Exploring XLPE-Concrete as a Novel Sustainable Construction Material

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Abstract. Cross-linked polyethylene (XLPE) is extensively used but complex to recycle. Alternative methods are thus needed to better recycle XLPE waste. It is also well known that the extraction of natural aggregates for the production of concrete has negative impacts on the environment. It is therefore here proposed to replace 5%, 10%, 15% and 20% of the medium sized aggregates in structural concrete by XLPE waste shreds. The mechanical and physical properties of XLPE-Concrete are investigated and compared to those of a control mix without XLPE inclusions. As the XLPE replacement ratio increases, the unit weight of concrete decreases, the amount of superplasticizer needed to maintain the same level of concrete workability increases and the modulus of elasticity tends to decrease. The tensile strength increases with the XLPE content, up to a replacement ratio of 15 %, and then starts to drop. The compressive strength also increases initially, for a replacement ratio of 5%, and then decreases gradually as the XLPE content is further augmented. Nevertheless, all XLPE-Concrete mixes maintain a level of strength that is compatible with structural applications.

INTRODUCTION

The extraction of natural resources for construction has negative environmental impacts, including the transformation of green areas into industrial fields. On the other hand, only part of a large amount of waste generated yearly is adequately recycled [1]. One may therefore consider substituting natural aggregates in concrete by waste materials. This said, the physical and mechanical properties of the resulting composite should be investigated first.

Indeed, the properties of concrete are affected by those of the waste materials used. Waste such as crushed bricks and ceramics exhibit more strength and have better surface texture than natural aggregates, which improves the properties of concrete [2-4]. Other materials, such as crushed concrete, have a higher absorption capacity and a lower strength compared to natural aggregates [5] which, on the contrary, tends to weaken the properties of concrete.

Polymers and specifically plastic materials are widely consumed. These fall into several categories that are not all well recycled [6]. The angular shape of polymers, their smooth surfaces and their weaker mechanical properties – as compared to natural aggregates – tend to decrease the mechanical properties of the resulting concrete [7-9].

Cross-linked polyethylene (XLPE) is produced from polyethylene (PE) by mixing the latter with organic peroxides through an extrusion process that increases the number of intermolecular connections and improves material properties [10,11]. XLPE is thus suitable for firefighting-systems and for the insulation of electrical cables, among other applications. However, XLPE materials are difficult to recycle [12].

A previous work by Shamsaei et al. [13] studied the effect of replacing several percentages of coarse aggregates by XLPE materials in Roller Compacted Concrete Pavement (RCCP) with zero slump. Improvements in concrete properties were noted at a replacement ratio of 5%.

This work studies the influence on the physical and mechanical properties of incorporating XLPE waste shreds to partially replace medium-size natural aggregates in workable structural concrete.

MATERIALS AND EXPERIMENTAL METHODS

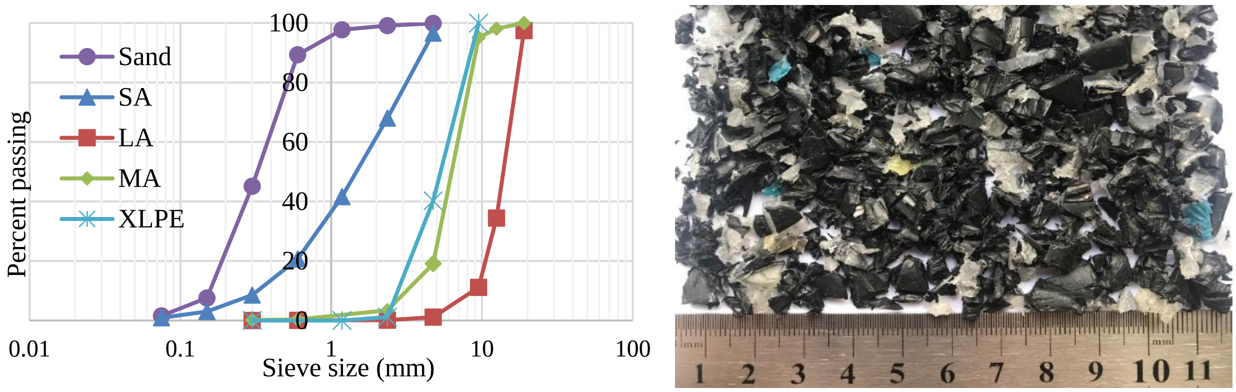
Materials and Mix Proportions

The cement used in all the mixes is type I Portland cement. The natural aggregates (excluding sand) are mainly limestone and are divided into three sizes: large aggregates (LA), medium aggregates (MA) and small aggregates (SA), having maximum nominal sizes of 19 mm, 12.5 mm and 4.75 mm respectively. The maximum nominal size of the sand used is 4.75 mm. The average specific gravities on an oven-dry (OD) basis and a saturated surface dry (SSD) basis are shown in Table 1, along with the average absorption capacities for the four types of aggregates. These are determined according to the ASTM C 127 and the ASTM C 128 standards.

TABLE 1. Specific gravities (OD) and (SSD), and absorption of LA, MA, SA and Sand

Aggregate type	SG (OD)	SG (SSD)	Absorption (%)
LA	2.62	2.64	0.73
MA	2.58	2.61	1.27
SA	2.60	2.64	1.53
Sand	2.59	2.64	1.69

The results of the sieve analyses, conducted according to the ASTM C 136 standard, are shown in Fig. 1 (a). The four aggregate types are combined into two categories, and in suitable proportions: (i) coarse aggregates (CA) comprising 25% of LA and 75% of MA, and (ii) fine aggregates (FA) comprising 50% of SA and 50% of sand. With these proportions, the resulting gradation curves of both CA and FA fit within the ASTM C 33 standard limits. The bulk density of the coarse aggregates is 1536 Kg/m3 (ASTM C 29). The fineness modulus of the fine aggregates is 2.61.



(a) (b)

FIGURE 1. (a) Gradation curves (b) shredded XLPE materials

The XLPE materials are shredded and sieved as shown in Fig. 1(a) and 1(b). The moisture content and the absorption capacity of XLPE are negligible. A superplasticizer is used to improve the workability of the different mixes of fresh concrete, thus compensating for the fact that it would be reduced due to the incorporation of XLPE shreds.

TABLE 2. Concrete mixes composition (in kg per m3 of fresh concrete)

					CA		FA				
Mix designation	XLPE replacement ratio	w/c	water	cement	LA	MA	SA	Sand	XLPE	Additional water	Superplasticizer [% of cement]
M00/CM	0%	0.54	190.0	351.9	245.9	738.0	414.2	417.6	0.0	19.0	0.35
M05	5%	0.54	190.0	351.9	246.1	701.3	414.8	415.7	12.7	19.3	0.40
M10	10%	0.54	190.0	351.9	246.1	664.3	414.5	415.6	25.4	19.4	0.46
M15	15%	0.54	190.0	351.9	246.0	627.8	414.5	415.3	38.1	19.0	0.51
M20	20%	0.54	190.0	351.9	246.1	590.4	414.4	414.8	50.9	19.5	0.80

Ratios of 5%, 10%, 15% and 20% of dry MA are replaced by the same volume of XLPE particles. A mix without XLPE is also considered as a control mix (M00). A free-water to cement ratio of 0.54 is retained for all the mixes.The moisture contents of the aggregates are determined before every mix and the mix proportions adjusted accordingly. A suitable quantity of superplasticizer is added to each mix to achieve a common target slump of 150 mm. The compositions (Table 2) of the different XLPE-Concrete mixes were determined according to ACI 211.1.

Test Methods

For each batch, the aggregate constituents are weighted separately then thoroughly mixed. While continuously mixing, part of the water is added, followed by the cement, then by the remaining water with the superplasticizer. A slump test is conducted on the fresh concrete according to ASTM C 143 before casting concrete cylinders. Nine cylinders of standard size (150 mm × 300 mm) are cast for each of the five mixes, yielding a total of 45 cylinders. The fresh concrete is filled into the molds in three equal layers. Each layer is rodded 25 times with uniformly distributed strokes over the cross-section and then tapped to release all trapped air according to ASTM C 192. After 24 hours, the concrete cylinders are demolded and cured in a water tank at ambient temperature. These cylinders are tested at the ages of 28 days. Nondestructive ultrasound pulse velocity (UPV) tests are performed on all the specimens (according to ASTM C 597), before destructive testing, to determine the influence of the XLPE content on the ultrasound wave transmission speed through XLPE-Concrete and thus on its dynamic modulus of elasticity. For each mix, the compressive strength is tested using unbonded caps according to ASTM C 39 and ASTM C 1231; the splitting tensile strength is tested as per ASTM C 496, and the static (secant) modulus of elasticity is determined according to ASTM C 469. Each test is conducted on three different specimens to insure repeatability.

RESULTS AND DISCUSSION

The unit weight of XLPE-Concrete varies with the XLPE content as shown in Fig. 2(a). Starting from 2365 kg/m^3 for the control mix (M00), the unit weight decreases to 2284 kg/m^3 as the XLPE replacement ratio is increased to 20% (M20). Clearly, this drop in density is due to the fact that the specific gravity of XLPE (0.89) is significantly smaller than that of the natural aggregates it replaces (2.58 for oven-dry MA). This outcome has positive consequences on the dead load of structural and non-structural elements made of XLPE-Concrete.

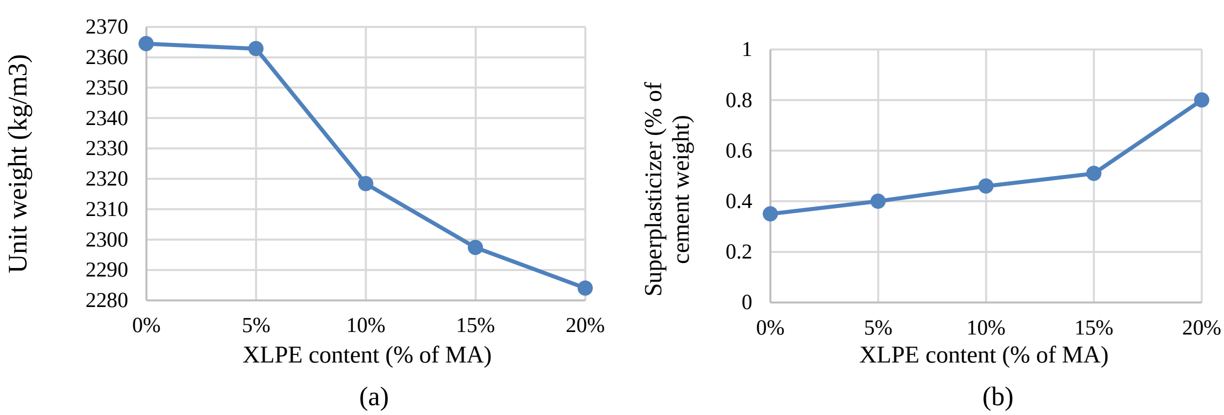


FIGURE 2. (a) Average unit weight (b) superplasticizer quantities used to reach a common target slump of 150 mm for all mixes

The quantity of superplasticizer that is needed to achieve a slump of 150 mm is plotted against the XLPE content in Fig. 2(b). Clearly, the replacement of MA by XLPE shreds tends to decrease the workability of the XLPE-Concrete mix, which requires suitable compensation by addition of superplasticizer. This outcome is most likely due to the differences in shape between the natural aggregates and the XLPE shreds. The natural aggregates used present a roughly rounded shape, while the XLPE shreds are more angular and thus characterized by a significantly larger angle of repose, which gives rise to more internal friction. It is also interesting to note that the workability decreases more sharply when the XLPE replacement ratio exceeds 15%, as the amount of XLPE particles becomes significant.

The compressive strength of XLPE-Concrete at the age of 28 days varies with the content of XLPE shreds as shown in Fig. 3(a). The average compressive strength of the control mix (M00) is 35.4 MPa. It increases significantly to reach 39.25 MPa when the XLPE replacement ratio is set to 5% (M05). The compressive strength then decreases gradually to 32.3, 31.9 and 28.6 MPa as the XLPE replacement ratio is further increased to 10% (M10), 15% (M15) and 20% (M20), respectively. The compressive strength increases by +11% for M05 and decreases by up to -19% for M20, as compared to the control mix. Again, a sharper drop is observed when the XLPE content exceeds 15%.

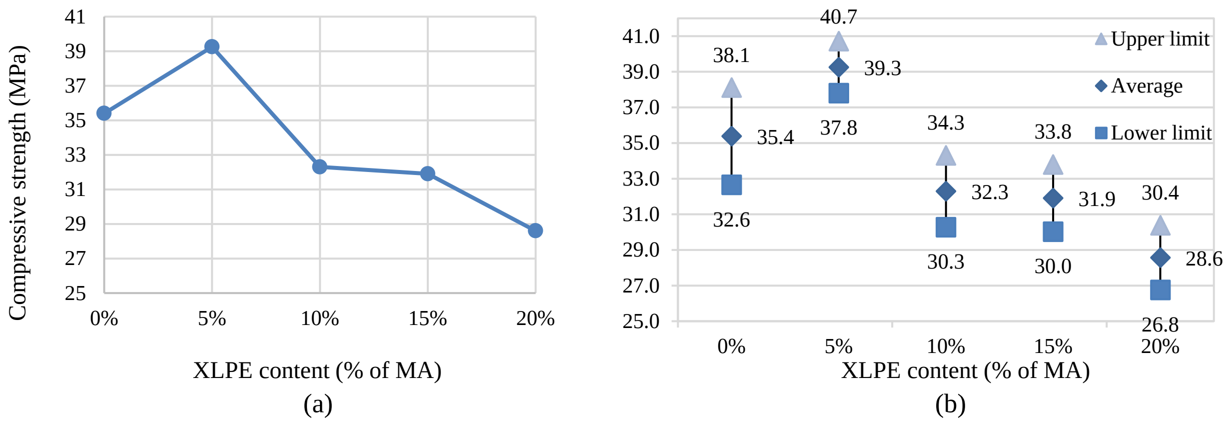


FIGURE 3. (a) Average compressive strength (b) 90% confidence intervals on the average compressive strength (at 28 days)

It is possible that, for sufficiently small proportions of XLPE replacement (5% of MA), the significantly lower stiffness of the XLPE shreds – as compared to that of the natural aggregates – contributes to a more even distribution of stresses within the concrete volume ultimately resulting in a larger compressive strength. This positive influence of XLPE compliance would however be outdone by the competing effect of the weaker bonds between the cement paste and the smoother surfaces of the shreds when the later are present in larger proportions (10% of MA or more). Indeed, reduced adhesion between particles and cement paste results in a weaker transition zone and thus in a lower concrete strength. In addition to this surface effect, the XLPE shreds have zero absorption capacity, which results in a higher local w/c ratio on the particle's surface, further weakening the transition zone and thus the concrete strength. It must nevertheless be noted that the compressive strength of all the mixes is larger than 28.5 MPa, which is significantly above the minimum requirements of ACI318M-14 for structural concrete. The 90% confidence intervals on the compressive strengths shown in Fig. 3(b) are tight around the average values. This reveals a satisfactory level of consistency and repeatability in the experimental results. It is important to note that, while testing the cylinders for compressive strength, a more ductile type of fracture was noted for larger XLPE contents. This might be due to brittle failure prevention by the XLPE bridging of cracks.

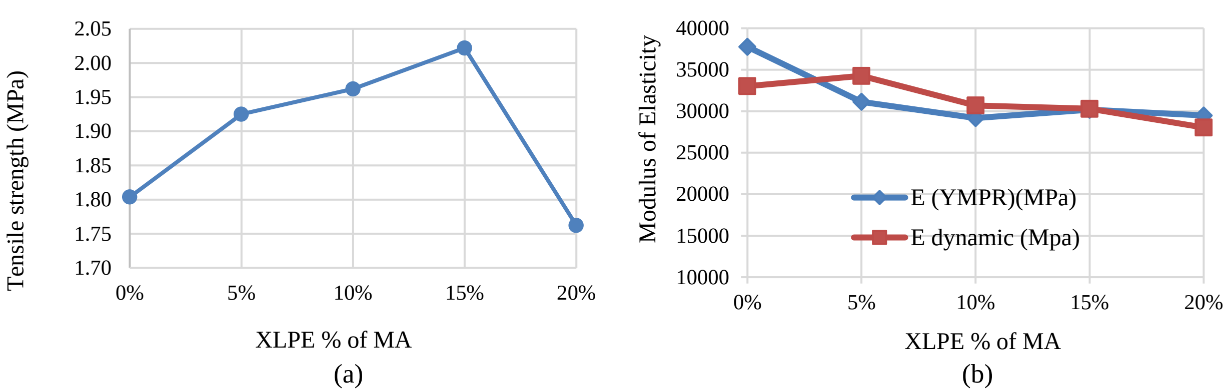


FIGURE 4. (a) Average tensile strength (b) modulus of elasticity of XLPE-Concrete

The average tensile strengths are plotted in Fig. 4(a). The gradual increase in tensile strength between 0% and 15% of XLPE content can be attributed to the XLPE shreds acting as fibers and bridging tensile cracks in the concrete.

However, larger proportions of XLPE particles (20%) tend to have a net weakening influence on the concrete's tensile strength by creating a connected network of preferential cracking surfaces across the interfaces between the concrete paste and the smooth XLPE shreds. This comes in addition to the well-known segregation effect that is due to large proportions of flat and elongated shapes in the concrete mix.

The static (secant) modulus of elasticity determined according the procedure described in ASTM C 469 and the dynamic Young modulus determined by testing of the pulse ultrasound velocity according to ASTM C 597 are shown in Fig. 4(b). Concrete stiffness appears to follow a globally decreasing trend as the percentage of XLPE replacement increases. The changes in stiffness observed can be explained by the larger compliance of the XLPE shreds as compared to the natural aggregates to which these are substituted.

CONCLUSION

In this study, XLPE waste materials were incorporated into concrete. The medium sized natural aggregates were replaced by XLPE shreds in proportions of 5 %, 10%, 15% and 20%. The mechanical and physical properties of concrete were investigated. The amount of superplasticizer needed to maintain the same level of workability increased with the XLPE content, while the unit weight decreased. The compressive strength increased by up to 11% as compared to the control mix with a 5% XLPE replacement ratio; it then decreased by up to 19% for a 20% XLPE replacement ratio. This said, the compressive strength of all the mixes remained significantly larger than the minimum value required for structural concrete. The tensile strength increased gradually by up to 10% as the XLPE content reached 15%; it then dropped sharply for an XLPE replacement ratio of 20%. As the XLPE content was increased, the elastic moduli had a globally decreasing trend. Incorporating XLPE waste into concrete reduces simultaneously: (i) the amount of natural aggregates extracted and (ii) that of landfilled materials. Further studies are needed to determine the behavior of XLPE-Concrete with respect to aging and its resistance to fire.

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