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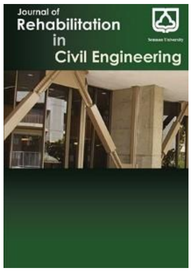

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Impact Resistance of Concrete Containing LLDPE–Waste Tire Rubber and Silica Fume

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ABSTRACT

Some of the desirable properties of concrete include high impact resistance and great energy-sucking capacity to name a few. These properties can be improved through the use of sustainable materials. This study investigated the effects of partly replacing fine aggregate with linear low-density polyethylene (LLDPE) and waste rubber (WR) as fine aggregates on the efficiency of concrete under impact loading. Two water to binder ratio (W/B) percentages of (0.40 and 0.55) were selected, with six (LLDPE-R) replacement grades (0%, 5%, 10%, 15%, 20%, and 30%) and two silica fume (SF) replacement grades (0% and 15%). Six cylinders with 150 and 60 mm were subjected to an impact by a 4.45 kg hammer striking. Test results indicated that impact resistance for the first visible crack and the ultimate failure increased with LLDPE-R content, where it increased by 4.76 times. This study also demonstrated that the impact resistance for the first visible crack of LLDPE-R concrete was improved by an average of 295% for specimens without SF and 292% for specimens containing SF. This enhancement for the ultimate failure is 291% and 290% for specimens without SF and containing SF, respectively.

1. Introduction

Concrete is a material that exhibits brittleness despite having high rigidity. Moreover, the brittleness degree increases with concrete strength. In addition, high impact strength and great energy-sucking are crucial requirements for many applications of concrete, such as shock absorbers, railway buffers, and the foundation pads of machinery. When these requirements are not met under certain conditions, additional ingredients must be included in the concrete mixture to improve its properties. As a result, numerous studies have evaluated the impact strength and energy-sucking of concrete. For

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example, rubberized concrete exhibits desirable mechanical properties, and the use of waste rubber (WR) in concrete is regarded as one of the best and most cost-effective ways to recycle used tyres [1]. Also, some researchers have investigated the properties of concrete including different kinds of plastic wastes such as polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), and polyvinyl alcohol (PVA) fibres [2]. Furthermore, the addition of WR to concrete mixes can improve the ductility of concrete. Another advantage of such rubberized concrete is being an environmentally-friendly concrete type that is produced by simply adding a rubber admixture to an ordinary concrete matrix. Therefore, it does not only solve the problem of WR disposal effectively but also improve concrete properties, such as its resistance to shock [3–5]. Most related studies have reported that rubber aggregates evidently improve the ductility and hardness of concrete and reduce its brittleness [6–10]. Thus, the use of tyre WR as fine aggregates is considered an economical and sustainable alternate for the fine aggregate. The application of natural materials in concrete production is currently an important issue in the field of construction. Therefore, developments in concrete technology can reduce the consumption of energy and natural resources, and then it can decrease the burden of exerted pollutants on the environment [11]. Also, using new materials in buildings to provide higher flexible behavior will enhance earthquake resistance [12,13]. In addition, rubberized concrete exhibits little modulus of elasticity [14–16], high ductility degree, and high sucking of impact energy (IE) [17]. Accordingly, many researchers have used rubber particles as concrete aggregates to address the problems of poor deformation capacity,low tensile strength, and the increase of energy-sucking capacity [18]. The results of previous studies have shown that the use of WR as a fine aggregate improves deformation and energy-sucking capacities but decreases workability and mechanical properties which indicates contradictory results [19–21]. However, data regarding the effects of using rubber particle aggregates on impact strength and durability properties are lacking. In references [22,23] the durability properties of rubberized concrete and mortar were investigated, and a volume of 10% rubber aggregates was determined as the optimum amount for producing economical and sufficiently durable rubberized concrete. Additionally, Silica fume (SF) and fly ash are pozzolanic materials, which can function as complementary cementitious [24]. Previous studies have shown that using SF and super-plasticizer (SP) can increase concrete strength [25,26]. Impact tests are generally used to find the ratio of impact strength and brittleness of concrete and analogous construction materials [26,27]. However, these tests are not considered standard partially owing to the absence of statistical data regarding the variation in results. To address this issue, the American Concrete Institute (ACI) Committee 544 [28] presented a drop load impact test for evaluating the impact strength for fiber concrete. This test is extensively used because it is straightforward and low-cost. However, the results of this test are quite frequently scattered. Hence, the present study focuses on providing insights into the effects of using LLDPE-R as a partial replacement for sand on the mechanical properties and impact strength of concrete.

2. Linear low density polyethylene (LLDPE)

The advantages of LLDPE have encouraged the market to utilize LLDPE-richer blends in applications like high-performance bags, cushioning films, tire separator films, industrial liners, elastic films, ice bags, and bags for supplemental packaging. The linear low-density polyethylene (LLDPE) is more commonly used than the low-density polyethylene (LDPE) due to its higher tensile strength and superior impact puncture resistance, even though the densities of LDPE and LLDPE (0.921–0.926 g/cc) are similar. This has enabled converters to produce thinner films without consuming strength, in addition to saving material, and reducing costs. "LLDPE's good toughness compared to other products has also provided new application field" [29,30].

3. Materials

In this study, the ordinary Portland cement having a specific gravity (SG) of 3.14 and SF with an SG of 2.2 were used in the concrete mixtures. Local natural sand with an SG of 2.65, a fineness modulus of 2.7, and water absorption of 1% was used for fine aggregates. Meanwhile, natural gravel with a maximum aggregate size of 12 mm and an SG of 2.65 was used as coarse aggregates (see figures 1 and 2). To obtain the desired slump flow of mixes, a PolyCarboxylate-based high-range water-reducing admixture like ASTM International C494 Type F was added [31]. LLDP-R with a maximum size of 2.36 mm, an SG of 0.95, and slight water absorption (see figure 3) were used in this work. Where LLDPE-R was a mixture of 50% LLDPE and 50% rubber (see figure 4). Two W/B ratios (0.40 and 0.55) were selected, with six LLDPE-R replacement grades (0%, 5%, 10%, 15%, 20%, and 30%) and two SF replacement grades (0% and 15%) used, as listed in Table 1. In this Table, the numbers after the name of specimens indicate the amount of LLPDE and the F letter is used for specimens containing SF. PRC0 is the control mixture without any SF or LLDPE. However, FPRC5 and PRC5 are concrete mixtures with 5 percent of LLDPE with and without SF, respectively. A drop load test was performed according to ACI Committee 544 [28]. Six cylinders with a height of 150 mm and a diameter of 60 mm were subjected to an impact loading using a 4.47 kg hammer from a 445 mm height in each case. The sum of required strikes to produce the first crack and the ultimate failure of the sample were recorded [30].

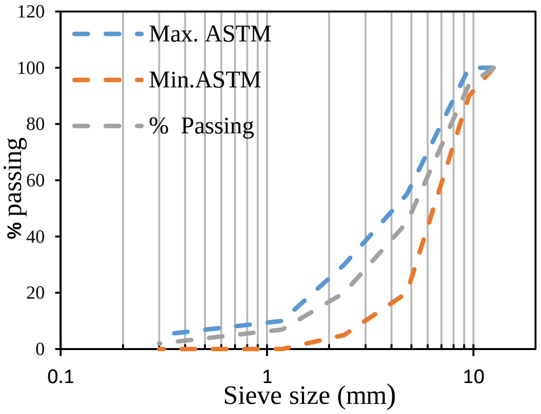

Fig. 1. Sieve analysis test results of fine aggregate.

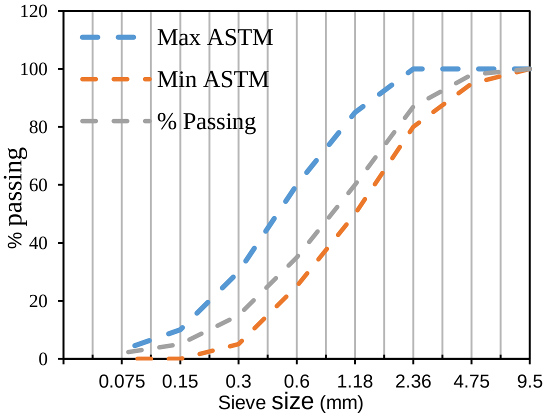

Fig. 2. Sieve analysis test results of coarse aggregate.

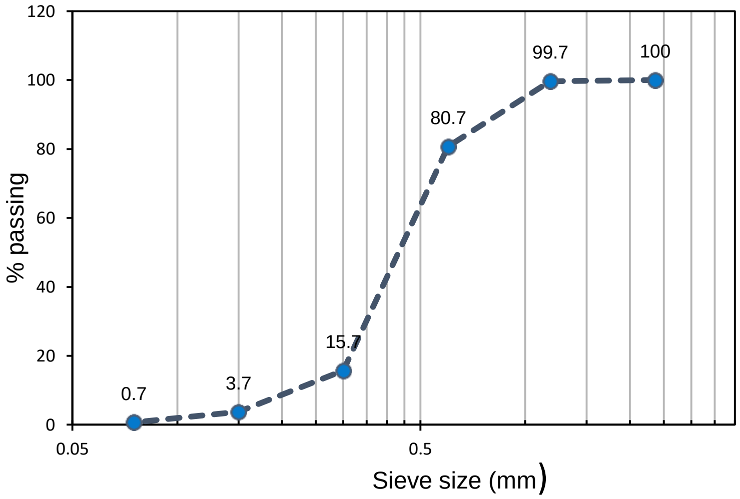

Fig. 3. Sieve analysis test results of LLDPE-R.

(a) (b) (c) (d)

Fig. 4. Materials: (a),(b) LLDPE, (c) silica fume, and (d) waste rubber.

Table 1. The constituents values of all mixes.

Type of mix	Cement (kg/m³)	SF (kg/m³)	Coarse (kg/m³)	Sand (kg/m³)	Rubber (kg/m³)	LLDPE (kg/m³)	LLDPE-R (kg/m³)	Water (kg/m³)	SP (%)
PRC0	400	0	735	925	0	0	0	220	0
PRC5	400	0	735	867.6	20	20	20	220	0
PRC10	400	0	735	810.2	40	40	40	220	0
PRC15	400	0	735	752.8	60	60	60	220	0
PRC20	400	0	735	695.4	80	80	80	220	0
PRC30	400	0	735	580.6	120	120	120	220	0
FPRC0	340	60	755	960	0	0	0	160	1.5
FPRC5	340	60	755	902.6	20	20	20	160	1.5
FPRC10	340	60	755	845.2	40	40	40	160	1.5
FPRC15	340	60	755	787.8	60	60	60	160	1.5
FPRC20	340	60	755	730.4	80	80	80	160	1.5
FPRC30	340	60	755	615.6	120	120	120	160	1.5

4. Preparation of samples

Three cubes measuring (100 × 100 × 100) mm were prepared from each mix and tested under static compression. Three cylinders with a dimension of 100 mm and 200 mm respectively, were prepared and subjected to an indirect tensile test to investigate the size effect. Meanwhile, three beams with height, width, and length of 100,100, and 500 mm, respectively, were prepared for the flexural performance test. In addition, six discs with a dimension of 150 mm and 60 mm were cast for testing under impact compression following the repeated drop load impact test of ACI Committee 544 [28]. Steel molds were used to cast the concrete specimens, and all the specimens were opened after 24 hours and then cured in a water tank for 28 days.

5. Drop load impact test

Among all types of impact tests, the repeated drop load impact test is probably the simplest test, and thus, it is widely used for quantifying impact strength. This test provides the sum of strikes required to produce the prescribed grade of damage in a test specimen. The sum of strikes is recorded and used to estimate the specimen's energy absorption at the specified distress grades. The repeated drop load impact test can easily establish the relative impact strength of various materials. The equipment used for ACI's drop weight impact test includes the following components: (1) a standard, manually operated 4.47 kg compaction hammer with a 445 mm drop height; (2) a hardened steel ball with a diameter of 63.5 mm; and (3) a flat baseplate with a positioning bracket (see figures 5 and 6). A mold for casting concrete specimens with a diameter of 152 mm by a depth of 63.5 mm [±3 mm] is also required. This process can be accomplished in accordance with the ASTM International C31 or C470 mold standard [32,33]. Specimens are made using cylinder molds with a diameter of 152 mm following the recommended procedures for compressive cylinders. These molds can be filled partially up to a depth of 63.5 mm and then the surface was finished. Specimens may also be sawed from full-sized cylinders to obtain samples with appropriate thickness. Specimens must be tested at ages 7 days and 28 days, as recommended by the ACI Committee 544 [28]. Table 2 provides the results of conducted experiments on specimens.

Fig. 5. Impact test machine.

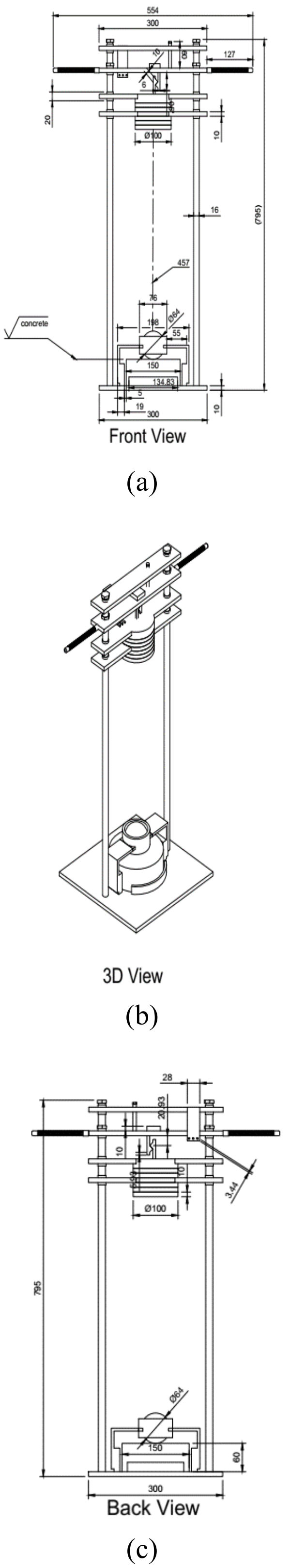

Fig. 6. Impact test machine diagrams:(a) front view, (b) 3D view, (c) back view.

6. Testing method

The test was performed repeatedly by raising a 4.45 kg steel ball to a height of 445 mm and then allowing it to fall freely on top of a specimen. The sum of strikes required to develop the first crack (N1) was recorded. Subsequently, ultimate crack strength was obtained via recording the sum of strikes that eventually resulted in failure (N2). IE was generally calculated in accordance with ACI Committee 544 [28], as follows:

$$IE = Nmgh, \quad (1)$$

Where:

N = number of blows at the crack level,

m = mass of the dropped hammer (4.45 kg),

g = gravity due to acceleration (9.81 m/s2), and, h = drop height (4.57 m).

$Joule = kg \times m \times m/s^2 = kg \times m^2/s^2$(IE unit)

The positioning bracket was fixed to hold the specimen in place, and then the hardened steel ball was set over the top of the specimen within the bracket. Subsequently, the drop hammer was positioned with its base on the steel ball and held in place with sufficient pressure to prevent bouncing away from the ball during the test. The base plate was fixed to a solid base (a cast concrete block). Then, the hammer was dropped repeatedly, and the sum of strikes necessary to produce the first visible crack on the upper part of the sample (N1) and those which resulted in the ultimate failure of the sample (N2) were recorded. N2 is described as the adequate opening of cracks inside a specimen, such that concrete pieces are in contact with three of the four positioning lugs on the base plate.

Table 2. Results of the mechanical properties of the tested mixtures.

Type of mix	Slump (mm)	Compressivestrength (MPa)	Split tensile strength (MPa)	Flexuralstrength (MPa)	Unitweight (kg/m³)
PRC0	160	42±1.5	3.8	6.9	2280
PRC5	170	38±0.8	3.5	5.6	2242.6
PRC10	140	34±1.7	3.23	5.3	2205.2
PRC15	130	29±0.6	2.8	4.4	2167.8
PRC20	150	20±0.5	2.1	3.73	2130.4
PRC30	160	17±0.34	1.6	3.12	2055.6
FPRC0	100	78±2.7	6.47	11.5	2280
FPRC5	95	69±0.9	5.7	10.6	2248.6
FPRC10	105	55±1.1	4.95	8.32	2211.2
FPRC15	85	46±0.9	4.7	6.82	2173.8
FPRC20	100	32.5±0.45	3.35	5.18	2136.4
FPRC30	100	27±0.3	2.65	3.9	2061.6

7. Results and discussion

The compressive strength was determined by testing three specimens for each type of mixture. Figure 7 shows the compressive strength of concrete with LLDPE-R for the w/b ratios of 0.55 and 0.4 at 28 days. Compressive strength decreased as the LLDPE-R replacement grade increased for both ratios. The compressive strength of the control concrete (i.e., without LLDPE-R) increased from 42 MPa to 78 MPa for 0.55 and 0.4 W/B ratios, respectively. Figure 7 also shows that the compressive strength of the control concrete and LLDPE-R concrete increased by replacing the grade of cement with SF. This can be attributed to the pozzolanic action as well as the filling effect of admixture resulting in a denser concrete. The compressive strength of the control concrete increased by 85.7% when 15% of the cement was replaced with SF. On the other side, the compressive strength of LLDPE-R concrete increased by 81.6%, 61.7%, 58.6%, 62.5%, and 58.8% when fine aggregates were replaced with 5%, 10%, 15%, 20%, and 30% of LLDPE-R with 15% of SF, respectively. Moreover, LLDPE-R concrete with SF exhibited higher compressive strength than LLDPE-R concrete without SF because SF enhanced bond strength between LLDPE-R particles and cement paste. In addition, an increase in the amount of water in the concrete mixture which is resulting in a higher amount of void in the mixture causes a reduction in the compressive strength of specimens. Moreover, the splitting tensile strength test was performed in accordance with ASTM International C496 [34]. The test found that the indirect strength of LLDPE-R concrete increased with increasing SF content. On average, the result of the split tensile test was 10.6% relative to the compressive strength of all the mixes. Moreover, the splitting tensile strength exhibited a considerable decrease with increasing LLDPE-R content, as shown in Figures 8 and 9.

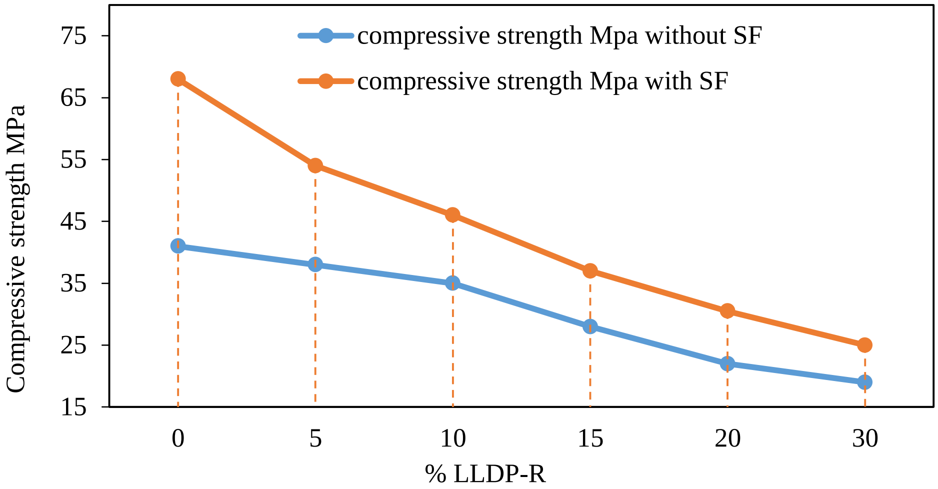

Fig. 7. Compressive strength of LLDPE-R concrete for specimens containing SF and without SF.

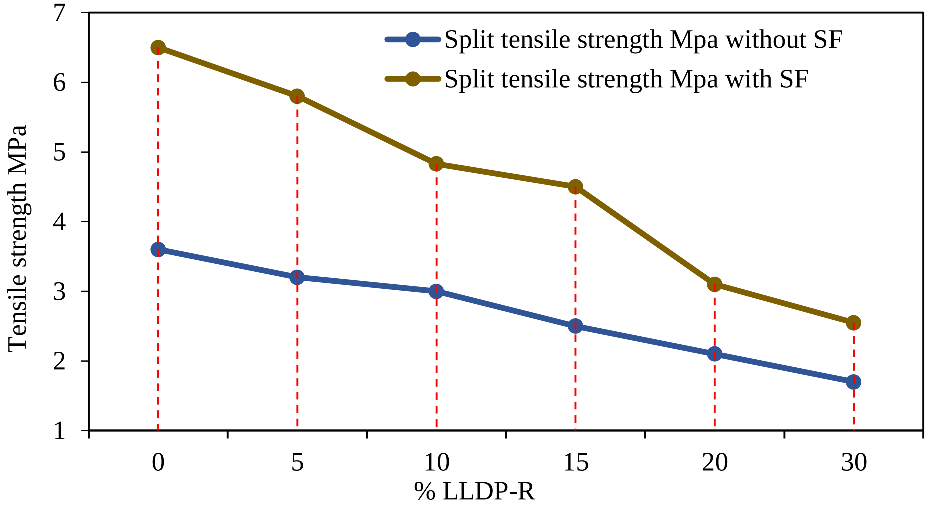

Fig. 8. Tensile strength of LLDPE-R concrete for specimens containing SF and without SF.

Fig. 9. Preparing and testing concrete specimens.

Meanwhile, the flexural strength under flexural loading of LLDPE-R concrete with and without SF is shown in Figure 10. The flexural strength of (100 × 100 × 500) mm prismatic specimens showed a decrease with increasing LLDPE-R content. Moreover, flexural strength was significantly improved by incorporating SF in specimens containing LLDPE-R. This may be attributed to the fact that silica fume enhances the strength of the interfacial transition zone (ITZ) in concrete. Compared with those of normal concrete mixes, the decrease in unit load of concrete with LLDPE-R mixes was not significant. Concrete weight was reduced to 11% when 30% LLDPE-R was added to the concrete mix as shown in Figure 11. However, such weight loss is unsuitable because of the additional costs to the price per cubic meter of concrete.

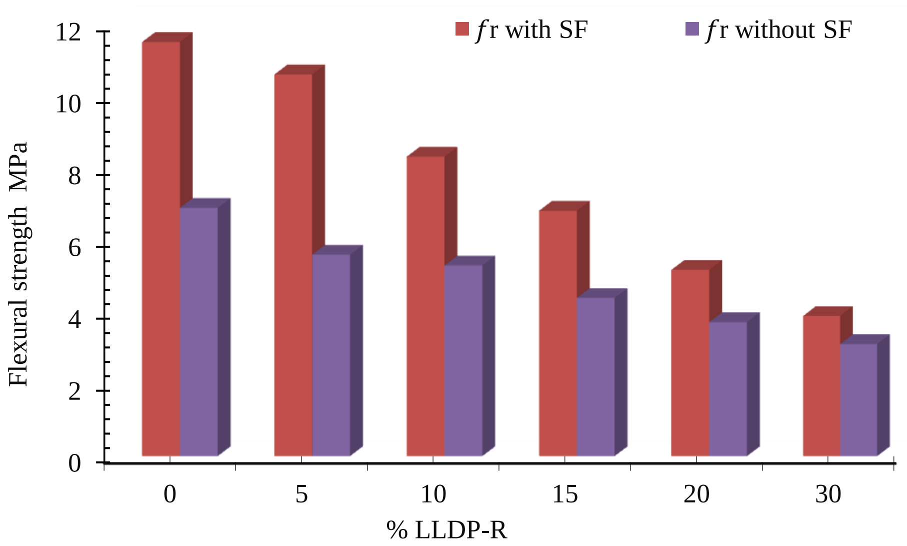

Fig. 10. Flexural strength of LLDPE-R concrete.

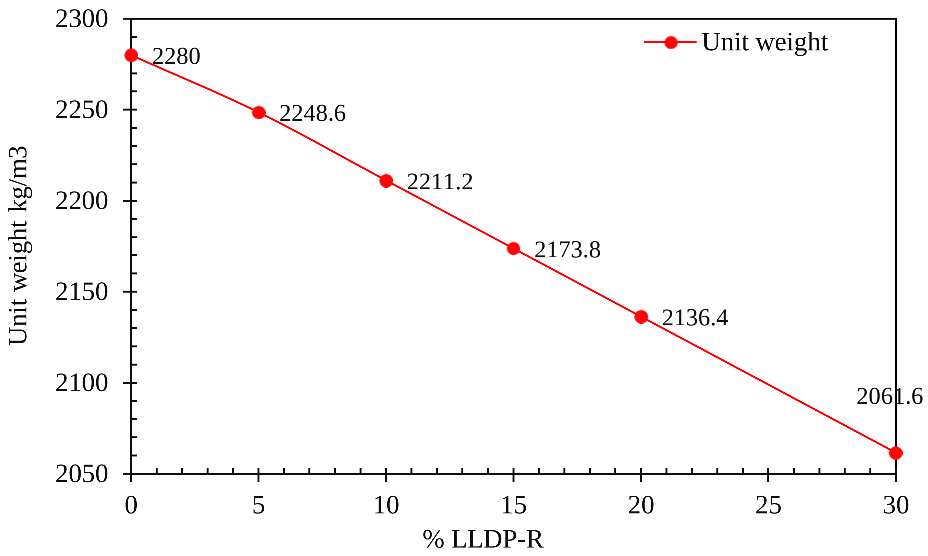

Fig. 11. Unit weight of LLDPE-R concrete.

Among different types of impact tests, the simplest is probably the repeated drop load impact test. This test is used to determine the sum of strikes required to induce the prescribed distress grades on a test specimen. This sum provides a qualitative estimation of the specimen's energy absorption at the specified distress grades. Moreover, this test can compare the relative advantages of various LLDPE-R concrete mixes, establishing the improved performance of LLDPE-R concrete compared with conventional concrete. The impact strength of LLDPE-R–SF concrete for two different W/B ratios (0.4 and 0.55) was recorded by considering the sum of strikes required to produce the first visible crack (N1) and the ultimate failure (N2) of a specimen. Figure 12 shows the quality of cracking in concrete specimens under falling weight impact load. How the LLDPE-R particles are dispersed inside the concrete is shown in Figure 13.

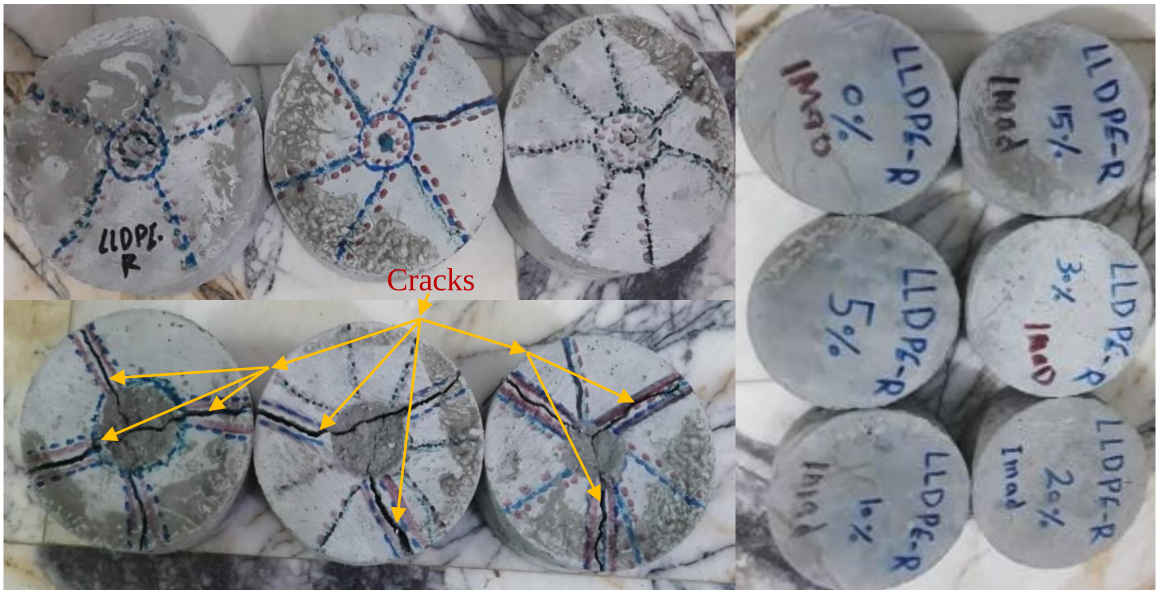

Fig. 12. Impact test of concrete using drop-weight.

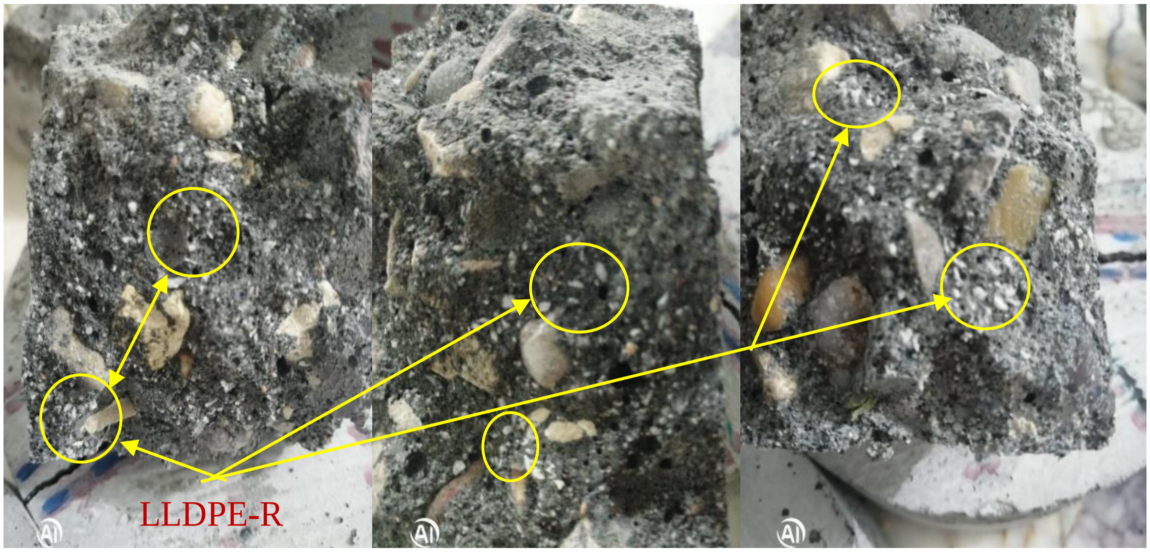

Fig. 13. LLDPE-R particles in concrete.

The average sum of strikes for the two selected W/B ratios of different mixes is presented in Figure 14 and Table 3. The sum of strikes required to produce the first crack and the ultimate failure increased remarkably with LLDPE-R content replacement grade for both W/B ratios. In addition, the difference of the sum of strikes required to reach the ultimate failure and the first crack, i.e., N2-N1, also increased considerably with LLDPE-R replacement grade for both W/B ratios. The difference was nearly double between the control concrete and the specimen with 30% LLDPE-R replacement for both W/B ratios. The aggregate particles were not displaced throughout the fractured surface and no visible cracks were observed in separated parts. Such findings may be attributed to the strong bond between the mortar and the aggregates.

Table 3. Impact resistance results of LLDPE-R concrete.

Type of mix	**First crack N1**	**Final crack N2**	**IE**		**Ductility index N2/N1**
			N1	N2	
PRC0	68	79	1357	1576	1.16
PRC5	96	110	1915	2195	1.15
PRC10	124	143	2474	2853	1.15
PRC15	196	226	3910	4509	1.15
PRC20	264	297	5267	5925	1.13
PRC30	324	376	6464	7501	1.16
PRC0	78	89	1556	1776	1.14
PRC5	108	121	2155	2414	1.12
PRC10	149	172	2973	3432	1.15
PRC15	229	258	4569	5147	1.13
PRC20	293	328	5845	6544	1.12
PRC30	361	415	7202	8279	1.15

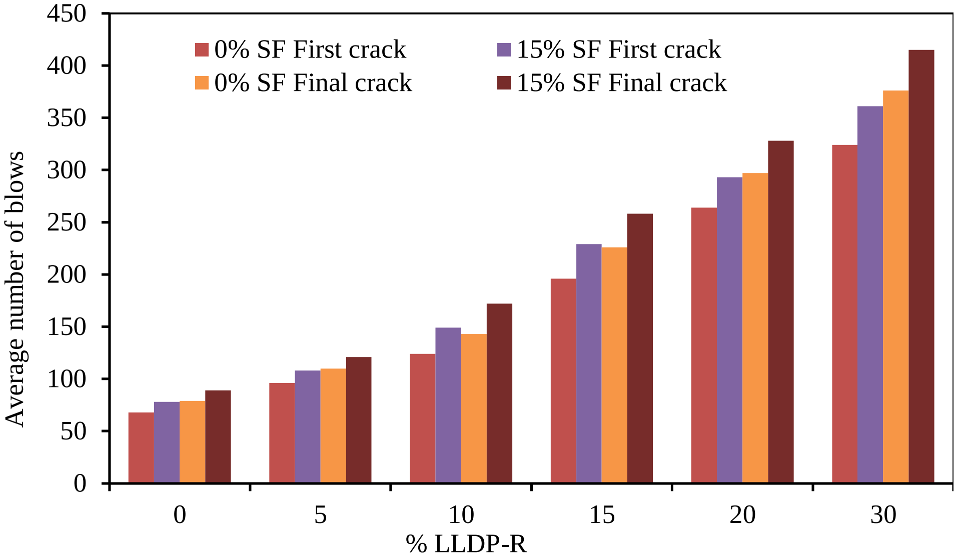

Fig. 14. Numbers of blows for the initial and final cracks.

Accordingly, the crack path was not around the surface of the particles, but instead, across the aggregate particles which was favorable. Particle bridging did not occur in the case of LLDPE-R concrete due to the small amount of LLDPE-R. However, it may occur in cases in which a large amount of LLDPE-R is used. Evidently, a wide discrepancy was observed in the results of all the LLDPE-R replacement ratios. Replacing fine with LLDPE-R increased concrete strength to crack initiation under an impact compression load. The ACI impact test can differentiate among the concrete specimens with varying LLDPE-R contents. Figure 14 and Table 3 respectively show the sum of strikes required until failure occurred for 12 LLDPE-R concrete specimens with and without 15% SF addition. SF addition clearly affected concrete strength to withstand crack initiation under impact compression load. In general, the addition of LLDPE-R to concrete significantly increased the sum of required strikes. The ultimate impact strength exhibited the same trend as that of the first crack. When the data was sorted, a higher LLDPE-R content resulted in a higher ability to resist more strikes, and consequently, a higher tendency to absorb energy, as illustrated in Figure 15. The capability of LLDPE-R aggregates in absorbing the energy of impacts without crushing during the imposing of the impact loads is the main reason for resisting the higher numbers of impacts in specimens containing LLDPE-R. Notably, the control mixture exhibited a narrow range of diversion. Consequently, the probability that a specimen would crack with N1 and N2 having a relatively low sum of strikes was higher than those for all the specimens produced from LLDPE-R mixes. In addition, LLDPE-R concrete particles were widely distributed, presenting a broad range of strikes.

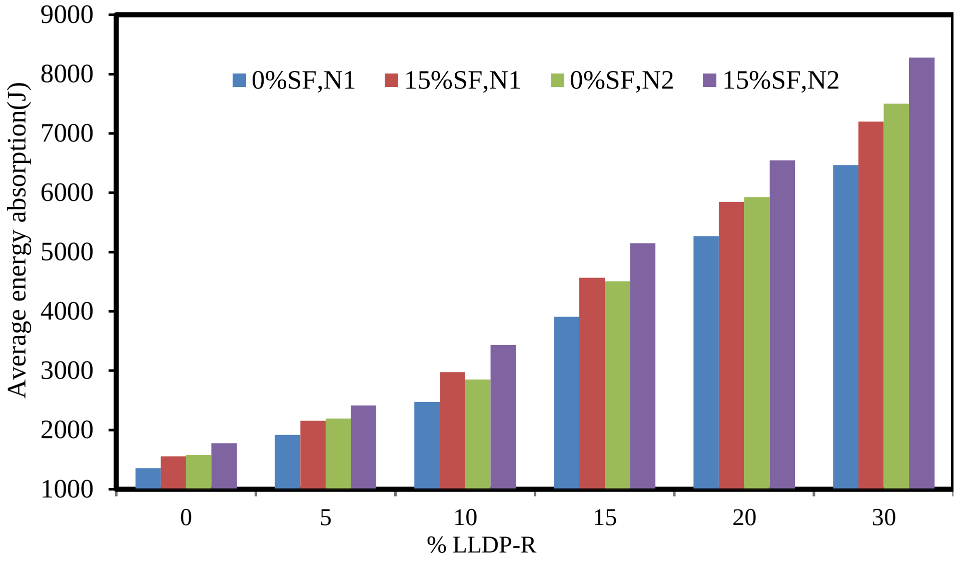

Fig. 15. Energy absorption for the initial and final cracks.

The variation in obtaining the impact strength of concrete is attributed to the ACI test being based on a single point of impact. Such a point may be located on a hard particle of the coarse aggregates or a soft area of the mortar. The preceding graphs also indicate that among all the examined specimens, PRC30 achieved the best distribution. The peak of both curves was observed at 30% LLDPE-R replacement grade. Furthermore, PRC30 required approximately 4.7 times more sum of strikes than PRC0. Therefore, a conclusion can also be drawn that a higher amount of LLDPE-R used to replace sand, i.e., 30%, can considerably affect interlocking between aggregates, improving impact strength but at the expense of losing mechanical properties.

8. Conclusions

The following conclusions were derived from discussion and test results:

- LLDPE-R could be used as a partial replacement of natural fine aggregate with a percentage that could be raised to 30%.
- Increasing LLDPE-R as a fine aggregate from 15% to 30% decreased slump values in the concrete mix.
- Using LLDPE-R in the concrete reduced the density when compared to conventional concrete which led to producing light-weight concrete.
- Compressive resistance decreased with the increase in LLDPE-R content.
- Compressive resistance of LLDPE-R concrete with SF improved by about 60% as compared to the control mix.
- Splitting tensile strength and flexural strength of concrete decreased as the LLDPE-R fine aggregate content increased in the mixture.
- Impact strength and energy-sucking capacity were increased with increasing the percentage of LLDPE-R.
- The difference between the recorded sum of strikes required for ultimate failure and first crack initiation increased significantly with LLDPE-R replacement grade, indicating an increase in the ductility of LLDPE-R concrete.
- Silica fume as a complementary component played a fundamental role in increasing the strength in light

weight concrete and improving its other desirable properties, where, it reduced the porosity and permeability and increased the durability and strength of concrete. The addition of silica fume to concrete reduced its workability. Using an appropriate amount of superplasticizer improved the workability and increased the uniformity of concrete texture.

- PRC30 on PRC0 outperformed the control samples in resisting repeated impact loading for the complete fracture by 4.8 times.
- The physical properties of LLDPE-R affected the impact of resistance. The highest impact resistance was observed for concrete with 15% SF and 30% LLDPE-R as fine aggregates.
- LLDPE-R as fine aggregate in concrete could be successful in its use for concrete application if LLDPE-R content is limited to a range of between 5-20% for structures that are exposed to impact load in order to mitigate, minimize and dampen its effect on the structure. Therefore, its use is recommended for the construction of industrial floors to reduce damages due to the impact load from a sudden drop of heavy machines or equipment.

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