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Influence of Latex and Vinyl Disposable Gloves as Recycled Fibers in 3D Printing Sustainable Mortars

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Abstract: The disposal of personal protective equipment (PPE) is a main concern of researchers. In recent years, the COVID-19 pandemic made this issue worse, so the production and use of large quantities of disposable gloves in recent years and the lack of a suitable solution for the disposal of these recycled materials are some of the consequences of this pandemic. To address this issue, the present study performed a comprehensive experimental program to determine the possibility of using recycled latex and vinyl gloves as recycled fibers within extrusion-based 3D printing concrete. Moreover, a graphene oxide (GO) nanomaterial was also used to compensate for some undesired properties of mixtures. Flow table, buildability, and mechanical tests were performed in this study. Results show that the synergic effect of recycled fibers and GO significantly improved the 3D printing characteristics of mortar. Although very promising results were obtained in this study, findings show that using a high content of recycled fibers reduces the concrete compressive strength. However, the addition of GO significantly compensates for this reduction.

Keywords: latex; vinyl; concrete; 3D printing; waste management; fiber; graphene oxide

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1. Introduction

With the outbreak of COVID-19, disposable gloves have been used more than ever during the last few years as personal protective equipment (PPE) [1]. Moreover, disposable gloves are commonly used in hospitals, scientific laboratories, manufacturing facilities, salons, museums, and public places related to the production and packaging of foods and fruits. Increasing consumption of single-use protective gloves, throwing them away at random points, and reaching landfills can lead to significant environmental pollution. Latex, vinyl, and nitrile gloves are the most famous types of disposable gloves used by people in public and high-risk locations. Different materials have been used to produce disposable gloves, including polyethylene plastic, polyvinyl chloride plastics, natural rubbers, and synthetic rubbers. Latex gloves are made of natural latex rubber, while synthetic materials are used for nitrile and vinyl glove manufacturing. Among the current disposable gloves, nitrile gloves have higher mechanical strength as compared to vinyl gloves. As vinyl gloves are made of polyvinyl chloride (a petroleum-based film), they are not safe enough to protect against chemicals, but they are more cost-effective than other gloves. For this reason, vinyl gloves must only be used in situations free of hazardous matters. Usually, vinyl gloves are used in low-risk jobs, such as food production and healthcare responsibilities. Compared to vinyl and nitrile gloves, latex gloves are more durable, have a considerable shield against chemical exposure, and are puncture-resistant against mechanical loadings. Exposure to blood, bodily fluids, or patients with contagious sicknesses are the high-risk jobs where latex and nitrile gloves are generally used. Vinyl or polyvinyl chloride plastic controls the disposable glove market. Vinyl is commonly known as "toxic plastic" because it poses toxic chemical hazards throughout its life cycle, including hazardous chemical additives that come out of the plastic. As there is no rubber material in disposable vinyl gloves, they are known as an "alternative anti-allergy" product to latex gloves for people with sensitive skin. Regardless of the concern of people being allergic to latex gloves, latex gloves (natural rubber) are very flexible and stretchable. Researchers working in chemical laboratories are extensively using latex during their tests to protect their skin against hazardous materials. Moreover, latex gloves are widely used in hospitals and medical clinics.

As reported by Marandi (2006) [2], approximately 5000 tons of latex gloves are used in Iran every year, showing that a national program is required for recycling them. This report was presented in 2006, showing that this estimate has increased in recent years. The COVID-19 virus pandemic has increased the demand for disposable gloves, especially for healthcare and food service workers. Using PPE will also be continued in the protective behavior of people in the post-COVID-19 world. By increasing glove production due to the pandemic, a huge waste of disposable gloves has been produced in recent years, which significantly increases the littering and growing landfill zones, thus leading to environmental hazards. The existence of contaminated disposable gloves in the environment and recycling rubber and plastic materials in the production cycle are the main challenges for researchers. The emergence of COVID-19 has exacerbated this dilemma. Waste plastic can be directly swallowed by organisms causing the release of contaminants into the environment [1]. Materials and components of these contaminated gloves gather in tissues and organs and represent various disorders and threats to animals and humans. These contaminated gloves can increase this risk by absorbing pollutants into plastics that may act as carriers of contaminants. Hence, efficient approaches should be introduced by researchers to recycle disposable gloves (made of natural rubber and plastic) to use in other industries, especially for natural rubber and polyvinyl chloride plastics. The disposal of polymeric and especially rubber materials has been becoming a potential hazard to human health and the environment [3,4]. In this field, Shu et al. (2014) [5] emphasized that burying rubber waste in large volumes can no longer be associated with rising land costs, so disposing of rubber waste becomes a costly method. To achieve great resistance properties against acids, alkali, and chemical solutions, a highly cross-linked thermoset structure of rubber material through the vulcanization process should be followed by companies to produce latex gloves. This causes difficulties in degrading natural rubber (from latex) in the environment [6,7].

Regarding the high disposal of used gloves, different industries have shown interest in using recycled rubber and plastic in their companies. Because of their availability, cheapness, and unique properties, waste disposable gloves are helpful to be used as a valuable source of sustainable materials [8]. Appropriate elastic behavior of disposable gloves can also be helped in damping mechanisms along with thermal and noise insulators [4]. Some previous studies reported that using waste gloves improved the mechanical characteristics of samples [6,9–11]. In the construction industry, previous studies performed extensive experiments to determine the effect of recycled rubber on the mechanical properties of concrete [12–14]. However, there are a few studies on using waste gloves in the field of civil engineering. For instance, Mortazavi et al. (2010) [15] used waste latex gloves to increase the ductility of modified bitumen. They found that the hybrid uses of 10% natural bitumen and 5% recycled latex with a vacuum bottom are appropriate to achieve modified 60/70 grade bitumen with enhanced rheological behavior and reduced possibility of cracking at low temperature and rutting at high temperature. In this field, ALbiajawi et al. (2021) [16] experimentally studied the effect of ground latex gloves and silicone catheters as coarse aggregate in concrete. They found that adding waste latex gloves and silicone catheters meaningfully increases the water absorption of the concrete samples. Moreover, they reported that the compressive strength reduced to 86% at a replacement level of 10% for waste latex gloves. More experimental studies are necessary to determine the effect of different types of recycled medical and non-medical gloves on the fresh and hardened properties of concrete mixtures. Additionally, the literature determined that one could not appropriately use recycled gloves in civil engineering.

Due to the appropriate elastic behavior of natural rubbers and polyvinyl chloride plastics, recycled disposable gloves should be considered as recycled fibers within mixtures. Hence, this study intends to fill these research gaps. Accordingly, the present study performs an experimental program to determine the effect of waste gloves, as recycled fiber, on the 3D printing characteristics of mortar. There has been a growing tendency in recent years to work on obtaining an efficient concrete mixture for extrusion-based 3D printing of concrete structures. Based on this technique, concrete layers are poured on each other as additive manufacturing to produce layer by layer structure. Extrusion-based 3D printing of concrete has many advantages, including considerably reducing the construction cost, improving the design flexibility of building forms, reducing the number of formworks, optimizing materials volume to decrease material wastes, and reducing the workers required to complete a project [17]. Previous studies confirmed that mixture composition has a significant impact on the 3D printing characteristics of structures [17,18]. Only fine aggregate is used in 3D printed concrete depending on the nozzle size and the ability of the automated device to extrude constantly. Different values were considered for the maximum size of sand particles in 3D printed concrete by the literature [19–21]. Generally, the emergence of 3D printed concrete increases the sustainability of concrete structures. However, as many mineral and chemical admixtures are added to 3D printed concrete, the sustainability level can be influenced. Hence, researchers are performing new experimental tests to use recycled materials to increase the sustainability aspect of 3D printed concrete. As using recycled fibers can affect the fresh and hardened properties of 3D printing mixtures, special mineral or chemical admixtures should be used to compensate for the reduced characteristics.

Regarding chemical admixture, previous studies severally showed that using nanomaterials is an efficient solution to solve many shortcomings in composite mixtures [22,23]. Among different types of nanomaterials, the exclusive features of graphene oxide (GO) nanomaterials, such as their rough surface and functional group, have a desirable effect on the fresh and mechanical behavior of cementitious materials [24]. GO is a derivative of graphene, and has a monolayer structure of sp^2-hybridized carbon atoms attached to a mixture of carboxyl, hydroxyl, and epoxy functional groups [25,26]. Using GO in cementitious composites improves the pore structure and transport properties. Moreover, reinforcing cementitious composites with GO is favorable concerning its higher aspect ratio (1500–45,000) as compared to commercial fibers [27]. In this field, Pan et al. (2013) [28] found that a low dosage of GO (0.05 wt.%) improves the compressive and flexural strengths of concrete up to 15–33% and 41–59%, respectively. A similar observation was obtained by Devi and Khan (2020) [29], where GO improved the compressive and tensile strengths by 21–55% and 16–38%, respectively. Regarding fresh properties, previous studies reported that the addition of GO within cementitious composites improved the viscosity and yield stress of mixtures, which is a promising option for use in 3D printing mixtures, where an appropriate level of buildability is required [30–32]. Similar to other nanomaterials such as carbon nanotubes (CNTs) [33], the general trend reported by the previous studies showed that using GO within cementitious composites slightly reduces the workability [23,29,34,35]. This reduction was attributed to the development of agglomerates and flocculation by electrostatic interfaces between GO and cement particles. Moreover, workability reduction can be due to the large specific surface area of nanomaterials, which generates more free water needed to wet the surfaces. However, some researchers found that different parameters can affect this workability reduction, including dosage of GO [36], ultrasonication energy in dispersion technique [37], the addition of superplasticizer [38], surface treatment of nanoparticles [39], surface coating of nanomaterials [40], and the w/c ratio of the mixture [41]. Hence, changing these variables can affect the trend so that in some cases, comparable and slightly higher workability was observed for GO-contained mixtures as compared to the reference mixture. For instance, Li et al. (2017) [36] reported a threshold for GO dosage, in which there is no workability reduction for GO content higher than 0.03%. In this field, Qureshi and Panesar (2020) [39] found that treatment of GO nanomaterials with Na_2CO_3 and PEG-PPG-PEG surfactant causes a comparable and slightly higher static flow in the GO-contained cementitious composite as compared to the reference mixture. Mowlaei et al. (2021) [40] reported that silica coating of GO nanomaterials surfaces compensates for workability reduction in GO-contained mixtures. Vallurupalli et al. (2020) [38] reported that using superplasticizers (up to 0.6%) helps in the de-flocculation of the cement particles and release of entrapped water, resulting in no workability reduction in composites containing GO nanomaterials. In this field, Suo et al. (2020) [41] showed that the water-to-cement ratio of mixtures containing GO nanomaterials affects the workability of cement. Rashidi et al. (2021) [37] found that the ultrasonication energy required to disperse nanomaterials appropriately within cementitious composites significantly affects the workability so that an increase in the ultrasonication energy decreases the flowability. Hence, the overall review of the literature confirms that the reduction in workability of composites containing GO nanomaterials can be compensated by using different methods and changing mixtures. Accordingly, GO nanomaterials can be a good option for using in mixtures containing waste materials to improve the fresh and mechanical performance of 3D printing mixtures.

As comprehensively explained in this section, there is no specific study on using recycled gloves in 3D printed concrete. Moreover, the hybrid use of disposable gloves and nanomaterials was not considered by the literature. Hence, the present study intends to fill this research gap. Because of that, the following objectives are considered for the present study:

(1) How much does the use of disposable gloves improve the 3D printing properties of mixtures?
(2) What is the effect of graphene oxide on the 3D printing properties of mixtures containing disposable gloves as recycled fibers?
(3) Comparing 3D printing characteristics of the mixture containing recycled latex gloves with vinyl gloves.

To achieve these objectives, a comprehensive experimental program was conducted in the present study. As shown in Figure 1, to obtain a reliable 3D printing mixture, a challenge exists for researchers. This mixture should have appropriate mechanical strength along with acceptable fresh properties. To attain this goal, different chemicals, and mineral admixtures can be used within the mixture. Hence, the fresh and hardened properties of mortars were considered in this experimental program. Flow table and shape stability tests were performed to determine the fresh properties of mixtures. Compression, tensile, and bending tests were carried out for mechanical properties. Two different recycled gloves were used in the experimental program, including (1) latex fibers; (2) vinyl fibers. Graphene oxide as a chemical admixture was also used in the samples to increase some characteristics of the mixtures. No mineral admixture was added to the mixtures in the present study.

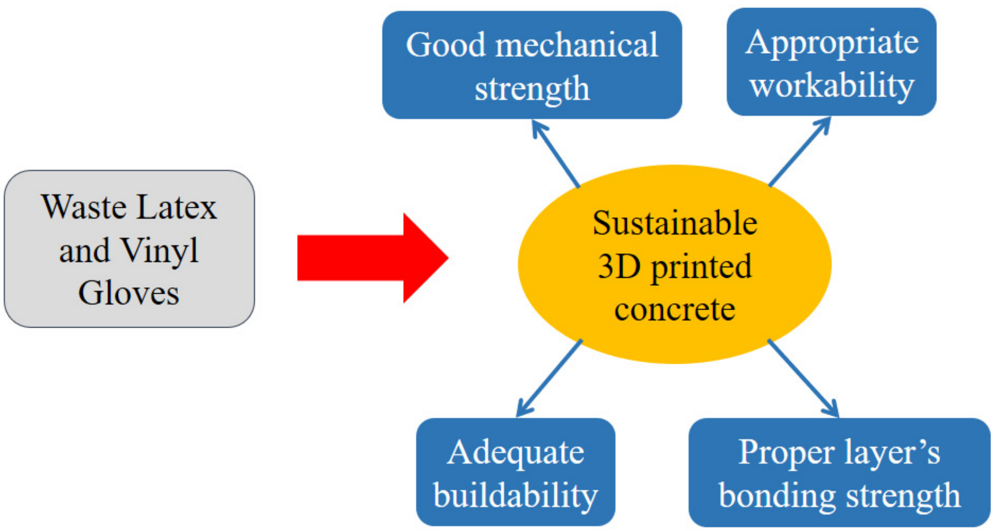


Figure 1. Main objective of the present study.

2. Experimental Program

2.1. Materials and Mixture

As per ASTM C150 Type-1, ordinary Portland cement was used in the experimental work to prepare the mixtures. The physical and chemical aspects of cement used in this study are shown in Table 1. Compositions of mortars are mentioned in Table 2. Seven mixtures were provided for the present study. A constant water-to-binder ratio of 0.42 was chosen for all mixtures. Fine sand with a maximum aggregate size of 2.36 mm was selected for this study. The sand-to-cement ratio of 1.5 (weight ratio) was considered for the sand quantity, which was recommended by the literature for 3D printing concrete. No superplasticizer was used in the experimental program. Latex and vinyl recycled gloves were turned into fibers to be used in mixtures with different volume fractions of 0.1% and 0.2% (Figure 2). The recycled fibers (latex and vinyl) have a thickness of 0.2 mm, and average length of around 16 mm. Additionally, the average width of stripes for latex and vinyl fibers is 2.9 mm. To study the effect of nanomaterials, graphene oxide (GO) with a dosage of 0.03% by weight of cement was used in mixtures. This dosage was recommended by Bhojaraju et al. (2021) [23]. GO has a specific surface area of 40 m^2/g, purity of 98.5%, average flake thickness of 60 nm, and particle (lateral) size of less than 7 μm. The TEM image of GO nanomaterials is shown in Figure 3. As shown in Figure 4, GO was first appropriately dispersed in mixing water before adding it to the mixture. Deionized water was used to disperse the GO. A magnetic stirrer and ultrasonic probe were used in the dispersion. The first container with GO was put on the magnetic stirrer for 10 min. After that, 60 min period was considered for putting in an ultrasonic probe. The dispersed GO in mixing water was added to the mixtures. The mixing process was followed from that found in the literature [23]. Directly after mixing, samples were covered with plastics for one day before demolding. A 28-day curing period was considered for all specimens in the curing tank with 20 C and 60% RH.

Table 1. Physical and chemical properties of ordinary Portland cement (OPC).

Physical Properties	Results	Chemical Properties	Results
Initial setting time (Min)	170	SiO_2	20.8
Final setting time (h)	3.5	Al_2O_3	5.2
Specific surface area (cm^2/gr)	3250	Fe_2O_3	3.65
3-day compressive strength (MPa)	26.48	CaO	63.3
7-day compressive strength (MPa)	38.74	MgO	1.8
28-day compressive strength (MPa)	49.52	SO_3	2.5

Table 2. Mix proportions of mortars (kg/m^3).

Mixtures	Cement	Water	Sand	GO *	Latex Fiber	Vinyl Fiber
RF	450	189	675	-	-	-
0.1Latex	450	189	675	-	1	-
0.2Latex	450	189	675	-	2	-
0.2Vinyl	450	189	675	-	-	2.2
0.1Latex + GO	449.86	189	675	0.135	1	-
0.2Latex + GO	449.86	189	675	0.135	2	-
0.2Vinyl + GO	449.86	189	675	0.135	-	2.2

* GO: graphene oxide.

2.2. Experiment Design

As illustrated in Figure 1, the appropriate mixture for 3D concrete printing should have good workability, adequate buildability, proper layer bond strength, and satisfactory mechanical characteristics. Accordingly, five different tests were considered for this study (Figure 5). For measuring the fresh properties of mixtures, the flow table test was conducted in terms of spread diameter based on ASTM C1437 [42] (Figure 5a). In this test, a cone with dimensions of 100 × 70 × 60 mm (bottom × top × height) was placed on a center of flow table instrument, and then fresh mortar was poured into two separate layers with 20 compaction strokes in the cone to compact the layers appropriately. Adequate compacting pressure should be applied for layers. After cleaning the upper surface of the cone, the mold is immediately raised vertically, and then the flow table is dropped 25 times in 15 s. The workability value can be determined by measuring the four symmetrical diameters in two axes. To determine the buildability of mixtures, a shape stability test was carried out in the present study (Figure 5b). Although there is no specific standard for measuring mixture buildability, previous studies confirmed the efficiency of this test [43–46]. This test measures the immediate axial deformation of mixtures exposed to increasing axial loads (by some specific weights) that denote the weight of upper layers. This parameter shows the buildability and retention of printed layers. A comprehensive description of this test is mentioned in Section 3.2 (Buildability). For each mixture, three 50 mm cubes were considered for the compression test (Figure 5c). Briquette specimens were used to determine the direct tensile strength of mixtures based on AASHTO T 132 [47] and ASTM C307 [48]. The bone-shaped briquette had a length of 76.2 mm, a thickness of 25.4 mm, and a cross-section of 645 mm^2 at mid-length (Figure 5d). To determine the bond strength between printed layers, a simplified three-point bending test was conducted in this study. In this test, two separate layers of concrete were poured into the $40 \times 40 \times 160$ mm prism mold with a delay of 10 min to simulate printing layers. After 28 days of curing, a lateral bending test was applied to the samples (Figure 5e).

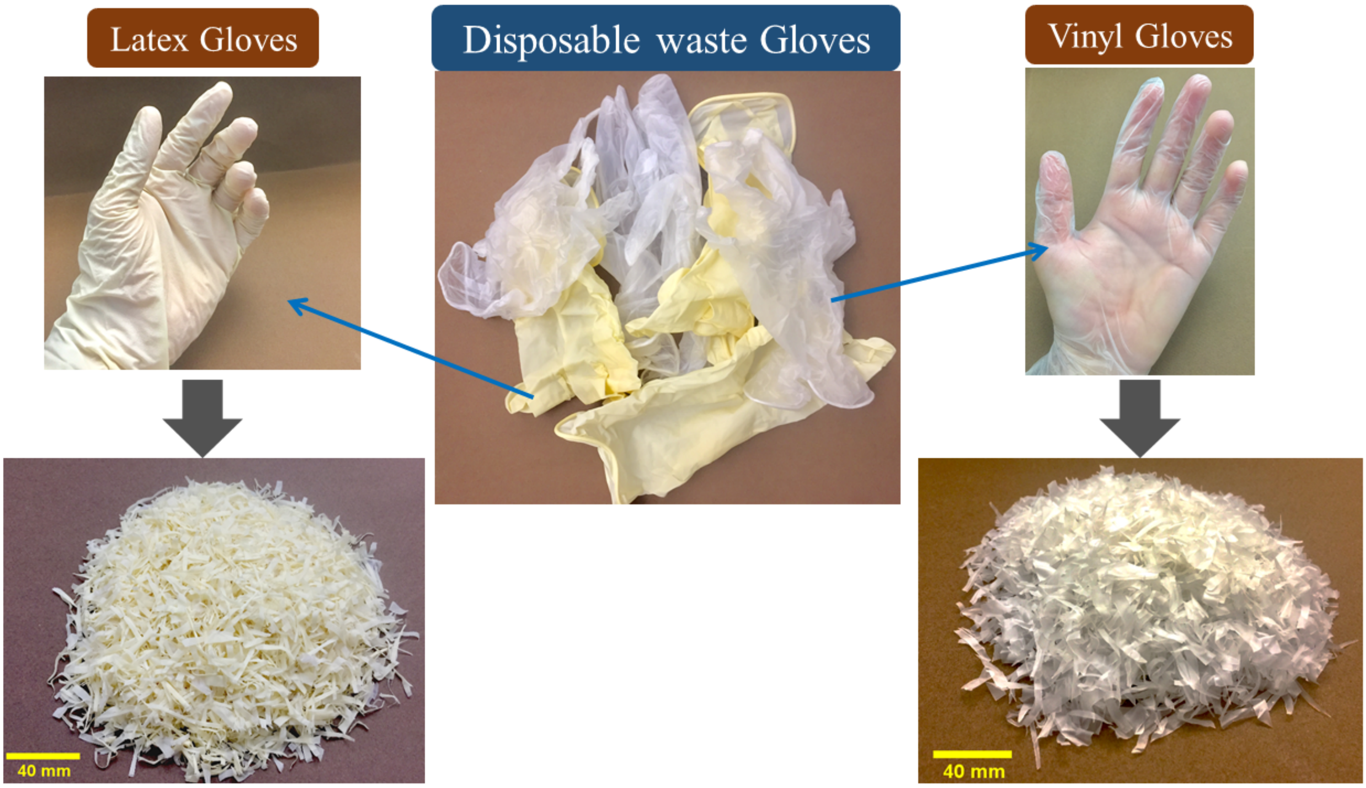


Figure 2. Recycled fibers used in the present study from waste latex and vinyl gloves.

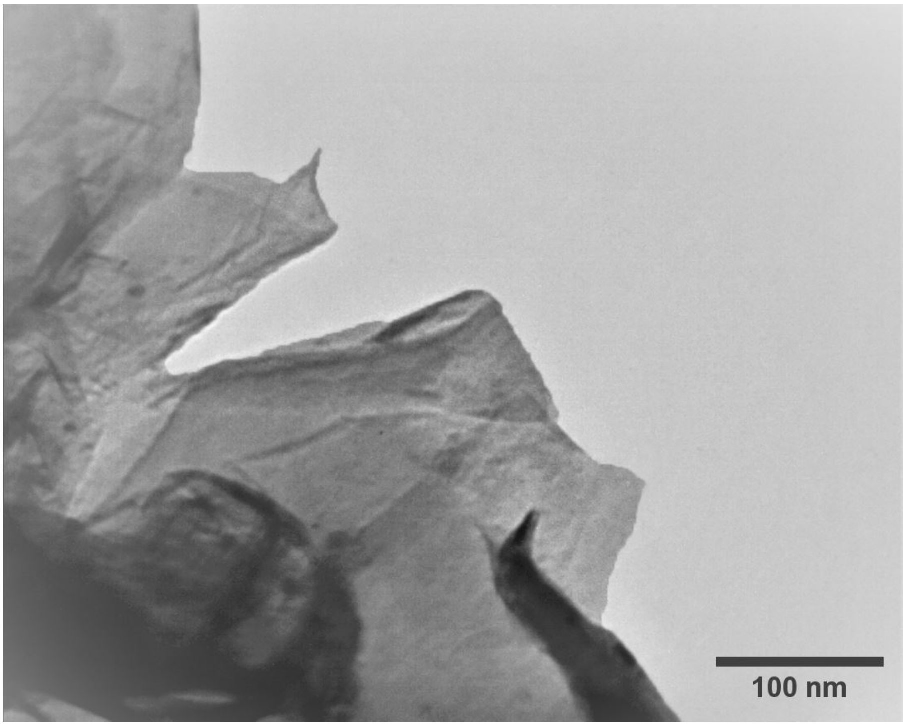


Figure 3. TEM image of GO nanomaterial.

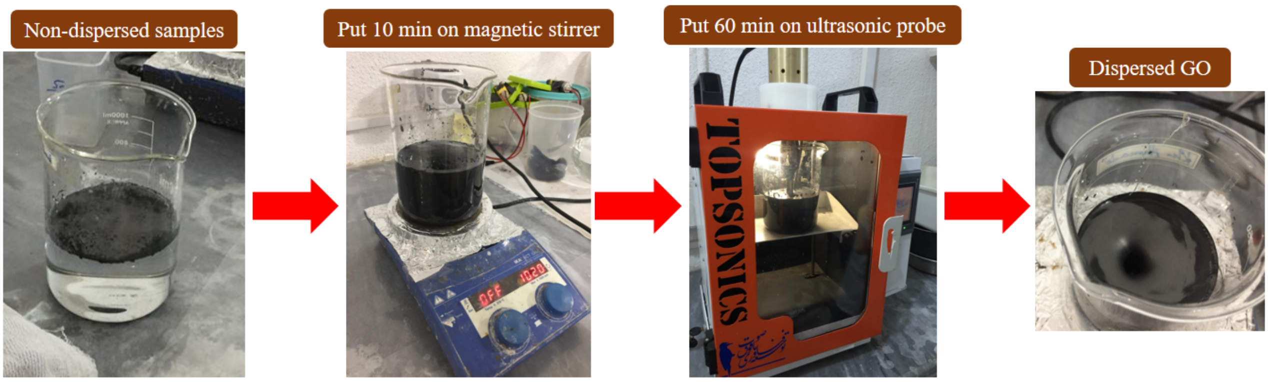
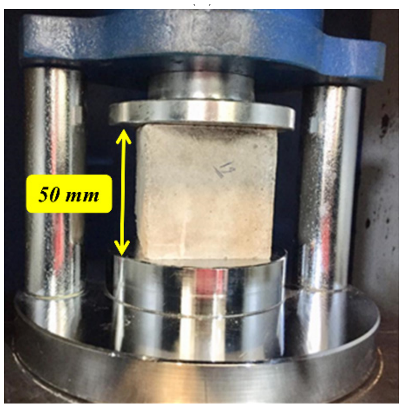


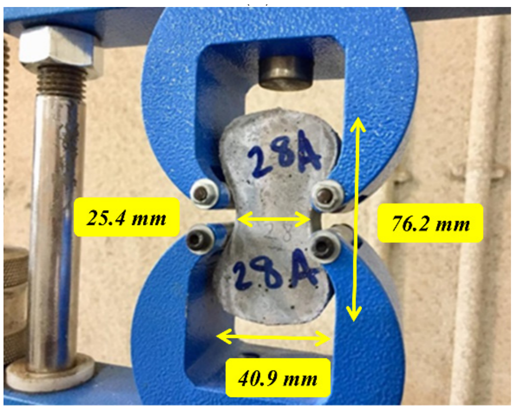
Figure 4. GO dispersion process within mixing water.

(**a**) (**b**)

Figure 5. *Cont.*



(**c**)



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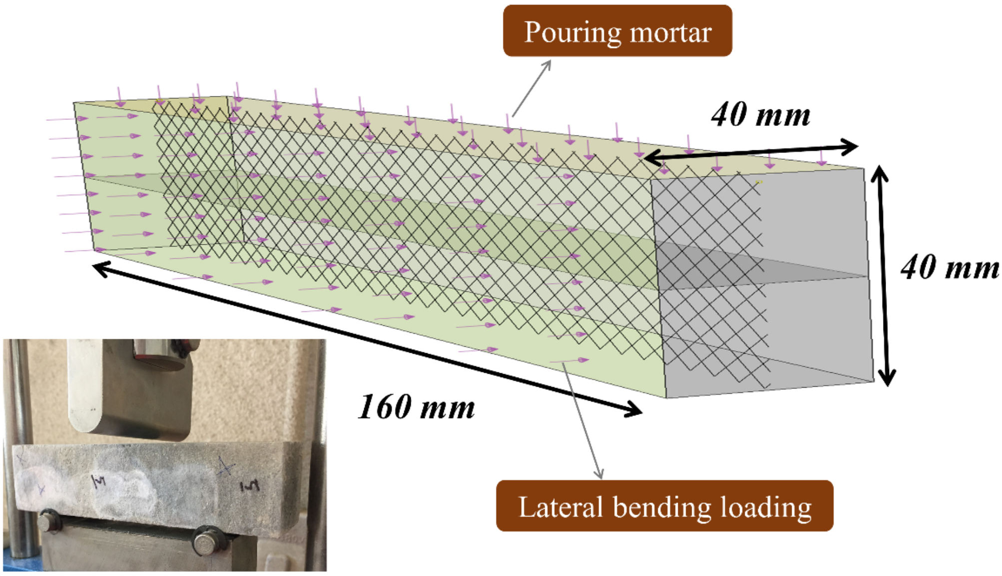

(**e**)

Figure 5. Experimental tests considered in the present study: (**a**) flow table test as a workability criterion; (**b**) shape stability test as a buildability (viscosity) criterion; (**c**) compressive strength test; (**d**) direct tension test; (**e**) bending test.

3. Results

This section intends to present the experimental results comprehensively. Hence, five subsections are considered in this section. As shown in Figure 5, workability results were obtained by flow table test, and the measured diameters for all mixtures are shown in Section 3.1. To determine the buildability of mixtures, a shape stability test was conducted, comprehensively explained in Section 3.2. Finally, mechanical results are mentioned in Sections 3.3–3.5. This section intends only to present the obtained results, while a comprehensive discussion regarding the efficiency of the obtained experimental results is carried out in Section 4 (Discussion).

3.1. Workability

The results of the flow table test are illustrated in Figure 6. Results show that a low dosage of latex fibers has no influence on the concrete workability, while a high dosage of latex fibers (0.2%) causes a 6.6% increase in the concrete workability as compared to the RF mixture. Similarly, adding 0.2% vinyl fibers results in a 9.8% increase in mixture workability. This can be due to the nature of natural rubber and polyvinyl chloride plastics. Previous results show that using ultra-high ductile concrete (UHDC) as a new and efficient generation of concrete for use in the 3D concrete printing technique causes a serious concern regarding the high volume of fibers in UHDC [46,49]. In this field, Ye et al. (2021) [49] showed that the high content of fibers causes a considerable reduction in spread diameter (workability). Results show that using GO has a promising impact on concrete workability: 13.7% and 4.6% increases were recorded for "0.1Latex + GO" and "0.2Latex + GO" mixtures, respectively. Moreover, the flowability of the "0.2Vinyl + GO" mixture is about 4.0% higher than the "0.2Vinyl" mixture. It is worth mentioning that although many researchers reported lower workability of mixtures containing GO nanomaterials as compared to the reference mixture, some researchers found another trend and showed that the dosage of GO [36], ultrasonication energy in dispersion technique [37], the addition of superplasticizer [38], surface treatment of nanoparticles [39], surface coating of nanomaterials [40], and w/c ratio of mixture [41] could change this trend and compensate workability reduction. The results of the present study are in line with this trend and indicate that using polymers and recycled rubbers in contact with GO nanomaterials within cementitious composites alleviates workability reduction.

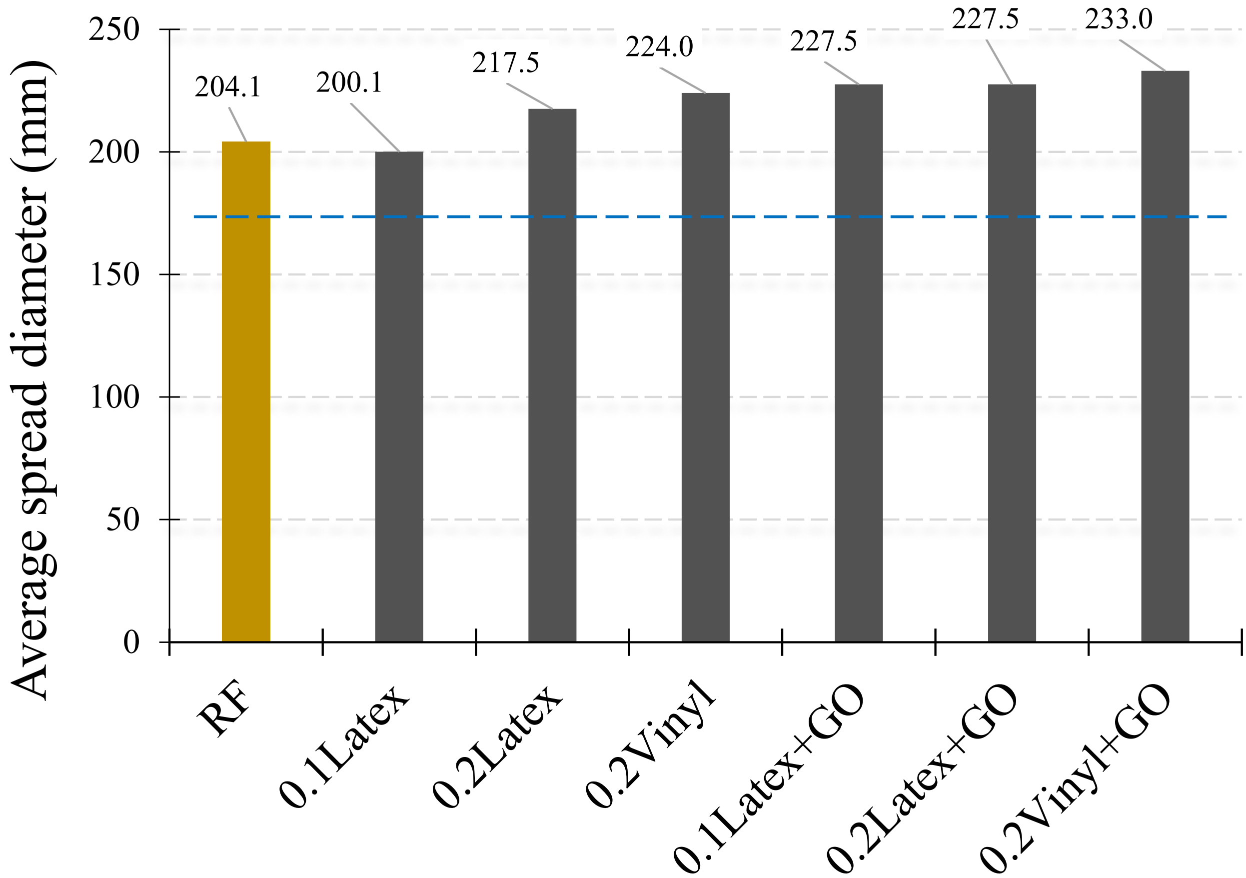

Figure 6. Results of workability from flow table test.

3.2. Buildability

To measure the buildability of mixtures, a parameter called "drop height percentage (DHP)" is defined in this section. As shown in Figure 7, a cylindrical mold with a diameter of 60 mm and a height of 60 mm was used. After demolding, incremental loading was applied on top of the fresh samples by applying weights (95.1 gr). DHP is the ratio of the sample height after demolding (H_n) to the sample height after applying loads (H_1). As the DHP factor increases, the buildability of the mixture increases. A low value of DHP corresponds to the weak capability of lower layers to sustain the weights of upper layers. This can be due to the low viscosity ability of mixtures. Results of DHP for all mixtures are shown in Figure 8. To compare the results, 50% DHP and the area under the DHP-weight are used in this section. In this section, the "Buildability Index" shows the area under the DHP weight, illustrated in Figure 9 for all mixtures. Generally, results show that the RF mixture has a weak buildability compared to other mixtures, so this mixture could not tolerate weights higher than 400 gr. The addition of recycled fibers from waste gloves considerably increases the 50% DHP and buildability index of mixtures. Regarding latex fibers, 209.7% and 361.6% increases were recorded for the buildability index of 0.1Latex and 0.2Latex mixtures, respectively. Similarly, using 0.2% vinyl fiber increases the buildability index to around 260.6%. Results also show that a vinyl-contained mixture has a lower buildability index as compared to the mixture containing latex fibers (Figure 9). Generally, results indicate that using GO considerably improved the buildability index of mixtures containing recycled disposable gloves. This result was previously confirmed for normal concrete without recycled fibers [23]. The addition of GO results in around 183% and 64% increase in the buildability index. Moreover, using 0.03% GO causes a 62.7% increase in the buildability index. Similar to the mixtures without nanomaterials, vinyl-contained mixtures with GO nanomaterials have a lower buildability index. Generally, comparing the results presented in Figures 6 and 9 indicates that vinyl increases the mixture's workability and reduces the concrete viscosity (or buildability). Hence, it seems that a greater dosage of nanomaterials is necessary to increase the buildability of mixtures containing vinyl fibers. Additionally, it can be deduced from the results of the present study that nanomaterials can be used in new generations of concrete used in 3D printed concrete to reduce the fiber dosages, such as UHDC.

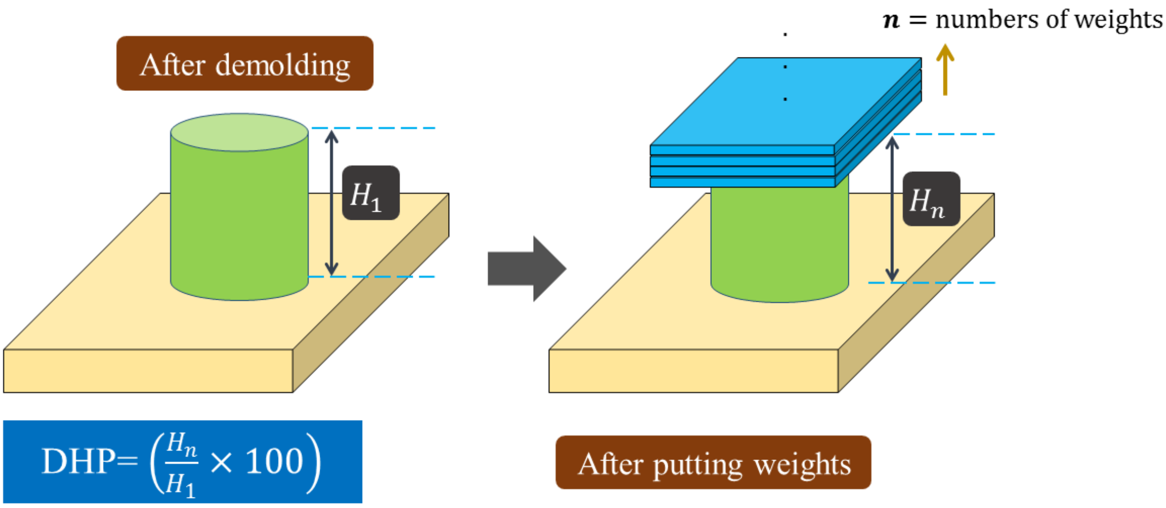

Figure 7. Configuration of the shape stability test.

3.3. Compressive Strength

The compressive strength of all mixtures is shown in Figure 10. Results show that the addition of 0.1% and 0.2% latex fibers causes 18.0% and 23.1% reductions in the compressive strength, respectively. Similarly, using 0.2% vinyl fibers results in a 27.5% reduction in compressive strength. The results indicate that vinyl fiber has a more destructive effect on compressive strength. Hence, it can be deduced from the results that vinyl–matrix interaction has higher porosity in the interfacial transition zone (ITZ) as compared to the latex–matrix interface. This phenomenon can be attributed to the fact that polyvinyl chloride, as the main material of vinyl fibers (synthetic polymer of plastic), interacts with cement constituents when they come in contact with water. This interaction results from ionic bonding, creating crosslinks that prevent the film-forming properties of polymers. This process substantially affects the crystallization process in the hydration process and thereby causes higher compressive strength reduction [50]. Generally, very promising results were observed using nanomaterials in mixtures containing recycled fibers. In this case, using GO causes 8.9%, 11.9%, and 3% increases in the compressive strength of mixtures containing 0.1% latex, 0.2% latex, and 0.2% vinyl, respectively. Similar results were reported in the literature for other nanomaterials [22]. There are different types of nano-sized pores in hardened mortar, including nano-sized spaces between particles in C–S–H gel and nano-sized porosity at the ITZ between matrix and fine aggregates. Controlling the size of these pores can considerably affect the hardened properties of mortar. Nanomaterials have two main roles in cementitious composites, including (1) filling the nano-sized spaces between particles in C–S–H gel; (2) pozzolanic reaction. These two main mechanisms of nanomaterials help in improving the pore structure of cement paste by generating a dense microstructure. Hence, it can be deduced from the results that using GO nanomaterials provides smaller pore size and porosity at the ITZ region and thereby increases the compressive strength, which was similarly reported for other nanomaterials [51]. However, as shown in Figure 10, results show that GO nanomaterials have less impact on the compressive strength of vinyl-reinforced composites as compared to mixtures containing latex fibers. It can be attributed to the higher porosity of the polymer–matrix interface as compared to the rubber–matrix one, making it difficult to be compensated by GO nanomaterials.

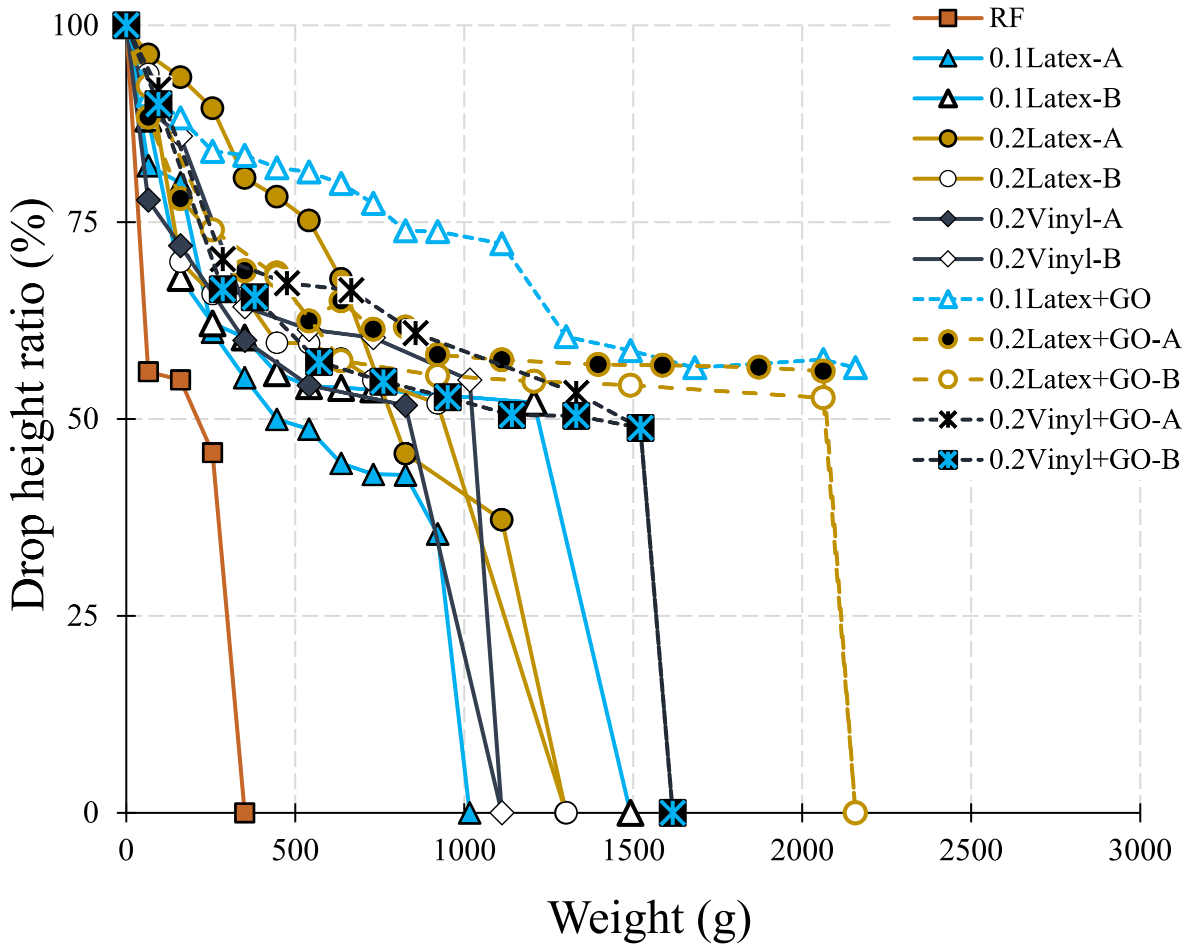

Figure 8. Results of shape stability test ("A" and "B" denote the repetitions).

3.4. Tensile Strength

The direct tensile strength of all mixtures is shown in Figure 11. Generally, the addition of recycled fibers improved the tensile strength of mixtures with a high standard deviation (SD). This high SD is normal due to the brittle nature behavior of cementitious materials. Results show that addition 0.1% and 0.2% latex fibers result in 37.5% and 30.9% increases in tensile strength, respectively. Additionally, using 0.2% vinyl fiber increases the tensile strength up to 53.6%. However, a clear trend was not obtained for mixtures containing nanomaterials. For instance, GO has no favorable impact on the tensile strength of mixtures containing 0.1% latex fibers. However, using GO nanomaterials in mixtures containing

0.2% latex and 0.2% vinyl fibers results in 10.1% and 4.5% increases in tensile strength, respectively. It can also be deduced from the results that vinyl fiber has more influence on enhancing the tensile behavior as compared to latex fiber (Figure 11).

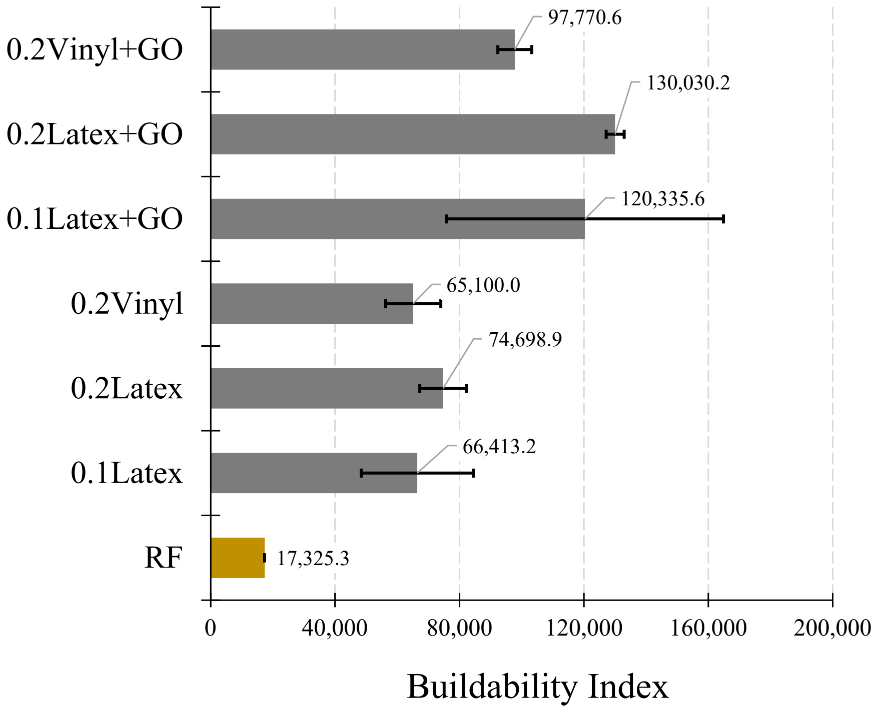

Figure 9. Results of shape stability test.

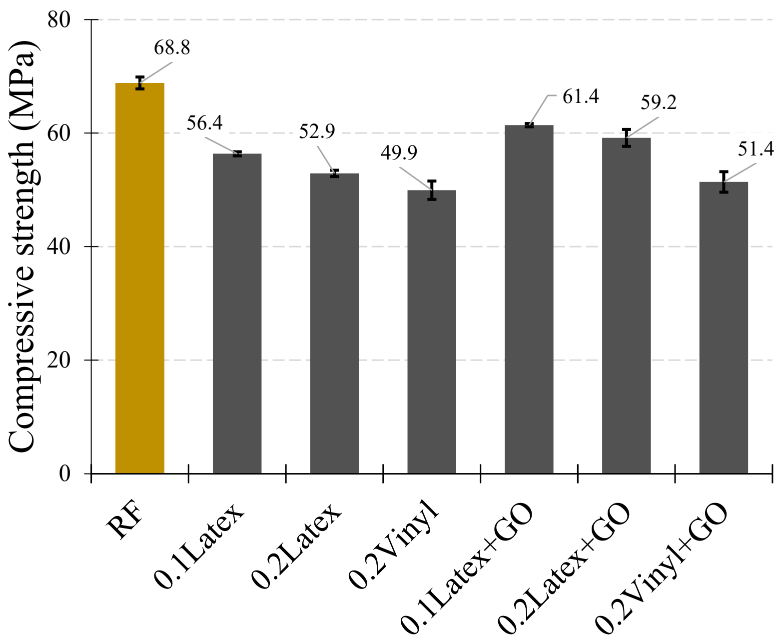

Figure 10. Results of compression test.

3.5. Flexural Strength

The flexural direct strength of all mixtures is shown in Figure 12. Generally, results show that the addition of recycled fibers made from disposable gloves improves the flexural strength of mixtures. In this case, using 0.1% and 0.2% latex fibers result in a 17% and 1.7% increase in flexural strength, respectively. Lower improvement of 0.2% latex compared to 0.1% can be attributed to the high compressive strength reduction in mixtures containing a high dosage of recycled latex fibers. However, in the case of vinyl-contained mixtures, more promising results were observed: using 0.2% vinyl fibers causes a 41.9% improvement in flexural strength. Regarding mixtures containing GO, no clear trend was observed, which was similarly reported by the literature for normal concrete [23]. As shown in Figure 12, the results of the present study show that using GO has no considerable influence on the mixtures containing latex fibers, while the addition of GO has a 13.6% enhancement in flexural strength.

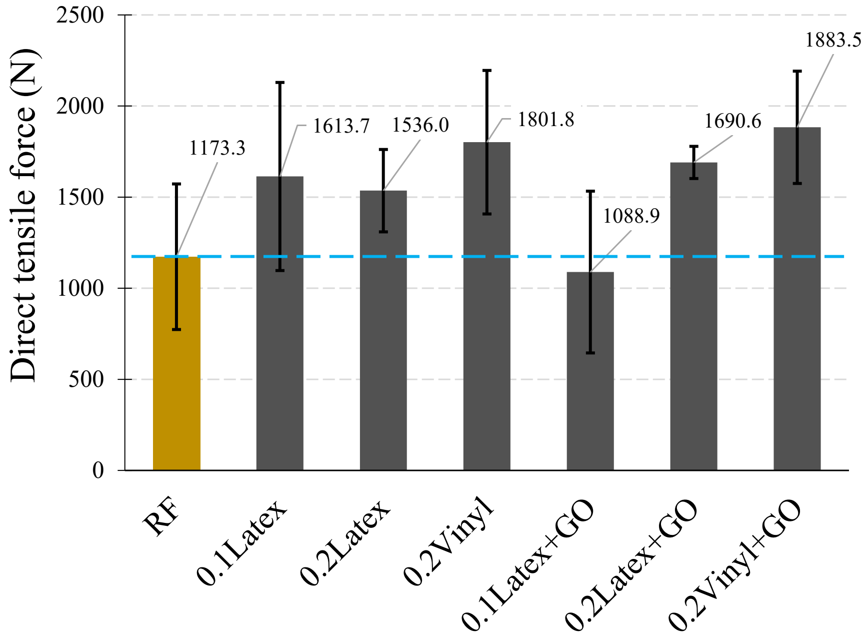

Figure 11. Results of direct tension test.

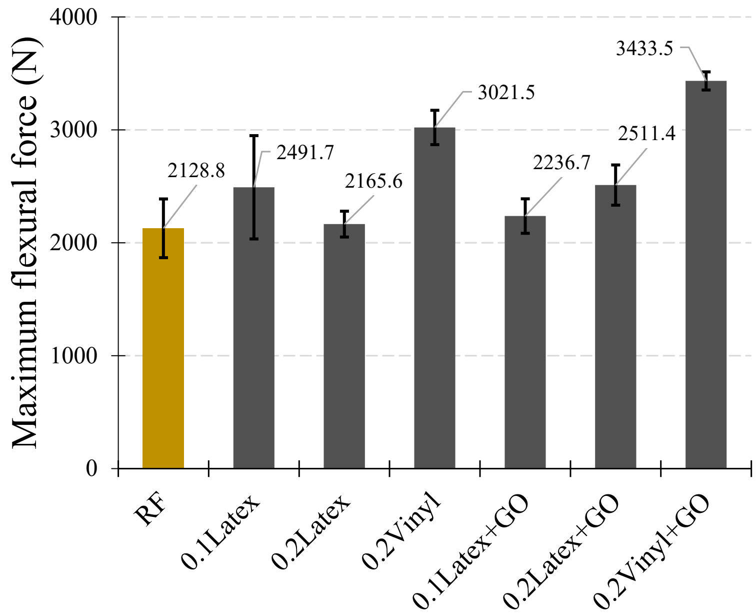

Figure 12. Results of bending test.

4. Discussion

A summary of all results is illustrated in Figure 13. Studied parameters are normalized with the results of the reference mixture "RF". A normalized value higher than 1.0 means an acceptable mixture with a higher property as compared to the RF mixture, while a normalized value lower than 1.0 shows undesired results. As mentioned in Figure 1, to achieve a reliable mixture for 3D printing concrete members, the mechanical and fresh characteristics of the mixture should be in harmony with each other. An optimum mix design for 3D printing concrete should have acceptable workability, good buildability, adequate compressive strength, and sufficient layer bond strength. To follow this approach, normalizing the studied parameter can efficiently help in finding an optimum mixture. As shown in Figure 13, the synergic influence of disposable gloves and GO nanomaterials is effective so that the buildability index of the proposed mixtures is significantly higher than the reference mixture (RF). Generally, results show that the best mixture studied in the present investigation is the mixture "0.1Latex + GO", where most of the studied parameters have normalized values higher than 1.0. However, as mentioned before in Figure 10, all mixtures have lower concrete compressive strength as compared to the RF mixture. Hence, one scenario is to choose the mixture with the lowest concrete compressive strength reduction ("0.1Latex + GO" mixture). Another scenario is to concentrate on the other parameters. Considering the second scenario, the "0.2Vinyl + GO" mixture can be a good option to select as the optimum mixture. Overall, the results ensure that latex–GO or vinyl–GO hybrid mixtures are good combinations. However, it is worth mentioning that more experimental studies should be conducted in future works to confirm the results of the present study and extend the observations by testing large-scale 3D-printed concrete members containing recycled disposable gloves and GO nanomaterials. As natural rubber and PVC are the main components of latex and vinyl gloves, respectively, it is essential to use mechanical results to explain the natural rubber/GO and PVC/GO interfacial adhesion. Results of the tensile and bending tests revealed that mixtures containing 0.2 vinyl and latex fibers along with GO nanomaterials have the highest strengths among other mixtures, showing the high value of bonding strength of the PVC/GO or natural rubber/GO interfaces. It can be deduced from the results that from the viewpoint of tensile behavior, PVC/GO interface is stronger than the natural rubber/GO interface (Figure 13). The obtained observation was marginally confirmed by the previous studies. For instance, Hu et al. (2014) [52] reported the efficient compatibility of GO nanoparticles with the PVC matrix. They found that the tensile stress at the break of PVC composites containing GO derivatives improved. In this field, Mindivan and Göktaş (2020) [53] found that the tensile strength of the polyvinyl chloride (PVC) composites containing 0.1% reduced GO improved up to 42%. Likewise, Wang et al. (2017) [54] showed that the tensile strength and impact toughness of the PVC composites were significantly enhanced even at a very low graphene loading (0.3 wt%). This promising trend regarding the PVC/GO interface can be due to the uniform dispersion of nanomaterials and high graphene–PVC bonding strength [55]. A similar trend for natural rubber/GO interaction was shown by previous studies. George, G. et al. (2017) [56] performed an experimental program in which graphene dispersion was mixed with natural rubber latex at various dosages. They achieved a high-performance nanocomposite with 60% and 40% improvements in electrical conductivity and tensile properties, respectively. In the context of natural rubber/GO interaction, Berki et al. (2017) [57] reported an increase in the tensile strength of rubber nanocomposite, along with a reduction in the ductility or tensile strain (elongation at break) with increasing GO dosage. Lim et al. (2020) [58] found that improvement of the tensile stress of the natural rubber latex composite containing GO nanomaterials is mainly attributed to the reinforcing effect of the reduced GO and natural rubber/GO interfacial bonding strength.

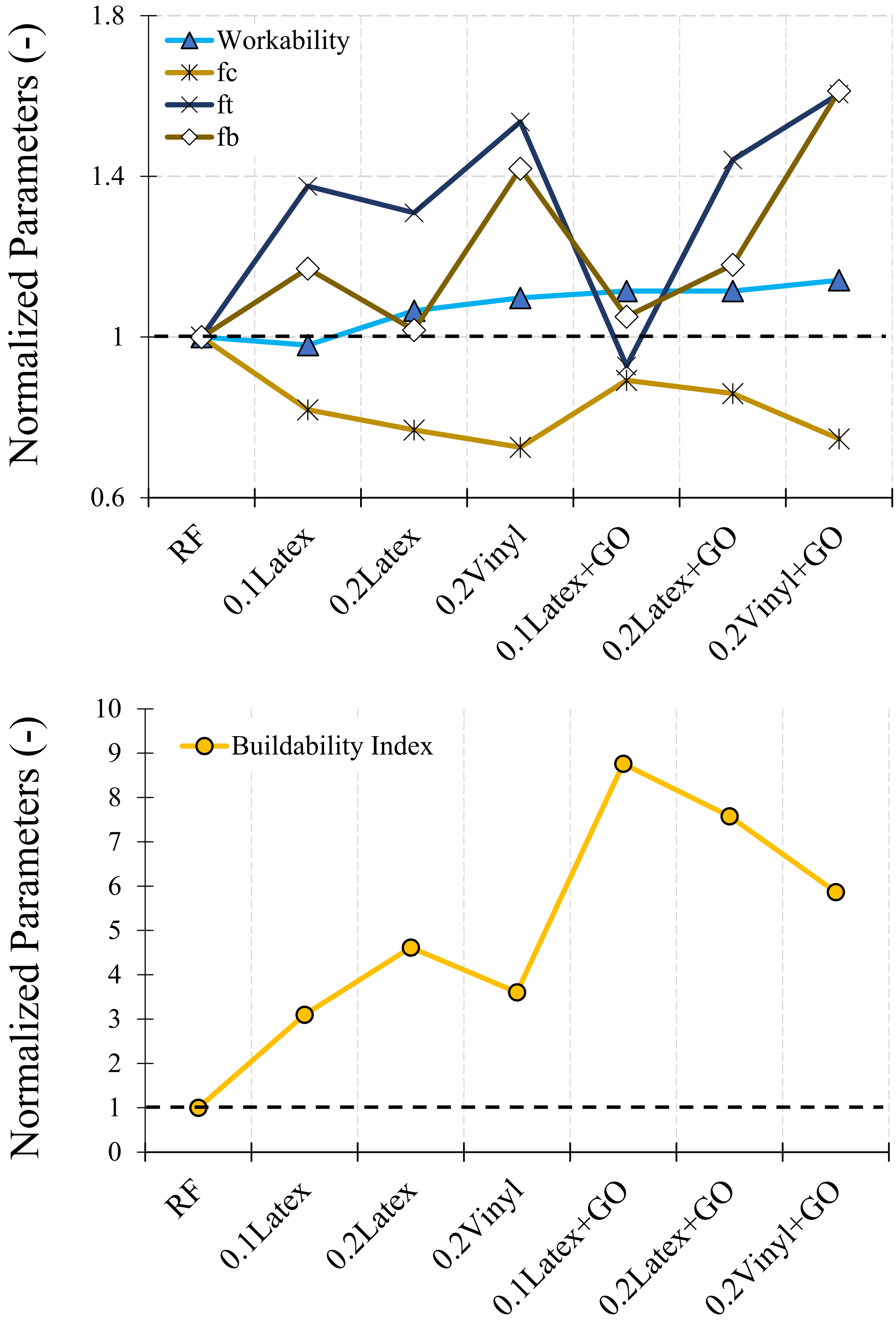

Figure 13. Normalization of the results to obtain the optimum mixture.

5. Concluding Remarks

This study conducted an experimental program to determine the possibility of using disposable waste gloves as recycled fibers in mixtures for 3D printing of concrete members. Latex and vinyl waste gloves were used to produce recycled fibers. We used 0.1% and 0.2% volume fractions of recycled fibers in the experimental program. Additionally, a

GO nanomaterial was used to improve the fresh and hardened properties. Based on the experimental findings, the following remarks can be drawn:

- Adding a high dosage of recycled fibers increases the flowability of mixtures. Additionally, GO improves this trend, especially for vinyl fibers.
- The hybrid uses of recycled fibers and GO significantly enhanced the buildability of mixtures. Moreover, using latex fibers causes more viscose mixtures as compared to vinyl fibers.
- Generally, using latex and vinyl fibers reduced the concrete compressive strength. A higher dosage (0.2%) of recycled fibers has a more destructive effect as compared to a low dosage (0.1%). Using GO compensates for this reduction, especially for mixtures containing a low dosage of latex fibers. A maximum of 37.9% strength reduction was recorded for the "0.2Vinyl" mixture.
- Regarding the direct tensile test, results show that using recycled fibers considerably improved the tensile strength, so "0.2Vinyl + GO" showed the best performance with a 60.5% improvement.
- Among studied mixtures, "0.2Vinyl + GO" represented better performance in bending behavior with 61.3% improvement.
- Overall results indicate that "0.1Latex + GO" and "0.2Vinyl + GO" can be the optimum mixtures, showing the synergic effect of recycled fibers with GO.

It is worth mentioning that along with the experimental program of the present study, more experimental efforts are required for future works to extend the results and concentrate on the chemical structure of the latex/GO and vinyl/GO interfaces. Moreover, future works can use the proposed sustainable mixture in large-scale 3D-printed concrete members. Additionally, future works are necessary to determine the long-term performance of the proposed mixture regarding durability concerns.

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