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Experiment on Activated Carbon Manufactured from Waste Coffee Grounds on the Compressive Strength of Cement Mortars

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Abstract: In this paper, we performed an experiment with activated carbon manufactured from waste coffee grounds on the compressive strength of normal cement mortars. The activated carbon reinforcement was manufactured from waste coffee grounds, and the collected coffee grounds were then transformed into activated carbon granules through the physical activation process. The activated carbon/cement composites were prepared by mixing cement with activated carbon granules with the weight fractions of 0.5%, 1%, 1.5%, 5%, and 10% cement. The experimental results show that adding activated carbon up to 1.5 wt% increased the early strength of cement mortars. Furthermore, we found that the composites incorporated with a small amount of activated carbon (≤1.5 wt%) had higher compressive strength over the curing period than the normal cement without activated carbon. We believe that these results would potentially have commonalities with morphological symmetry phenomena that occur on the surfaces of activated carbon granules.

Keywords: mortar; blended cement; image analysis; characterization; scanning electron microscopy (SEM)

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1. Introduction

Concrete has been used as one of the most popular construction materials for decades, while the concerns regarding the use of limited resources for concrete production have accumulated. Concrete technology developers and industries have discussed solutions to meet the global consensus of sustainable development and promote sustainability for concrete construction. Potential solutions include utilizing waste materials (e.g., fly ash and slag), saving materials in design, recycling concrete, and maximizing concrete performance under the given resources. Hence, the use of waste materials as an additive or a substitute for concrete components to enhance concrete performance has recently received considerable attention, owing to waste management. Kim et al. [1] studied the effect of recycled aggregates on the mechanical properties and durability of concrete. Blending recycled coarse aggregates generally promotes the flowability of concrete while satisfying the design compressive strength. Batayneh et al. [2] reported that crushed glass aggregates as a partial substitute for fine aggregates improved the strength of concrete. Binici et al. [3] blended marble and limestone dust as additives with the concrete mixture. They found that those waste materials increased the compressive strength of normal concrete and promoted the resistance to sodium sulfate.

In recent years, activated carbon has also received favorable attention as a reinforcement of cement-based composites. Chowdhury et al. [4] found that activated carbon could promote moisture resistance in cement and mitigate the risk of moisture attacks. Mahoutian et al. [5] evaluated the effect of activated carbon on the air void characteristics of concrete. They reported that activated carbon reduced the air content in concrete, leading to an increase in strength. Activated carbon can be also used to improve indoor air quality. Krou et al. [6] researched the adsorption capacities of hardened cement pastes that contained activated carbon as an additive. They exposed the cement specimen to volatile organic compounds (VOCs) and measured the number of hazardous compounds, such as acetaldehyde and toluene. The results revealed that activated carbon powder was able to absorb the greater part of toluene, and thus, hardened cement paste containing activated carbon could be a potential construction material that helps to improve the depolluting effect. Zhang et al. [7] also observed that activated carbon could reduce the radon exhalation rate in concrete.

Activated carbon and biochar share many properties, and it is difficult to differentiate one from the other. While biochar is primarily used for soil amendment, activated carbon is widely used to adsorb dissolved contaminants in water and wastewater treatment [8]. The large surface area per unit mass of activated carbon makes it a great absorbent. This implies that small amounts of activated carbon can effectively adsorb contaminants from the solution. Activated carbon is available in two different forms: granular activated carbon (GAC) and powdered activated carbon (PAC). GAC is generally used as filter media infiltration, and PAC is typically mixed in water in reactors and then settled or filtered out downstream [9]. However, the production of activated carbon from typical carbonaceous sources such as natural coals and petroleum residues is complex and expensive, demanding considerable energy consumption, so there exists a need to explore alternative options. One possible alternative is using coffee waste as a base material for activated carbon. Several studies reported that spent coffee grounds proved to be a suitable base material for activated carbon [10–17]. In this paper, we investigated a novel, sustainable cementitious composite that utilized activated carbon reinforcement manufactured from waste coffee grounds. The surface morphology of lab-manufactured activated carbon and the effect of activated carbon, particularly on the compressive strength of normal cement mortar, are discussed.

2. Materials and Methods

2.1. Cement Mortar Composition

A commercial Portland cement (Type I and II) supplied by Sakrete that complied with ASTM C150 [18] was used in this study. Oven-dried clean sand passing a No. 10 sieve with a fineness modulus of 2.38 was used as a fine aggregate. The particle size distribution of the fine aggregate in Figure 1 was determined by the standard sieve analysis. The results show that the fine aggregates used in this study conformed to the specifications defined by ASTM C33 [19].

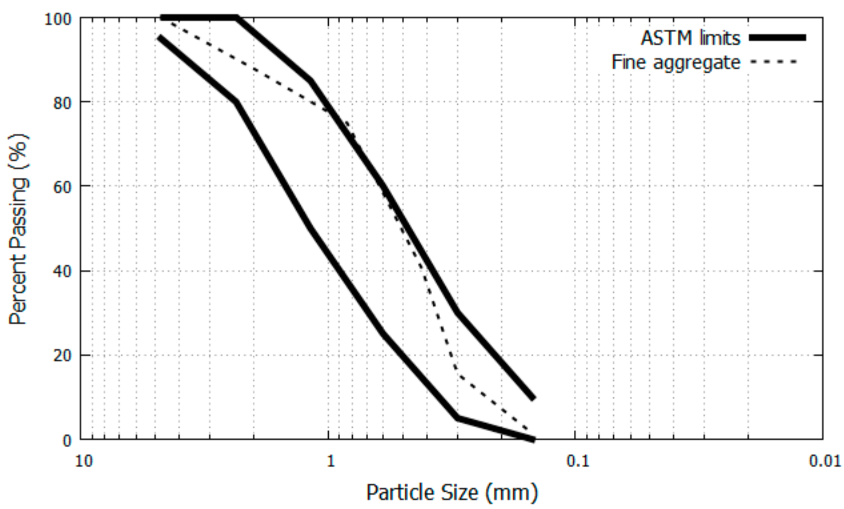


Figure 1. Particle size distribution of fine aggregates.

2.2. Waste Coffee Grounds

Waste coffee grounds were collected at a Starbucks coffee shop on Marshall University's campus. Spent coffee grounds were collected in a 5 gallon plastic pail with a lid. The collected grounds were completely wet. As soon as the coffee grounds were collected, the grounds were dried in an oven at 100 °C for 24 h in the lab and then cooled to room temperature. The dried coffee grounds were stored in a refrigerator until the activation process to minimize possible microbial activity. In addition, the collected coffee grounds consisted of various types of coffee. As grain sizes, colors, and shapes vary in a batch, the collected coffee grounds were gently mixed to homogenize them.

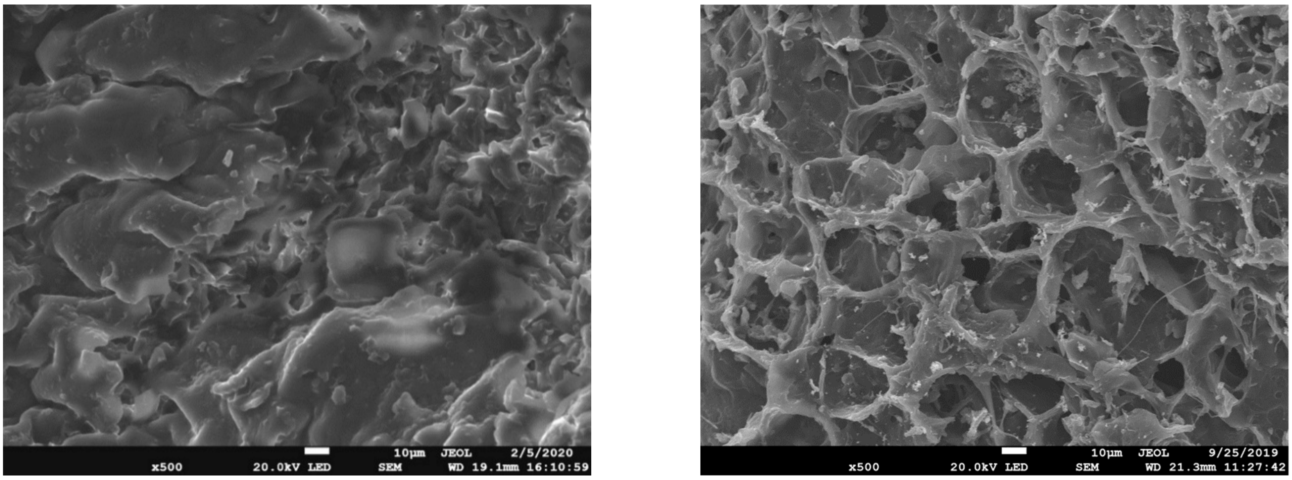
2.3. Activation Process

There are several methods for turning coffee residue into activated carbon. In the physical activation process, both the carbonization and activation steps are done by heating. Some studies reported that activated carbon could be produced just by the physical carbonization step without the activation step [20]. In this study, the physical carbonization process was performed for coffee waste. The coffee grounds were prepared by washing and rinsing with distilled water to remove impurities, drying for 24 h at 100 °C and then sieving to control the grain size. The prepared coffee grounds were then heated to 600 °C for an hour in a muffled furnace. Once cooled to room temperature, the grounds were washed and then rinsed in deionized water again. The grounds were dried for 48 h at 100 °C and sorted using sieves No. 16 and 60 (sieve openings of 1.18 and 250 micrometers, respectively). During the heating process, volatile molecules of the base material sublimed, leaving porous structures throughout [9]. The prepared activated carbon was stored in closed bottles. Dried coffee residue and activated carbon granules obtained after the treatment are shown in Figure 2a,b. Figure 2c,d shows images of both the coffee grounds and activated carbon granules from a scanning electron microscope at a magnification level of 500×. The images revealed that the activation process developed a honeycomb-shaped pore structure that led to a high surface area in the activated carbon, which may have caused morphological symmetry phenomena. We leave the analysis of the morphological symmetry of activated carbon granules for future work, since this paper focuses on the activated carbon/cement composites.

(**a**)

(**b**)

Figure 2. *Cont.*



(**c**) (**d**)

Figure 2. (**a**) Dried coffee residue and (**b**) activated carbon granules obtained after the treatment, as well as SEM images of (**c**) dried coffee residue and (**d**) activated carbon granules at 500×.

2.4. Mix Design and Sample Preparation

Cement mortar samples with different proportions of activated carbon were prepared to evaluate the effect of activated carbon on the compressive strength of normal cement mortar. The cement-to-fine aggregate ratio used was 1:2.75 by weight, according to ASTM C109 [21], and the water-to-cement ratio (w/c ratio) was fixed at 0.44 to achieve full hydration, which had a minimal range between 0.36 and 0.40. Mixing of all cement mortar samples followed the mixing procedure described in ASTM C305 [22]. The activated carbon was first blended with water, and then the blend was mixed with cement to achieve the uniform distribution of activated carbon in a mixture.

Cement mortar cube samples with dimensions of 2 in × 2 in × 2 in were molded. Activated carbon particles passing a No.10 sieve but retaining in a No. 200 sieve were used in this study. The activated carbon/cement composites were prepared by mixing cement with activated carbon with the weight fractions of 0%, 0.5%, 1%, 1.5%, 5%, and 10%. These ratios were chosen to identify the maximum compressive strengths of carbon/cement composites. The literature suggests the maximum compressive strength of cementitious composites with carbon additives (e.g., activated carbon or carbon fiber) are found when they are added around 1% by weight [23–27]. In addition, 5% and 10% were selected to investigate extreme scenarios when excessive amounts of activated carbon were used. Thirty-six cube specimens were cast for each mixture. All cube specimens were cured in water at room temperature until compression strength testing at 7, 21, and 28 days. Twelve specimens for each mixture were tested after each specified curing day. The mix design of the cement composite mortars is presented in Table 1.

Table 1. Mix design of activated carbon/cement composites.

Material	Weight Ratio
Portland Cement	1
Dry Graded Sand (−No. 10)	2.75
Water	0.44
Activated Carbon (−No. 10 and +No. 200)	0, 0.005, 0.01, 0.015, 0.05, and 0.1

2.5. Compressive Strength Test

The compressive strengths of the cube samples were measured at 7, 21, and 28 days in accordance with ASTM C 109. Each representative compressive strength was the average of twelve specimens. The measurement of strength was carried out using a concrete compression machine (MC-300CL, Gilson Company) with a maximum capacity load of 300,000 lbs.

3. Experimental Results

Compressive Strengths of Test Specimens

The results of the compressive strength tests are presented in Table 2. It should be noted that the samples of 5% and 10% activated carbon at 21 days were not tested due to the substantial decrease of the strength measured at 7 days. The results verify that the compressive strength of normal cement mortar increased as the curing time increased. The same trend was also observed in the activated carbon composite samples. The 7 day strength of cement mortar without activated carbon reached 66% of the 28 day strength, while the 7 day strength of the 0.5% and 1% activated carbon composite reached 80% and 73% of the 28 day strength, respectively. This implies that a small concentration of activated carbon may accelerate the strength hardening process. Excessive concentrations equal to and greater than 1.5% removed the early strength effect. Furthermore, the excessive content of activated carbon greater than 5% led to a substantial decrease in strength. Adding 5% activated carbon decreased the 7 day compressive strength of normal cement mortar by 28% and the 28 day strength by 21%. Adding 10% sharply decreased the 7 day strength by 50%, while the 28 day strength decreased by 52%. These results indicate that the incorporation of activated carbon greater than the optimal range harms the strength of normal cement. The optimal range of the content that increases the compressive strength was observed between 0.5% and 1.5% in this study.

Table 2. Compressive strength of cement/activated carbon composites.

Activated Carbon (%) by Weight	Compressive Strength (psi)		
	7 Days	**21 Days**	**28 Days**
0	3742.1	5316.0	5599.5
0.5	5535.3	5743.8	6870.6
1	4344.1	5939.4	5969.4
1.5	4203.2	5623.5	7084.9
5	2697.2	N/A	4413.4
10	1869.9	N/A	2671.2

Figure 3 visualizes the relationships between the carbon contents, strength, and weight of the cement mortar. The graph on the left indicates the change of strength with respect to the carbon content, and the graph on the right presents the strength versus the weight of the test specimen. In addition, the graph at the bottom exhibits the carbon content versus the weight. It is worth noting that adding carbon slightly decreased the weights of the specimens. This is because lightweight carbon granules might replace relatively heavyweight fine aggregates or cement in a confined volume of the specimen. Despite the loss of weight, the carbon-blended samples showed increased strength compared with the normal cement mortar specimens.

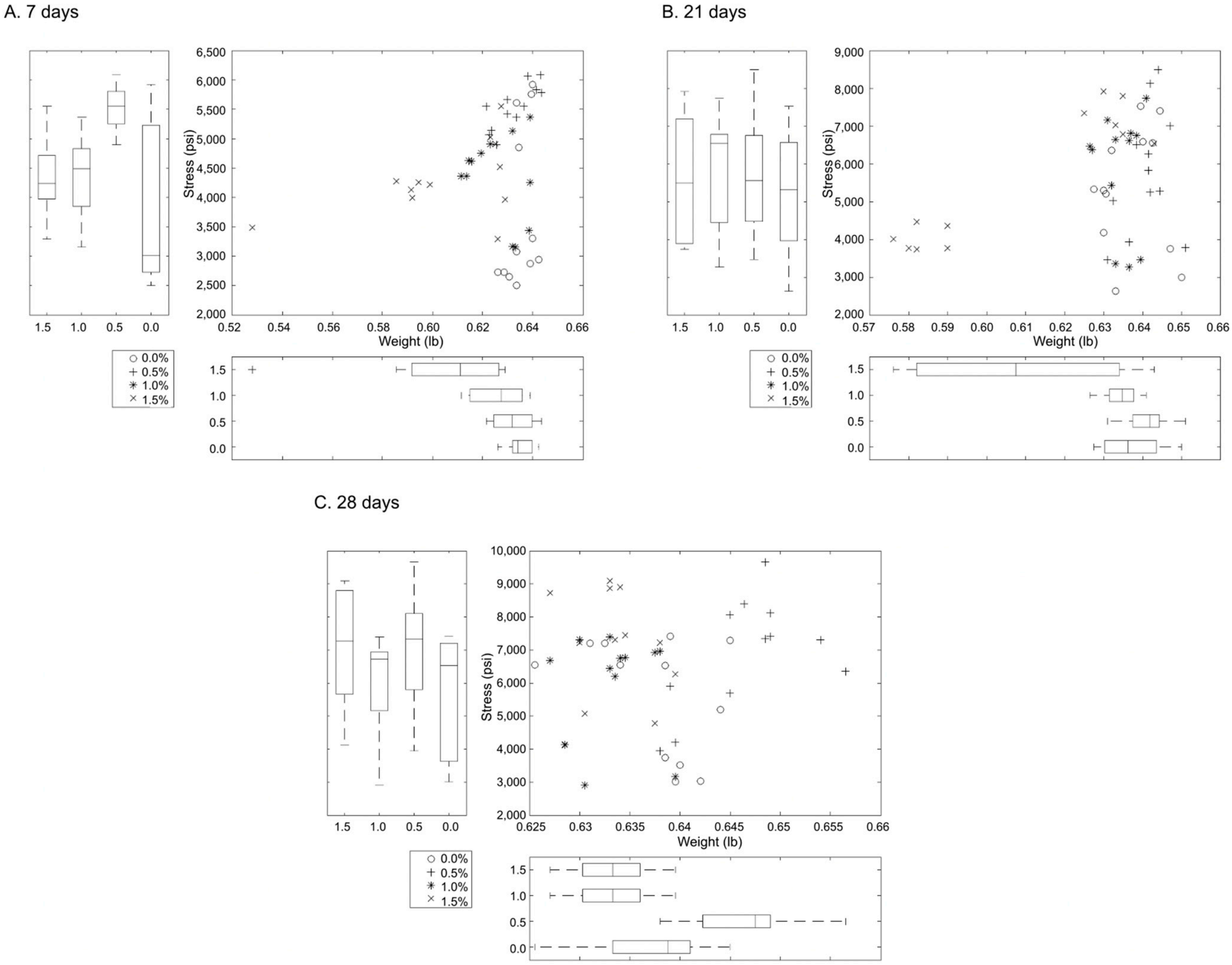


Figure 3. Relationship between activated carbon contents, compressive strength, and specimen weight.

The effect of the activated carbon content on the compressive strength is shown in Figure 4. The results show that the cement mortar strength increased as the incorporation of activated carbon content increased up to 1.5%. Adding 0.5% activated carbon drastically increased the 7 day strength by 48%, while incorporating 1.5% increased the 28 day strength by 27%. Similar results that showed an increase of the strength by the addition of activated carbon have been reported by other studies. Zeng et al. [28] found that the incorporation of 4% activated carbon into fly ash cement increased the 28 day compressive strength by 18%. Justo-Reinoso et al. [23] also reported that the replacement of fine aggregates with a small amount of granular activated carbon (1% and 2% by weight) increased the 7, 14, and 28 day compressive strength of cement mortar, whereas greater concentrations from 4% to 10% reduced the strength.

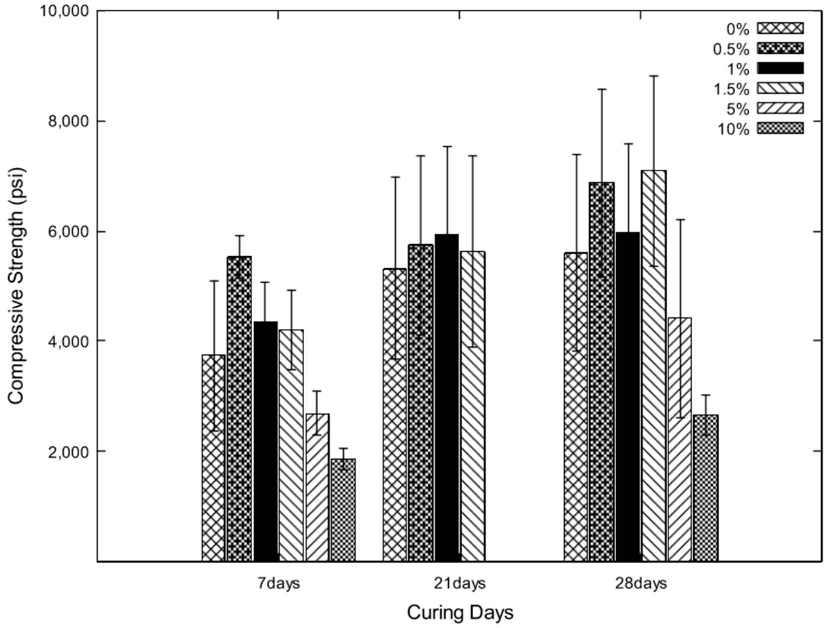


Figure 4. Effect of the activated carbon content on the compressive strength of cement mortar.

4. Discussion

The compressive strength test results revealed that a small amount of activated carbon up to 1.5 wt% increased the compressive strength of normal cement mortar, whereas the excessive amount equal to or greater than 5% substantially decreased the strength. Similar results have been reported by other studies, although the number of studies pertinent to activated carbon as an additive to cementitious materials is limited. Ersan et al. [29] found that the addition of granular activated carbon increased the 7 day and 28 day compressive strengths by 9% and 13%, respectively. Justo-Reinoso et al. [23] replaced a small portion of fine aggregate from 1% up to 10% by mass with powdered activated carbon in cement mortar. They investigated the effect of activated carbon on both the compressive and tensile strengths of cement mortar and found that increased strength was observed at 1% and 2%, while the highest strength was measured at 1%. However, higher contents exceeding 4% gradually decreased the strength.

Understanding the mechanism that causes the change of strength would gain insight into the effect of activated carbon on the strength of normal cement mortar. Justo-Reinoso et al. [23] proposed that porous activated carbon acts as micro-reservoirs. Some amount of water in normal cement mortar would be lost to bulk evaporation during the process of hydration reaction. In activated carbon cement mortar, however, water adsorbed to activated carbon granules is redistributed and delivered to cement particles during the progression of the curing process. This microscale curing process caused by local hydration contributes to an increase in the global strength of the cement mortar.

It should be noted that they used activated carbon as a substitute for a portion of fine aggregates. Thus, blending a large amount of activated carbon resulted in strength reduction due to the intrinsic compressive strength of activated carbon granules, which are weaker than fine aggregates. Zheng et al. [30] reported that calcium hydrate (CSH) and ettringite populated by activated carbon filled the hydration gap in fly ash cement composites, resulting in an increase in strength. The type and composition of the cement mortar used in this study were different from other studies. However, it can be assumed that the enhanced strength observed in this study may be attributed to the holding water capacity of activated carbon and the microscale curing process. In addition, the excessive addition of activated carbon above the threshold might hinder the hydration of cement due to a lack of water in the cement.

5. Conclusions

The effect of activated carbon manufactured from waste coffee grounds on the strength of normal cement mortar was studied. The results revealed that adding activated carbon smaller than or equal to 1.5% (by weight to cement) increased the compressive strength of the cement mortar. Furthermore, activated carbon could also accelerate the strength hardening process, resulting in the reduction of curing time. Particularly, a small amount of the content (0.5%) had more meaningful increases in strength at the early stage, while a higher content (1.5%) had better increases at 28 days. However, a large amount of activated carbon exceeding 5% substantially decreased the strength. This study concludes that activated carbon recycled from waste coffee grounds can expect performances similar to those reported in other studies that used commercially available activated carbon products. Therefore, the recycled one can be also used as a potential additive to enhance the compressive strength of cement mortar.

Author Contributions: Conceptualization, S.N. and S.Y.; methodology, S.N. and S.Y.; data analysis, S.N. and S.L.; investigation, S.N.; writing—original draft preparation, S.N.; writing—review and editing, S.N., S.Y., and S.L.; visualization, S.L.; supervision, S.Y. All authors have read and agreed to the published version of the manuscript.

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