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Flexural and Compressive Strength of Sustainable Concrete with Electric Arc Furnace Slag Aggregates and Polypropylene Fibers

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Abstract **-** The objective of this study is to evaluate the effect of polypropylene fibers on flexural strength and tensile strength of concrete in which natural aggregates were replaced with 30%, or 50% recycled Electric Arc Furnace Slag (EAFS) coarse aggregates. The partial replacement of natural aggregates with EAFS aggregates is intended to preserve natural aggregates while recycling slag, a byproduct of industry, therefore, achieving a more sustainable concrete. Since EAFS aggregates may be used for slabs or slabs-on-grade, in addition to other structural elements, mechanical properties in general and flexural strength are essential properties. The fundamental goal of using polypropylene fibers, however, remains the control of cracking. The w/b ratio was maintained at 0.45 for all mixes regardless of EAFS replacement percentage or size of fibers. Two types of fibers were evaluated, Polyolefin-based microfibers ranging from 11 to 13 long with a diameter of $35 \pm 5\ \mu m$, and Polypropylene macrofibres that are 48 mm long and 0.48 mm in diameter. The flexural and splitting tensile strengths were determined for samples cured in water for 28 days while compressive strength was determined after 7, 28, and 56 days of curing. After 7 days of curing, samples with micro and macro fibers developed slightly higher compressive strength than the control mix without fibers. However, after 28 days and 56 days of curing, there was negligible effect for polypropylene fibers on compressive strength, regardless of the content of EAFS aggregates. Nonetheless, the flexural strength of concrete with polypropylene fibers, with and without ACBFS aggregates, was higher than the control mix without fibers. The increase of the 28-day flexural strength of concrete with polypropylene fibers compared to control mix was largely similar (14.1% to 15.2%), regardless of EAFS aggregates content. Macrofibres achieved slightly better 28-day flexural strength compared to control mix with natural aggregates. Similarly, polypropylene fibers increased the 28-day splitting tensile strength compared to control mix, but with a much smaller range of 3.1% to 5.1% compared to control mix. The 5.1% increase in splitting tensile strength was the mix with 50% EAFS aggregates. The study paves the road to using EAFS aggregates to produce environmentally friendly concrete with polypropylene fibers to control cracking and enhance flexural strength.
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Keywords**:** electric arc furnace slag; polypropylene fibres; tensile strength; flexural strength; compressive strength; concrete.

1. Introduction

Slag is the byproduct of the steel industry with the highest volume and must be landfilled if not reused. Depending on the production processes, several types of slags are produced including, but not limited to blast-furnace slag, ladle-furnace slag, and electric-arc furnace slag [1]. According to the Steel Word Association, 400 kg of blast-furnace slag is produced for each tonne of crude steel versus 170 kg of electric arc furnace slag. In this article, electric-arc furnace slag (EAFS) processed and graded for use as coarse aggregates for concrete is studied. EAFS is studied as a sustainable alternative to natural aggregates to achieve two sustainability goals, including preservation of natural resources and recycling slag produced by industry.

Despite the benefits of recycling EAFS, there are challenges to its use. Concrete with EAFS aggregates exhibits one to six times the carbonation depth of concrete limestone aggregates [1]. Similarly, the depth of water penetration in concrete with EAFS aggregates is higher than equivalent concrete with limestone aggregates, which is attributed to the inherently higher porosity.

Through careful mix design, it is possible to replace natural aggregates with large percentages of EAFS coarse aggregates achieving similar or higher compressive and tensile strengths, as well as elastic modulus [2]. However, the study indicates that replacing natural fine aggregates with EAFS may reduce flexural strength.

Air-cooled blast furnace slag (ACBS) has long been used as coarse aggregates in road pavement applications, and to some extent in building and bridge structures. When ACBS was used as fine aggregates for concrete applications, a densification of the interfacial transition zone (ITZ) on particle surfaces was observed [3]. ITZ is the zone surrounding the aggregates with contours around 15 – 40 μm in size [4], and whose properties are also influenced by the shape and texture of the aggregates. The ITZ exists in concrete around aggregates, regardless of the type of aggregate, due to variation in water-to-binder (w/b) ratio between the surface of the aggregates into the matrix, leading to heterogeneity of porosity, anhydrous phases, and hydration products [5]. The densification of ITZ when using slag aggregates is caused by reactivity and production of hydrotalcite-like phase at the ITZ. Similarly, Panchmatia [6] reported that the porosity of mortar ITZ with blast furnace slag aggregates was lower than that of siliceous aggregates. In addition, the content of calcium hydroxide and C-S-H at the ITZ of mortar with ACBS aggregates was higher than that of siliceous aggregates. Use of ACBS might makes concrete and mortar more vulnerable to sulphate attack from the surrounding environment as it releases sulphur into the pore solution.

In concrete with EAFS aggregates, the ITZ is smaller and less porous than in equivalent concrete with natural aggregates [7]. The properties of ITZ around EAFS aggregates was attributed to slow migration of CaO, which is abundant in EAFS, to the surface of aggregate particles and subsequent formation of calcium carbonate. The failure mechanism of concrete with EAFS shows fracturing of aggregates in a manner that suggests stronger bond between the EAFS aggregates and surrounding matrix.

Singh [8] reported that partial replacement of natural sand with granulated blast furnace slag fine aggregates increases the compressive of concrete up to an optimum replacement percentage of 50%. Compressive strength of concrete with more than 50% slag fine aggregates is lower than the optimum percentage.

The effect of various fibre types on durability and mechanical properties of geopolymers and conventional concrete was studied extensively [9]. Similarly, the use of ground granulated blast furnace slag as sole binder, or as partial replacement of ordinary Portland cement (OPC) were also studied extensively [10], [11], [12]. However, limited studies address the effect of reinforcing fibres on concrete with EAFS aggregates.

This paper presents the findings of a study aimed at evaluating the effect of polypropylene micro and macrofibres on flexural and compressive strengths of concrete in which natural aggregates were partially replaced with electric arc furnace slag aggregates. Replacement of natural aggregates with EAFS saves natural resources and recycles slag that should otherwise be landfilled. The development in compressive and tensile strengths when using EAFS as partial replacement of natural aggregates offers significant potential for recycling slag and reusing it as aggregates while maintaining competitive concrete mechanical properties.

2. Experimental Procedure and Material Properties

The water-to-binder (w/b) ratio was maintained at 0.45 for concrete mixes evaluated in the study. The w/b along with carboxylic-based superplasticizer produced acceptable workability and no bleeding. The binder used was ordinary Portland cement (OPC), fine aggregates were dune sand from Al Ain city, UAE, coarse aggregates were natural crushed limestone from the Emirate of RAK, UAE. Total natural coarse aggregates content was 1570 kg/m^3, sand content was 340 kg/m^3, and OPC was 380 kg/m^3. The electric arc furnace slag (EAFS) weas provided by a local supplier, produced by sprinkling water on molten slag that was separated from iron during processing. The water absorption of EAFS aggregates, measured according to ASTM C127 [13], ranged from 1.1% to 1.4%, depending on particle size. This is much higher than the water absorption of natural coarse aggregates which ranged from 0.4% to 0.8%, depending on size. The higher water absorption of EAFS aggregate compared to natural aggregates is due to its porosity. Fig. 1 shows the EAFS coarse aggregates used in the study with distinct rough texture and high porosity. The saturated surface dry density of EAFS aggregates, ranged from 3.51 t/m^3 to 3.56 t/m^3, much higher than natural limestone aggregates whose density ranged from 2.66 to 2.69 t/m^3. Therefore, the partial replacement of natural limestone with 30% and 50% EAFS is intended to alleviate the impact of the heavier EAFS aggregates on concrete unit.

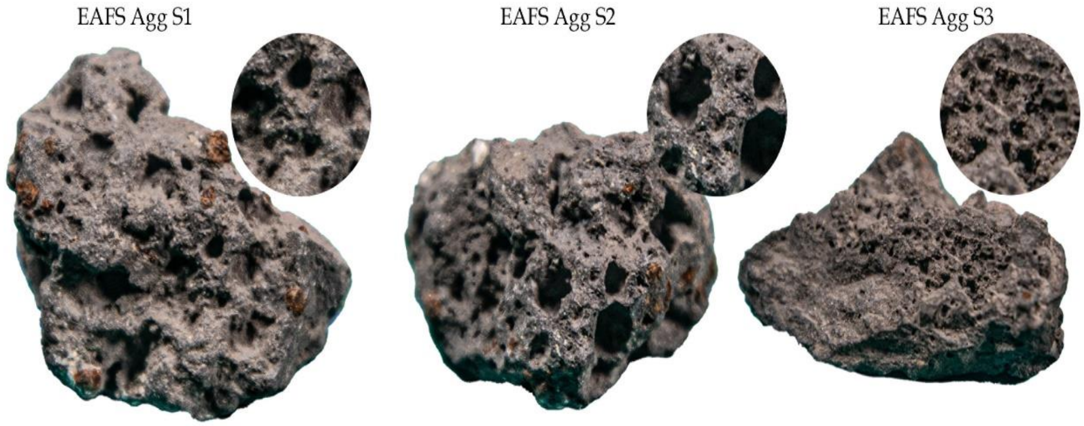

Fig. 1: Electric arc furnace slag (EAFS) aggregates with visibly rough texture and high porosity

Sieve analysis of the EAFS aggregates used in the experimental program is shown in Fig. 2. The chemical composition of EAFS aggregates is shown in Table 1.

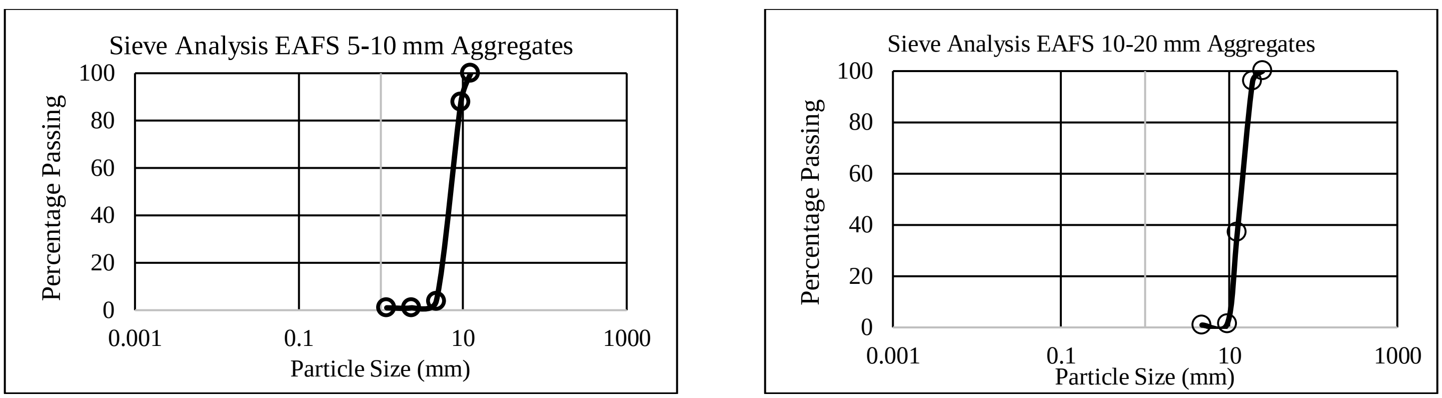

Fig. 2: Sieve analysis of EAFS coarse aggregates.

Table 1: Chemical composition of electric arc furnace slag aggregates

Compound	MnO	SiO_2+IR	CaO	PbO	Al_2O_3	Cr_2O	MgO	Fe_2O_3
Content	1.79%	19.11 %	31.87 %	0.01 %	4.35 %	0.18 %	7.31 %	34.91 %

Three main concrete mix groups were prepared based on coarse aggregates type/content: 1) 100% natural aggregates (control), 2) 30% EAFS aggregates + 70% natural aggregates, and 3) 50% EAFS aggregates + 50% natural aggregates. Mixes with 100% EAFS aggregates required substantial amount of superplasticizer to maintain workability and was therefore not included in this article. For each of the three mix groups (based on coarse aggregates), samples were prepared in three sets: 1) without fibres (control), 2) with polypropylene microfibres, 3) with polyolefin macrofibres., The polypropylene-based microfibres, shown in Fig. 3(a), were 11 to 13 mm long x 35 mm $\pm$ 5 mm in diameter. The polyolefin-based macrofibres, shown in Fig. 3(b), were 48 mm long x 0.84 mm in diameter. The micro and macrofibres were applied at the manufacturer recommended dosage of 0.6 kg/m^3. The polypropylene macrofibres are compliant with ASTM C1116/C1116M Type III Fiber - Reinforced Concrete [14], and ASTM D7508/7508M [15].

(a) (b)

Fig. 3: Fibres uses in the study include a) Polypropylene micro fibres, b) Polyolefin macrofibres

Concrete cubes (150 x 150 x 150 mm^3) prepared for compression test and cylinders (150 mm diameter x 300 mm long) prepared for splitting tensile strength were cured under water until test day. Beams (150 x 150 mm in cross-section x 740 mm long) were cured under water under ambient laboratory conditions until test day. The flexural and splitting tensile strengths were determined after 28 days of curing. After demoulding, the unit weight of concrete samples without EAFS aggregates averaged 2440 kg/m^3, while the samples with 30% EAFS aggregates weighed 2535 kg/m^3, and the samples with 50% EAFS aggregates averaged 2610 kg/m^3. The higher concrete unit weight of samples with EAFS aggregates is due to the density of EAFS which is higher than natural limestone aggregates.

Compression test was conducted on samples cured for 7, 28, and 56 days. For compression test, the values reported represent the average of three samples, while for flexural and splitting tensile strengths the values reported represent the average of two tests.

Water permeability test was conducted on samples with and without EAFS aggregates, as well as with and without polypropylene fibres. The test was conducted according to BS EN 12390 Part 8:2019 [16] and the water permeability reported is the average of two measurements.

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3. Discussion of Results

Water permeability is an important transport property and indicator of concrete durability. The water permeability test was conducted according to BS EN 12390 Part 8:2019 on samples cured for 28 days. Fig. 4 shows that water permeability of concrete samples without EAFS aggregates (100% natural aggregates) increased with the addition of polypropylene microfibres or polyolefin macrofibres. When 30% or 50% of natural aggregates were replaced with EAFS, and in the presence of propylene microfibres, water permeability decreased compared to control samples (without ACSB aggregates). As shown in Fig. 4 (b), when polyolefin macrofibres were used along with partial replacement of aggregates with EAFS aggregates, the water permeability decreased below the control mix (without EAFS aggregates). It therefore clear that EAFS aggregates played a critical role in reducing water permeability since fibres increased water permeability of concrete made with natural aggregate as shown in Fig. 4(a) and (b). It likely that the angular shape of EAFS aggregates enhanced the bond between aggregates and cement paste leading to more homogeneous and denser matrix, especially at the interfacial transition zone, resulting in a decrease in pore connectivity and water permeability.

Fig. 5 shows that polypropylene microfibres or polyolefin macrofibres increase the 28-day flexural strength of concrete, regardless of the replacement percentage of EAFS aggregates. This is consistent with published literature [9]. There is a difference between micro- or microfibers in terms of effectiveness in increasing flexural strength is negligible when EAFS aggregates content was 30% or 50%. The increase in flexural strength of concrete was 14.63% with micro or macro and 30% EAFS aggregates. In the case of 50% EAFS aggregates, the increase in flexural strength due to the addition of micro or macro fibres was 15.2%. When concrete was prepared using control mix, without EAFS aggregates, the increase in flexural strength due to the addition of polypropylene micro fibres was 9.17% while the increase was 14.17% in the case of macrofibres. That means macrofibres are more effective than microfibers in increasing flexural strength of conventional concrete with natural coarse aggregates.

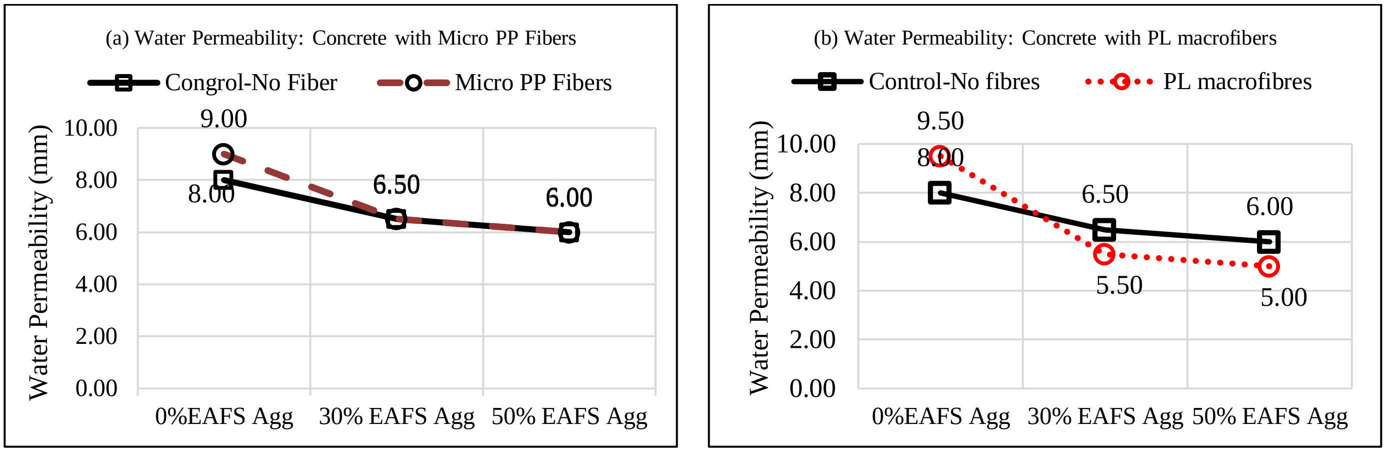

Fig. 4. Water permeability of concrete with a) Polypropylene (PP) microfibres, and b) Polyolefin (PL) macrofibres

Fig. 5(b) shows that micro- and macro-fibres increase the splitting tensile strength of concrete. In concrete without EAFS aggregates, the increase in splitting tensile strength was 16.93% and 14% for polypropylene microfibres and polyolefin macro fibres, respectively. When EAFS aggregates represented 50% of the total aggregates, the increase in splitting tensile strength was 24.75% and 25.76% for polypropylene micro and macro fibres, respectively.

When natural aggregates were replaced with 30% EAFS aggregate the flexural strength of concrete without fibres increased marginally from 6.00 MPa to 6.15 MPa (2.5%), as shown in Fig. 5 (a). When the replacement percentage of EAFS aggregates was increased to 50%, flexural strength of concrete without fibres increased from 6.0 MPa to 6.25 MPa (4.17%). The effect of EAFS aggregates on flexural strength is likely to be influenced by other factors such as the water-to-binder (w/b) ratio, binder type, and fibre content/type. The splitting tensile strength increased by a minimal 1.58% when natural aggregates were replaced with 30% EAFS aggregates, and 11.29% when they were replaced by 50% EAFS aggregates, as shown in Fig. 5(b). The positive effect of EAFS on tensile strength was attributed to the enhanced bond strength between EAFS aggregates and surrounding matrix [17]. Kim [18] reported that the flexural strength of concrete beams with EAFS aggregates is comparable to that of beams with natural aggregates. The enhancement of flexural strength may also be related to the improvement in ITZ in the form of decreased porosity when EAFS is used compared to natural limestone [7]. The enhancement in ITZ in the case of EAFS is related to migration of CaO which is abundant in slag aggregates.

Fig. 5 shows that the 7-day compressive strength of concrete without EAFS aggregates (all natural aggregates) increased by 7.44% and 8.44% when adding polypropylene micro and macro fibres, respectively. However, when concrete was prepared with 50% EAFS aggregates, the compressive strength increased by 8.64% and 12.96% due to the addition of polypropylene micro and macro fibres, respectively. Partial replacement of natural aggregates with 30% and 50% EAFS aggregates increased the compressive strength of concrete without any fibre by 7.44% and 14.89%, respectively.

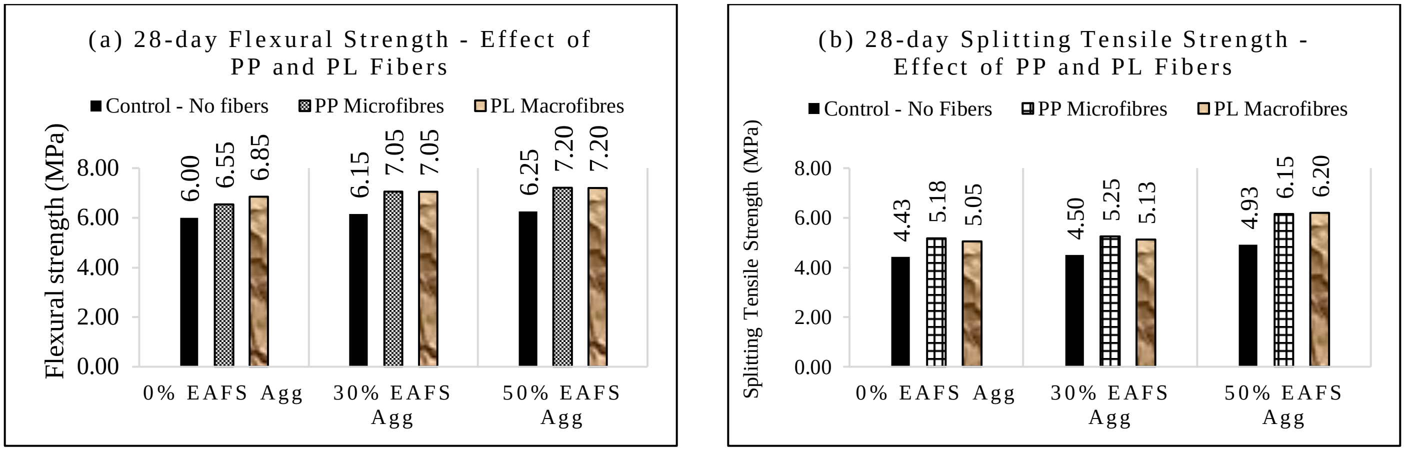

Fig. 5: Effect of polypropylene (PP) and polyolefin (PL) fibres on 28-day: (a) flexural strength, (b) splitting tensile strength

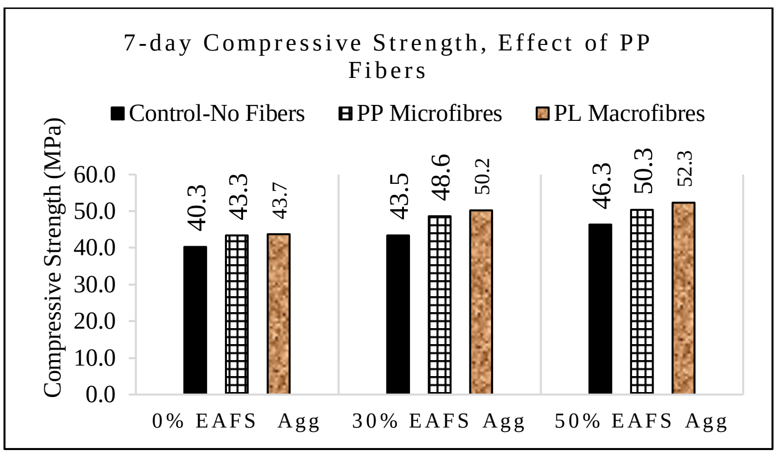

Fig. 6: Effect of PP fibres on 7-day compressive strength

Fig. 7(a) shows that at the age of 28 days, the effect of polypropylene micro or macro fibres on compressive strength is insignificant. The 28-day strength of concrete without EAFS (control mix) decreased slightly due to the presence of polypropylene microfibres and polyolefin macrofibres by 2.8% and 4.8%, respectively. Similarly, the 28-day strength decreased slightly due the addition of polyolefin or polypropylene fibres to concrete with 30% and 50% EAFS aggregates. A possible reason is the lower strength of polypropylene material in compression compared to the hardened matrix or aggregate. The polyolefin and polypropylene fibres induce relative disruption of the matrix homogeneity and might cause some stress concentration points at the interface between the fibres and surrounding matrix. Apart from the effect of fibres, Fig. 7(a) indicates that the partial replacement of aggregates with 30% and 50% EAFS enhances the 28-day compressive strength of the control mix (without fibres) by 8.8% and 11.4%, respectively. The increase in compressive strength due to use of EAFS aggregates is documented in the literature [19] but the extent varies widely depending on various factors including but not limited to the amount of replacement, w/b ratio, and physical characteristics and chemical composition of EAFS aggregates.

Fig. 7(b) shows that after 56 days of curing, the effect of micro and macro fibres on compressive strength diminishes and compressive strength is largely dominated by concrete strength. This is particularly true for the control concrete with polypropylene microfibres, and the mixes with 30% and 50% EAFS reinforced with micro- and macro-fibres. Fig. 7 (b) shows that the strength of control mix increased by 5.1% (54.8 MPa to 57.6 MPa) due to replacement of aggregates with 30% EAFS. Similarly, the control mix increased by 8%, from 54.8 MPa to 59.2 MPa due to replacement of 50% of the natural aggregates with EAFS aggregates. The increase is possibly due to the densification of the ITZ around the EAFS aggregates, especially in the long term, due the development of hydration products. Increase in compressive strength at a particular age due to the partial replacement of limestone aggregates with EAFS is hypothesized to be related to the peculiar characteristics of the ITZ around EAFS aggregates.

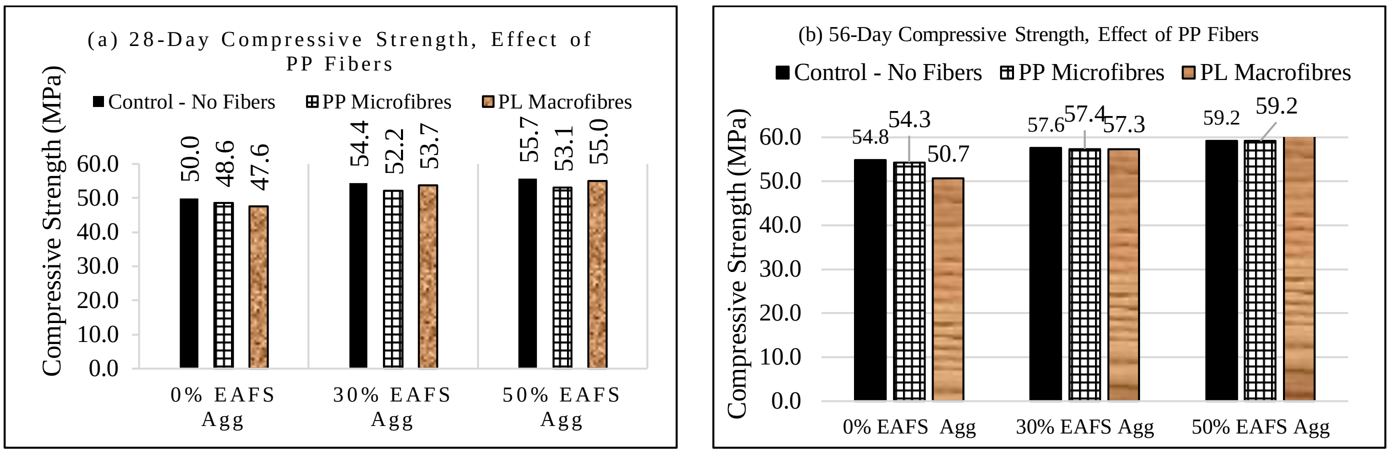

Fig. 7: Effect of polypropylene (PP) micro, polyolefin (PL) macro fibres, and EAFS aggregate content on compressive strength after: (a) 28 days of curing, (b) 56 days of curing.

4. Conclusion

- In concrete prepared using 100% natural limestone coarse aggregates, the addition of polypropylene fibres to concrete decreases water permeability. In addition, partial replacement of natural aggregates with 30% or 50% electric arc furnace slag (EAFS) aggregates decreases water permeability compared to control concrete (with natural limestone aggregates). The use of polypropylene macrofibres along with EAFS aggregates as partial replacement of natural aggregates decreases water permeability, below that of the control mix.
- When the mix contained 30% to 50% ACSB aggregates, the addition of micro and macro polypropylene fibres increased flexural strength by 14.2% and 15.2%, respectively. For concrete without EAFS aggregates (100% natural aggregates), the increase in flexural strength was 9.14% and 14.17% due to adding micro and macro polypropylene fibres, respectively.
- The 28-day and 56-day compressive strength of concrete with polypropylene fibres remained similar to or slightly less the control mix without fibres, regardless of the type of aggregates. This because concrete matures at later ages to higher matrix strength while the PP fibres remain weaker than concrete matrix.
- After 28 days and after 56 days of curing, compressive strength of concrete with 30% or 50% EAFS aggregates developed higher compressive strength than the control mix (with 100% natural coarse aggregates). This is likely due to the densification and additional hydration products in the interfacial transition zone (ITZ) around the EAFS aggregates. The abundance of CaO in EAFS aggregates, the internal water within the pores due to higher porosity, contribute to development of hydration products.

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