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The impact resistance of Fiber-Reinforced concrete with polypropylene fibers and GFRP wrapping

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ABSTRACT

Developments in polymer technology have introduced new choices such as using fibers and fiber-reinforced polymers (FRP) to improve the impact behavior of concrete structures. In this research, 52 concrete samples (half of which wrapped with glass fiber-reinforced polymers-GFRP) with different compressive strengths (20, 30, and 40 MPa) and polypropylene fibers were constructed. These samples were subjected to weight dropping (46.7 kg and 66.8 kg). The number of weight droppings related to 30% weight loss was recorded. Results indicated that the impact resistance of the concrete samples, corresponding to the number of weight droppings, increased using higher-strength concrete, higher polypropylene ratios, or GFRP wrapping, separately and in application with each other. However, the effects of GFRP wrapping on the improvement of the impact resistance much higher than those of the polypropylene fibers or concrete strength.

1. Introduction

During the last 80 years, building construction has been dominated by the use of concrete materials [1]. Despite the clear advantages and necessity of concrete as a building material, its production and use cannot be considered environmentally friendly. This is mainly for a huge amount of cement consumption and its production process which lead to vast CO_2 emissions [2,28,30]. Hence, to be in line with global and local climate strategy, the material consumption of reinforced concrete (RC) structures must be reduced while their strength, ductility, and impact resistance are maintained under extreme conditions as well as normal conditions [3]. One of the most visible consequences of global warming is an increase in the intensity and frequency of extreme weather events. Such extreme events must be considered in newly built structures. Extreme conditions and their effects can cause substantial damage on both material [4,5]- and structural-level [7] resulting in the worst case, for example, in structural collapse causing civilian casualties [8,29]. Although the serious consequences of impact effects are known, there are still many open questions in the calculation of the resistance of concrete structures against impact loads: standards such as Eurocode 2 for the design of concrete structures mainly discuss the load side in detail [8], but not the resistance side. Recent technological proceedings facilitated the production of high-strength materials (HSMs), which led to decreases in the dimension of structural elements, consuming much fewer materials and time to build RC structures [9–12,27,28]. On the other hand, using HSMs can have repercussions e.g., a possible reduction in ductility and energy absorption of RC structures [11,12]. Moreover, cracking is known as a major source of nonlinearity in RC structures which must be restricted. To overcome these setbacks, fiber-reinforced concrete (FRC) was introduced by researchers. FRC is a type of concrete that has short fiber strands uniformly distributed in every direction. Various types of fibers such as steel, glass, natural and synthetic fibers which have been used in the construction industry. Natural fibers are made by plants and geological processes. They have several benefits, e.g., lower density, better thermal insulation, and being broken down by bacteria in the case of not use. As for synthetic fibers, they are different types such as polyethylene (PE), polyvinyl alcohol (PVA), polyethylene terephthalate (PET), and polypropylene (PP) [13]. PP is one of the important polymeric fibers which enhances concrete mix cohesion, pumpability over long distances, freeze–thaw resistance, resistance to spalling in case of a fire,

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impact resistance, abrasion resistance, structural strength, and ductility. However, the efficacy of polypropylene fibers rely on several parameters such as fiber length, fiber diameter, fiber amount, etc.

Fiber-reinforced polymer (FRP) application is a newly suggested retrofitting approach in RC buildings. FRP can be used as sheets, laminates, and bars in structures. However, the application of FRP as sheets is more popular to retrofit existing structures than the other shapes of FRP. It must be added that FRP is a composite substance built by a polymer matrix reinforced with fibers. The procedure of FRP production has two different phases: a) productions of the fibrous materials, and b) bonding the fibrous materials with the matrix. FRP can have different shapes as laminates, tubes, rods, etc. The fibers could be glass in glass-fiber-reinforced polymers (GFRP), carbon in carbon fiber-reinforced polymers (CFRP), aramid in aramid fiber-reinforced polymers (AFRP), or basalt. Besides, the polymer can be an epoxy, vinyl ester, or polyester thermosetting plastic. FRP could increase the stiffness, strength, energy absorption, and ductility of RC elements subjected to static loading [14]. The retrofitting performance of FRP depend on different parameters such as: fiber types, thickness of FRP, being uni- or multi-directional, etc. The retrofitting performance of FRP can be evaluated by experimental and analytical methods (such as incremental dynamic analysis, endurance time method, time-history analysis, etc.) [15,16].

Structures can be subjected to projectile penetration due to several incidents such as hurricanes, tsunamis, vehicle collisions, etc. As such, it is essential to research strategies to improve the impact resistance of RC structures. During recent years, researchers have mostly studied the responses of RC members with fibers and FRP under static loading [14]. However, few studies have been focused on the dynamic responses (especially under blast or impact events) of FRP-retrofitted elements or FRC ones. Chi et al. numerically studied the finite element modeling of FRC structures with polypropylene by modified concrete damage plasticity (MCDP) method [17]. They showed that MCDP could accurately model the behavior of FRC structures. The impact behavior of columns wrapped by both the GFRP and steel spiral rebars by a drop-hammer was experimentally studied by Huang et al. [18]. They showed that an increase in the thickness of GFRP improved the impact behavior of samples. Qin et al. analytically investigated the influence of the reinforcement ratio on the flexural performance of hybrid FRP beams using the finite element method [19]. They showed that a hybrid reinforcement system consisted of steel bars and FRP improved the ductility and strength of the beams. In another study, the impact resistance of polypropylene FRC samples using the Split Hopkinson Pressure Bar (SHPB) device was investigated by Zhang et al. [20]. They focused on the influences of fiber ratio, water to cement ratio (w/c), and strain rate. They showed that an increase in fibers ratios affected significantly the impact resistance of samples. Mahendra et al. experimentally investigated the flexural and shear behavior of CFRP and GFRP retrofitted beams [21]. They resulted that the CFRP retrofitted samples showed better shear and flexural behavior. The impact resistance of FRC slabs with coconut fibers and flax fiber-reinforced polymer was experimentally studied by Wang and Chouw [22]. They concluded that these samples had better performance in terms of energy absorption and keeping the integrity of concrete in comparison to plain concrete. The rehabilitation of RC beams by FRP was reviewed by Siddika et al. [23]. They showed that using externally bonded FRP wraps in RC beams had conspicuous in shear and torsion capacities. The dynamic response of RC slabs reinforced with steel and GFRP bars under impact loading was experimentally and numerically investigated by Sadraei et al. [24]. They demonstrated that an increase in the reinforcement ratio or the slab thickness improved the behavior of RC slabs under impact loading. Kheyroddin et al. (2020) studied the impact behavior of CFRP-confined samples with polypropylene [8]. They reported that CFRP confinement was a better strategy to enhance the impact resistance of the concrete samples than using polypropylene fibers. The influence of armor-perforating projectile on a bullet-resistant silicon-carbide-graphene composite through finite element analysis (FEA) was investigated by Guleria et al. (2021) [25]. They focused on the effect of Young's modulus of the material and thickness of the aimed plate on residual velocity of the projectile, and the effect of supplementing graphene to silicon carbide matrix to the infiltration of the projectile. Bagha and Bahl (2021) studied vapor grown carbon fibers (VGCF) reinforced in polypropylene (pp) matrix using reinforced square representative volume element (RVE) to predict its mechanical properties such as the storage modulus, loss modulus and strain energy for different loadings using FEA [26]. They reported that there was conspicuous improvement in longitudinal modulus of the VGCF/pp nanocomposite for supplement of small quantity of nanofiber.

As mentioned in the paragraphs above, RC structures may be exposed to impact loading during their lifetime. Then, it is essential to study the impact behavior of FRC wrapped with GFRP sheets and polypropylene fibers to find suitable strategies to improve the impact resistance of concrete members. This research studied the effects of polypropylene fibers and GFRP on the impact behavior of concrete samples. 52 concrete samples with different compressive strengths and with different fiber ratios were constructed and exposed to weight dropping. The observations demonstrated that the optimum fiber content ratio was 2%. Moreover, they indicated that the more appropriate strategy to improve the impact resistance of the concrete samples was using GFRP wrapping than using fibers with or without GFRP.

2. Experimental program

In this experimental campaign, 52 concrete samples with different compressive strengths (20, 30, and 40 MPa at 28 days) and with different fiber ratios (0%, 1%, 1.5%, and 2%) were constructed. Half of the concrete samples were wrapped by GFRP samples. Then, they were exposed to weight droppings until they lost 30% of their weight.

2.1. Materials

2.1.1. Glass fiber-reinforced polymers (GFRP)

Bidirectional GFRP sheets were circumferentially attached to 26 of the samples by means of epoxy resin. There was a difficulty in the tests of the cylinders due to their confinement. It was essential to decrease the confinement thickness and disperse the fibers in different directions. Fig. 1(a) and (b) demonstrate the GFRP sheets and wrapping process of GFRP. Table 1 shows the properties of the used GFRP.

2.1.2. Polypropylene fibers

In this research, polypropylene fibers with the ratios of 0%, 1%, 1.5%, and 2% were used. Polypropylene fibers (also known as polypropene) are thermoplastic polymers with several usages. Polypropylene is made of the monomer propylene employing the polymerization procedure. It must be added that polypropylene is linked to the category of polyolefins. The color of polypropylene is white and is the second-most widely used fiber in FRCs. Fig. 2 illustrates the used polypropylene fibers. Table 2 shows the properties of the polypropylene fibers used in the samples.

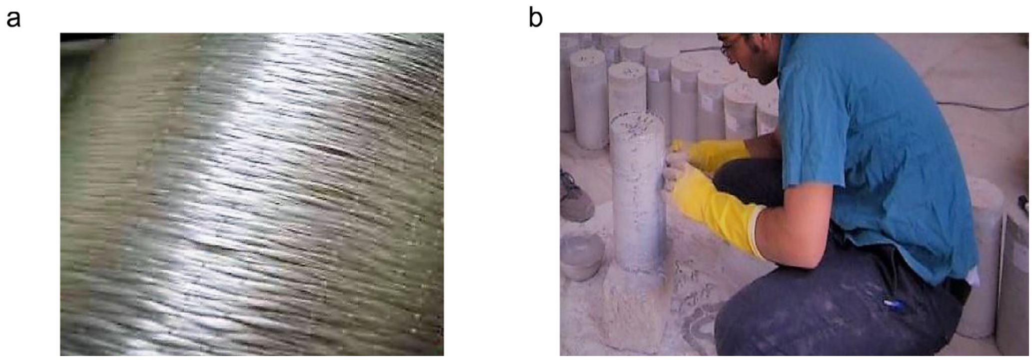

Fig. 1. (a) GFRP sheets, and (b) GFRP wrapping.

Table 1
Properties of the GFRP sheets.

Product name	Fiber types	Fiber strength (MPa)	Fiber stiffness (GPa)	Areal weight (g/m^2)	Fiber thickness (mm)	Style
Kor-GFW420	E-glass	2300	76	420	0.16	Woven UD

Fig. 2. Polypropylene fibers.

Table 2
Properties of the polypropylene fibers.

Fiber lengths (mm)	18
Tensile strength (MPa)	400
Elasticity module (Young's module) (GPa)	2.7
Melting temperature (^{0}C)	165
Percentage increase in length (%)	80
Colour	White

2.1.3. Sample characteristics

In this research, 52 samples were made of C20, C30, and C40 grade concrete. The concrete samples had cylindrical shapes with dimensions of 150 × 300 mm^2. The concrete was compacted by 25 impacts by means of steel rods to take out the air from the concrete in three separate layers. It must be added that the concrete had normal weight aggregates with a nominal maximum size of 10 mm. Additionally, the concrete was constructed by Portland cement type 2 with a water-cement ratio of 0.5. These concrete samples were symbolized by a specific rule in which the first letter (C) showing the concrete grade, the second word (PP) polypropylene, and the subsequent number shows its content ratio. The third word (GFRP) stands for the wrapping category.

2.1.4. Setup device

Fig. 3 shows the experimental setup. An impact-loading device (set on a strong floor) was employed to inflict impacts on the models. The weights were fixed on the top of the models (at a height of 1.6 m) by means of ropes that went through a spool connected to the mid-span of the upper beam of this device. The weights were square-shaped with the dimensions of 300 × 300 mm^2, and made of cast iron. The weights were set on the top of the models in a way that the centers of the weights and models coincide with each other employing laser plummet, and then the ropes were cut. After the concrete models were placed on the strong floor under the weights (46.7 kg and 66.8 kg). The weights were released by cutting the ropes on the concrete models. After colliding the weights

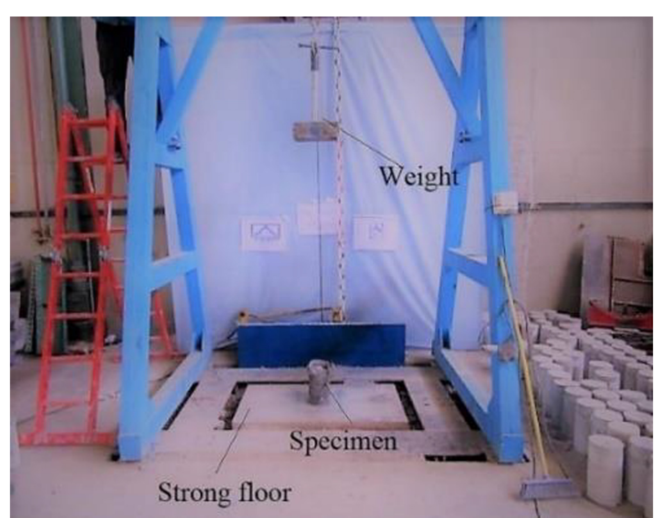

Fig. 3. Laboratory setup.

to the concrete models, the weight of the models was measured and compared to their initial weights. This procedure lasted until the devastation of the models (30% weight loss) was observed. The number of weight-dropping necessitated to 30% weight loss (representative to the impact resistance) was recorded.

3. Experimental results

3.1. Impact behavior

Fig. 4 presents the impact numbers of each sample obtained from the experiments. First, it was observed that the impact resistance of the samples increased using higher-strength concrete. The increases in the impact numbers of samples in C30 and C40 were 33.3% and 66.6% under 46.7 kg projectile and were 50 and 50% under 66.8 kg. The experimental observations showed that the fiber content ratio of 2% performed better in both the confined and unconfined C30 and C40 samples under 46.7 kg projectile. This ratio was 1.5% for samples with C20 concrete under 46.7 kg weight. As for 66.8 kg weight, the optimum ratio was 1.5% for confined C20 and C30 samples, and 2% for the confined C40 samples. The optimum fiber ratio for the unconfined C20 samples was 1.5%, and for unconfined C30 and C40 samples was 2%. The results indicated that using GFRP confinement had a considerable impact on the impact resistance improvement of the samples. Their effects were even more than both the compressive strength of concrete and polypropylene fibers. Then, using GFRP wrapping in terms of both the impact resistance improvement and economic considerations was the best choice among using higher-strength concrete or polypropylene fibers.

3.2. Failure mechanism

The experimental observations demonstrated that unwrapped FRC samples had more cracks in their body and bottom parts in addition to the cracks on their upper parts on which the impacts were straightly inflicted. In the wrapped samples, the cracks were observed only in the upper parts. The observations showed that applying higher ratios of fibers reduced cracking in the samples. The wrapped samples had destruction after layer-by-layer GFRP rupturing by inflicting more impacts on them from top to bottom. Figs. 5 and 6 show the cracks and damages of C20-GFRP and C20-PP1.5%-GFRP samples after imposing impacts. This phenomenon demonstrated that the failure mode of the wrapped samples was GFRP debonding. In contrast with the unconfined samples, there were no damages, such as the destruction of the whole sample, the segregation of a large piece of samples.

4. Conclusion

In this research, the influences of polypropylene fibers and bidirectional GFRP on the impact resistance of concrete samples were experimentally studied. For this purpose, 52 concrete samples with the different compressive strengths of 20, 30, and 40 MPa, and with fiber ratios of 0%, 1%, 1.5%, and 2% were exposed to impacts (weight dropping). It must be added that only half of these samples were wrapped with GFRP and the other half were without GFRP. The numbers of weight-droppings required to 30% weight loss (representative of the impact resistance) were recorded. Based on the experimental observations it can be concluded that:

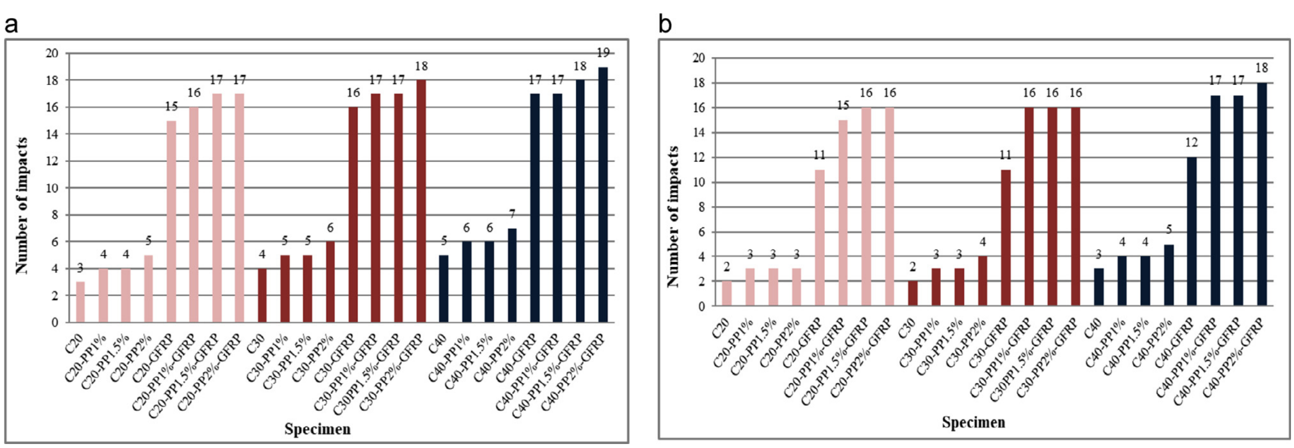

Fig. 4. Impact number of samples with polypropylene and CFRP under: (a) 46.7 kg weight-dropping, and (b) 66.8 kg weight-dropping.

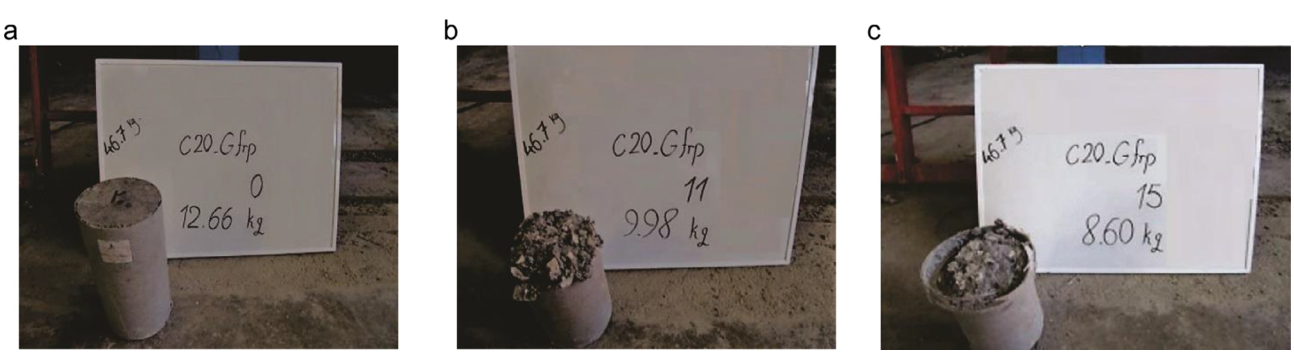

Fig. 5. The damages of C20-GFRP sample: a) before impacts, b) after 11th impact, and c) after 15th impact.

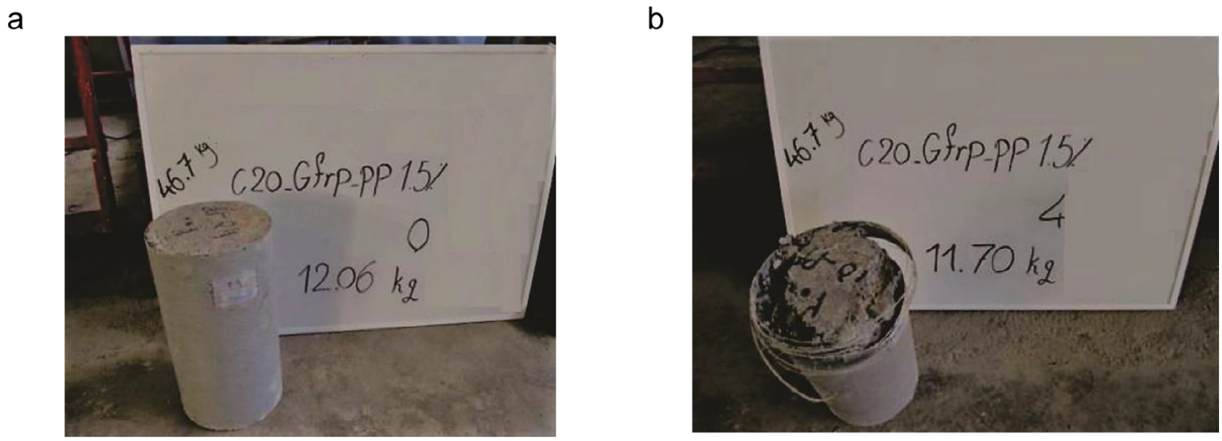

Fig. 6. The damages of C20-GFRP-PP1.5% sample: (a) before impacts, and (b) after 4th impact.

- Impact resistance of the samples improved by using higher-strength concrete.
- Impact resistance of the concrete samples increased by employing polypropylene fibers or GFRP wrapping, separately.
- The effect of GFRP wrapping on increasing the impact resistance was higher than that of the polypropylene fibers (about 150%).
- Although the effects of using both the GFRP wrapped and polypropylene together on the impact resistance were higher than the GFRP application separately, these effects were not considerable enough. Then, using only the GFRP application was the better strategy to improve the impact resistance regarding economic considerations.
- The results showed that using GFRP wrapped decreased the number of cracks and damage intensity of samples significantly.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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