO	65.05	5	34.61	0.77	0.09
MgO	1.73	1.22	9.33	1.14	0.29
TiO_2	0.39	1.59	0.63	<0.01	1.39
K_2O	0.47	0.77	1.04	2.14	0.17

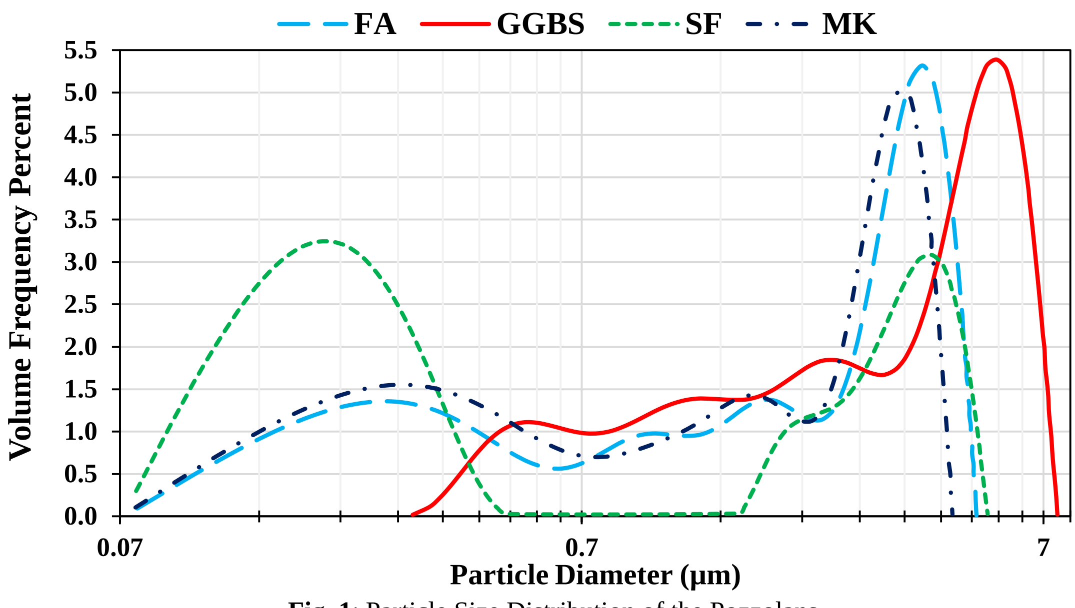

Fig. 1: Particle Size Distribution of the Pozzolans.

2.2. Mix Designs

This investigation considered five mixes, the control (labelled 100% RHPC) and four binary mixtures, obtained by replacing various portions of the cement content of the control with each of the pozzolans. Table 2 presents details of the mixtures, and each mix label indicates the replacement material and replacement level. The water-binder ratio was held constant for all mixes and superplasticiser added as a percentage by mass of the total binder in varying quantity to have the same consistency.

Table 2: Mix Proportions.

Materials (Kg/m^3)	Mix Designs				
	100% RHPC	**FA-30**	**GGBS-50**	**SF-10**	**MK-30**
Portland Cement	320.3	224.2	160.15	288.3	224.2
Fly Ash	-	96.1	-	-	-
Blast-Furnace	-	-	160.15	-	-
Silica Fume	-	-	-	32.0	-
Metakaolin	-	-	-	-	96.1
Coarse Aggregate	1001	1001	1001	1001	1001
Fine Aggregate	821.1	821.1	821.1	821.1	821.1
Water Content	205	205	205	205	205
Superplasticiser [a]	0.6	0.3	0.5	0.9	1.3
Slump (mm)	170	160	160	170	160

[a] as a percentage by mass of the total binder

2.3. Casting and Curing

The concrete was poured into moulds of 100 mm cube and thoroughly vibrated. After casting, the cubes were covered with polythene sheet to prevent the rapid loss of moisture. They were demoulded after 24 hours and cured in water at a constant temperature of 23 ± 2°C. The durability index tests began after 28 days of curing.

2.4. Durability Index (DI) Tests

The durability index measurements were carried out as prescribed by the Durability Index Testing Procedure Manual [6]. Concrete specimens of circular discs with diameter and thickness of 70 ± 2 mm and 30 ± 2 mm, respectively, obtained from coring the cured cubes, were stored in a ventilated oven for 7 days at a constant temperature of 50 ± 2 °C, prior to testing. Upon removal from the oven, the specimens were kept in a desiccator for 2 hours to cool before measuring the diameter and thickness at four points equally spaced across the perimeter of the concrete discs. A set of three tests per index was performed in this experiment, with each test requiring four specimens.

2.4.1. Oxygen Permeability Index (OPI) Test

Immediately after recording the dimensions, the specimens for the OPI test were placed in the oxygen permeability cells and the cells checked for leakages or a sudden drop in pressure of 5 kPa/min. When no leakage was detected, the data logger was activated, and the test began. The data was automatically logged at an interval of 5 minutes, and the test was terminated after 6 hours.

2.4.2. Water Sorptivity Index (WSI) and Porosity Test

It should be noted that specimens for the OPI test were the same ones used in the WSI and Porosity test. After the OPI test, the specimens were retrieved from the permeability cells, sellotaped on the curve edges, weighed, and the mass recorded as the dry mass. The specimens were then placed in a plastic tray containing 10 layers of absorbent paper towel saturated with calcium hydroxide solution and weighed at 3-, 5-, 7-, 9-, 12-, 16-, 20- and 25-minutes intervals. Afterwards, the specimens were placed in a vacuum saturation tank standing on the curved edges, and the tank evacuated to a pressure between -75 and -80 kPa and maintained for 3 hours ± 15 minutes. Subsequently, calcium hydroxide solution was allowed in and submerged the specimens without air entering the vacuum saturation tank. The pressure was then re-established to between -75 and -80 kPa and maintained for 1 hour ± 15 minutes. After this period, the pressure was released, and the specimens allowed to soak in the calcium hydroxide solution for 18 hours, followed by recording the vacuum-saturated mass of the specimens.

2.4.3. Chloride Conductivity Index (CCI) Test

The specimens' dry mass was recorded before being placed in the vacuum saturation tank and vacuumed as in similar manner as described in the water sorptivity test, except that the saturating solution was now 5M of sodium chloride. After obtaining the vacuum-saturated mass, the specimens were placed in a conduction cell and both chambers of the cell filled with the NaCl solution. Next, the conduction cell was connected to the circuit consisting of a DC power supply, an ammeter, and a voltmeter, and the voltage and current were read simultaneously.

2.5. Compressive Strength

The compressive strength test was conducted with an automatic compression machine at the loading rate of 150 kN/min. According to the South African National Standards (SANS), the cubes were tested in saturated surface dry condition and the values presented are based on the average of three.

3. Results and Discussions

3.1. Durability Indexes

3.1.1. Oxygen Permeability index

The results of the oxygen permeability index are presented in Fig. 2, which shows that the higher the OPI, the better the durability of the concrete. Accordingly, MK-30 attained the highest resistance to oxygen permeation, followed by GGBS-50, FA-30, 100% RHPC and SF-10. The performance of MK-30 is attributed to the metakaolin's rapid rate of reaction with calcium hydroxide and its high aluminate content that result in the formation of C-S-H as well as additional alumina-bearing hydrates, respectively, leading to finer pores and a denser microstructure [7, 8]. The performance of GGBS-50 is ascribed to the dual nature of blast-furnace slag: latent hydraulic and pozzolanic, which usually outperforms fly ash even at the same replacement level. Pozzolans are known for improving the microstructural properties of concrete, including the resistance to gas permeation. However, the mix containing silica fume underperformed than the control. The poor performance of SF-10 can mostly be ascribed to the particles size distribution of the silica fume used (see Fig. 1 above), which had only about 64% of its particles finer than 1µm; as silica fume usually has 95% of its particles finer than 1µm [7]. This condition may have reduced the reactivity of silica fume and the filler effect.

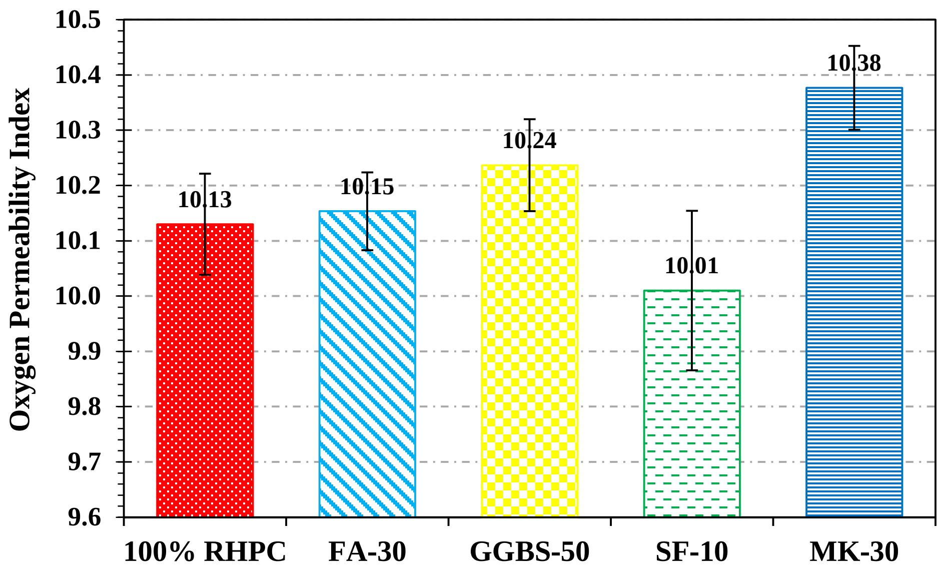

Fig. 2: Oxygen Permeability Index of the Mixes.

3.1.2. Water Sorptivity Index (WSI) and Porosity

The results of the water sorptivity index follow a different trend than those of the oxygen permeability and are presented in Fig. 3. The samples of SF-10 exhibited the highest resistance to water absorption, followed by MK-30, GGBS-50, 100% RHPC and FA-30. The lowest water absorption shown by SF-10 is typical of silica fume and is one of the most reputable properties of silica fume in terms of durability [7]. MK-30 and GGBS-50 performed as expected, and the difference between the two may seem negligible. Samples of FA-30 exhibited the highest rate of water uptake. The low resistance to water absorption displayed by the FA-30 mixture is ascribed to the replacement level and the slow reactivity of the fly ash [9]. Although blast-furnace slag is also a slow-reacting pozzolan and replaced a higher percentage of the Portland cement than fly ash, GGBS-50 exhibited better resistance to water absorption than FA-30.

The porosity results showed an unexpected trend, samples of SF-10 exhibited the highest porosity, while samples of MK-30 showed the lowest. In ascending order, the porosity results are MK-30, GGBS-50, 100% RHPC, FA-30 and SF-10. The trend of this porosity results was verified by those obtained from the chloride conductivity index test. The high porosity of SF-10 is directly linked to the poor performance displayed in the OPI test. The major effect of silica fume on the microstructure of concrete is the refinement of the pore structure, that is, the conversion of large pores into smaller ones [10], which results in higher resistance to water permeation and capillary suction as seen in the WSI test, but not the reduction of the total porosity. Results of the porosity based on WSI test are presented in Fig. 5, along with the porosity results obtained from the chloride conductivity index test.

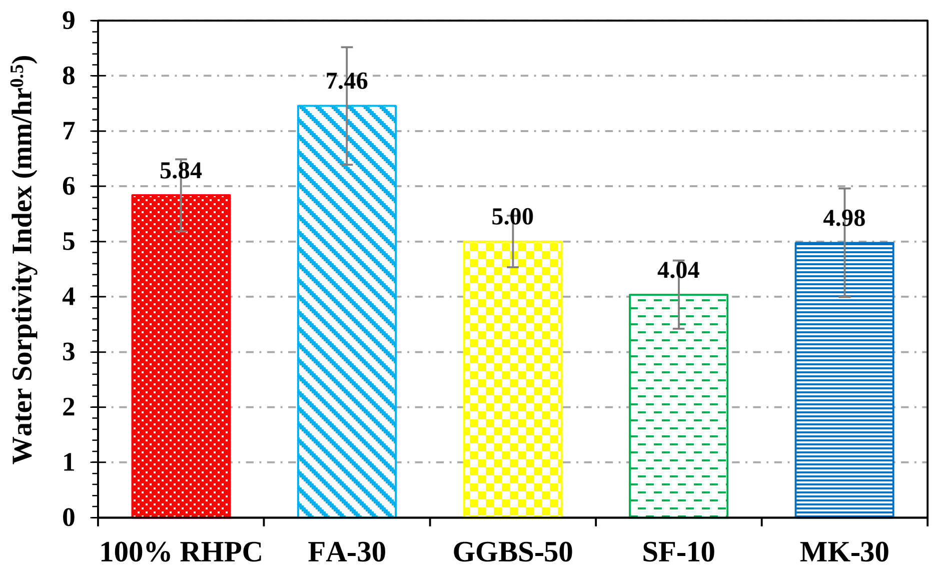

Fig. 3: Water Sorptivity Index of the Mixes.

3.1.3. Chloride Conductivity Index (CCI)

Results of the chloride conductivity index test are presented in Fig. 4. Samples of MK-30 showed the highest resistance to chloride conduction, followed by GGBS-50, SF-10, 100% RHPC and FA-30. The FA-30 mix showed the lowest resistance to chloride conduction. This behaviour is distinctive of fly ash-based concrete at ages less than 90 days. Research has shown that the diffusivity of chloride in fly ash-based concrete at an early age is usually higher than those of plain Portland cement concrete [11]. The results presented here agree with the well-known fact that depending on the age tested, the partial replacement of Portland cement with pozzolans improved concrete resistance to chloride penetration.

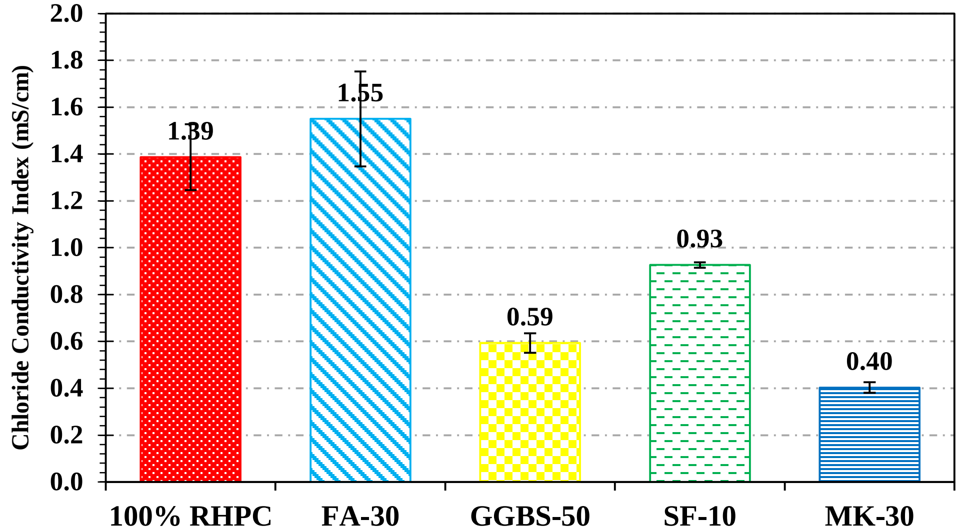

Fig. 4: Chloride Conductivity Index of the Mixes.

The porosity results based on the CCI test are presented in Fig. 5 and follow the same order as the porosity obtained from the water sorptivity and porosity test, thus, validating the trend. However, it is worth noting that the porosity values obtained by the CCI test are lower than those of the water sorptivity index and porosity test. The difference is mainly due to the density of the solutions used in each test. Hence, the porosity calculations, which is based on the difference of the final and initial mass of the saturated specimen divided by the product of the specimen's volume and the density of the solution. The CCI test uses 5M solution of sodium chloride, while the WSI test uses water containing 3 gram of calcium hydroxide per litre [6].

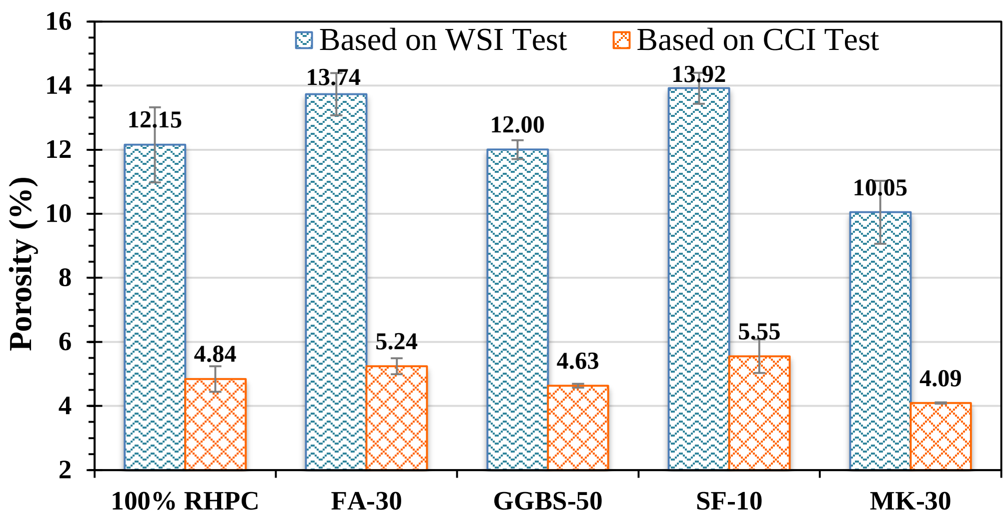

Fig. 5: Porosity of the Mixes.

3.2. Porosity and OPI Relationship

A relationship is observed between the porosity and the OPI of the mixes. When the porosity is plotted as a function of the OPI, an inverse trend is observed, as shown in Fig. 6. The mixes with high porosity are associated with a low resistance to oxygen permeation and vice versa. These two variables (porosity and OPI) seem to be potential indicators of one another. Therefore, the porosity of concrete proves to be an influential factor in its resistance to oxygen permeation.

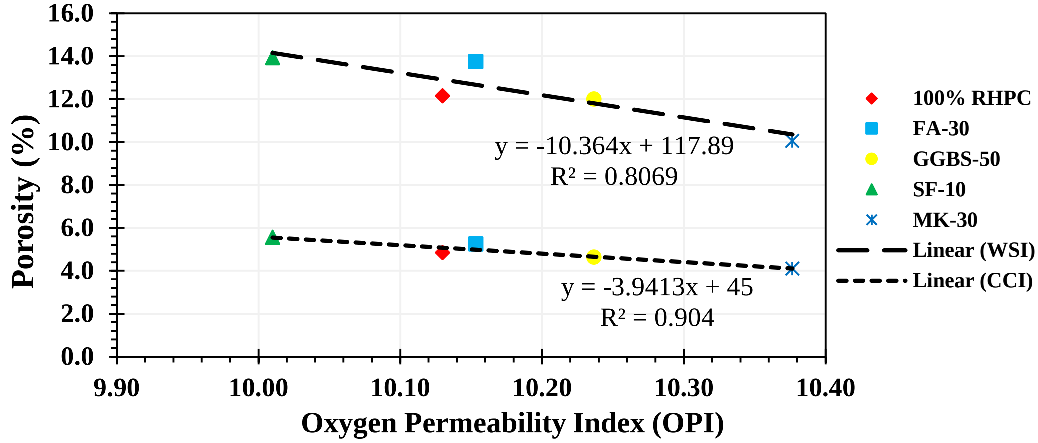

Fig. 6: Porosity vs Oxygen Permeability Index.

3.3. Compressive Strength

The compressive strength test was conducted up to the 56th day after casting, and the results are presented in Fig. 7. MK-30 attained the highest 56th day compressive strength while FA-30 obtained the lowest. The control exhibited rapid strength development up to the 7th day, after which the rate of strength development declined. Silica fume and metakaolin are highly reactive pozzolans and usually exhibit rapid early strength development because of their extreme fineness. However, the rate of early strength development of SF-10 and MK-30 was slower than the control. The slow rate of strength development of SF-10 and MK-30 is undoubtedly due to the comparatively coarser particle of the silica fume, as discussed in Section 3.1.1, and the 30% replacement level of the metakaolin, respectively. At 30% replacement level, metakaolin-blended concrete usually produces lower strength than Portland cement concrete up to the 7th day [12, 13].

FA-30 and GGBS-50 were the least in terms of strength development, with GGBS-50 being the slowest regarding early strength development. The lower rate of strength development observed in the FA-30, and GGBS-50 is typical of these materials [13]. These materials are far less reactive than silica fume and metakaolin because of their small surface area. Consequently, the replacement of the Portland cement with less reactive pozzolanic materials generally results in slower strength development.

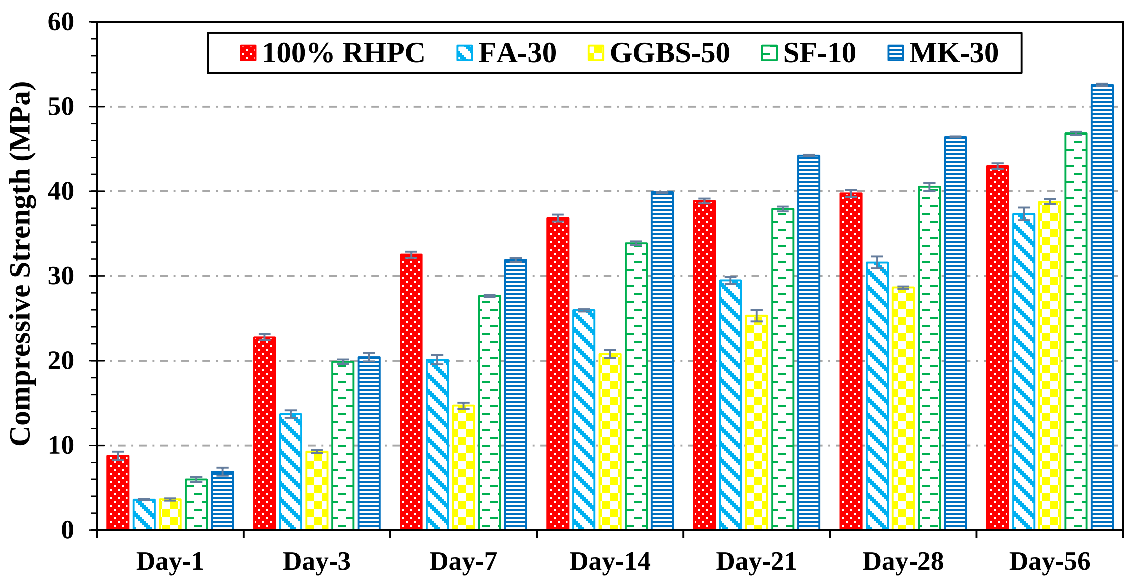

Fig. 7: Compressive Strengths of the Mixes.

4. Conclusion

This investigation was aimed at evaluating the influence of pozzolans on the penetrability of concrete, which is a function of the microstructure development. The evaluation was done using the South African durability index tests; resistance to oxygen permeation, water absorption and chloride diffusion were assessed. Based on the conditions tested, the following conclusions can be drawn:

1. The influence of pozzolans on the penetrability of concrete depends solely on the type of pozzolan, the replacement level, the fineness and the age tested.
2. Metakaolin and blast-furnace slag mixes displayed the most resistance to oxygen permeation, water absorption and chloride conduction.
3. The influence of silica fume on the transport properties of concrete is mainly observed in the resistance to water absorption and chloride conduction. However, the behaviour observed for the silica fume in this study was influenced by the comparatively coarser particles.
4. The slow rate of strength development of the GGBS and fly ash blends in this study are typical for both materials and can be attributed to the slower reactivity rate at early ages.

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References

[1] D. Bjegović, M. Serdar, I. S. Oslaković, F. Jacobs, C. Andrade, A. V. Monteiro, P. Paulini, and S. Nanukuttan, ‘Test Methods for Concrete Durability Indicators’, in *Performance-Based Specifications and Control of Concrete Durability: State-of-the-Art Report RILEM TC 230-PSC*, H. Beushausen and L. Fernandez Luco, Eds. Dordrecht: Springer Netherlands, 2016, pp. 51–105.

[2] Y. Ballim, M. Alexender, and H. Beushausen, ‘Durability of Concrete’, in *Fulton's Concrete Technology*, Ninth Edition., G. Owens, Ed. Midrand: Cement & Concrete Institute, 2009, pp. 155–188.

[3] M. G. Alexander, Y. Ballim, and K. Stanish, ‘A framework for use of durability indexes in performance-based design and specifications for reinforced concrete structures’, *Mater. Struct.*, vol. 41, no. 5, pp. 921–936, 2008.

[4] M. Otieno, ‘Sensitivity of the rapid chloride conductivity index test to concrete quality and changes in various test parameters’, *Cem. Concr. Compos.*, vol. 86, pp. 110–116, 2018.

[5] S. O. Nwaubani, ‘Waste Steel Slag and their Influence on the Properties of Cement Blends’, *MRS Adv.*, vol. 3, no. 34, pp. 2027–2040, Jul. 2018, doi: 10.1557/adv.2018.186.

[6] M. G. Alexander, ‘Durability Index Testing Procedure Manual’. Apr. 2018.

[7] R. Siddique and M. I. Khan, *Supplementary cementing materials*. Springer Science & Business Media, 2011.

[8] S. O. Nwaubani, ‘Hydration kinetics, pore characteristics and chloride ion diffusivity of blended cements’, *Int. J. Civ. Eng.*, vol. 12, no. 3, pp. 354–362, 2014.

[9] K. Sideris, H. Justnes, M. Soutsos, and T. Sui, ‘Fly Ash’, in *Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials: State-of-the-Art Report of the RILEM Technical Committee 238-SCM, Working Group 4*, N. De Belie, M. Soutsos, and E. Gruyaert, Eds. Cham: Springer International Publishing, 2018, pp. 55–98.

[10] R. C. Lewis, ‘Silica Fume’, in *Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials: State-of-the-Art Report of the RILEM Technical Committee 238-SCM, Working Group 4*, N. De Belie, M. Soutsos, and E. Gruyaert, Eds. Cham: Springer International Publishing, 2018, pp. 99–121.

[11] R. B. Holland, K. E. Kurtis, and L. F. Kahn, ‘Effect of different concrete materials on the corrosion of the embedded reinforcing steel’, in *Corrosion of Steel in Concrete Structures*, Elsevier, 2016, pp. 131–147.

[12] D. D. Vu, P. Stroeven, and V. B. Bui, ‘Strength and durability aspects of calcined kaolin-blended Portland cement mortar and concrete’, *Cem. Concr. Compos.*, vol. 23, no. 6, pp. 471–478, 2001.

[13] S. O. Nwaubani, J. M. Khatib, and S. Firat, ‘Compressive Strength Properties of Cement Mortars Incorporating Pulverised Glass’, in *2nd International Workshop on Earthquake and Sustainable Materials*, Gazi University, Ankara, Turkey, 2013, pp. 159–167.