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ARTICLE

Low-Energy Recycled Cardboard Powder (RCP) as a Cement Substitute in Concrete: Strength-Based Assessment for Sustainable Construction

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ABSTRACT

Production of cement is one of the major contributors to carbon dioxide emissions in the world, as such, there is motivation to come up with sustainable alternatives to cement production that would cut on the consumption of cement without affecting the structural performance. Out of all the municipal solid waste, cardboard waste is produced in huge amounts and has the potential to be reused in cementitious materials because it contains fibrous cellulose. The paper examines the possibility of recycled cardboard powder (RCP), which is a by-product of a low-energy soaking-drying-grinding procedure, as a partial cement replacement in M25 grade concrete. The concrete mixes with 0%, 0.5%, 1.0% and 1.5% of RCP (weight of cement) were tested regarding the workability and mechanical properties such as compressive strength, split tensile strength, and flexural strength after 7 days and 28 days. Findings have shown that the hygroscopic characteristics of cellulose residues make workability decrease gradually as the cellulose content in RCP increases. Nevertheless, the properties of strength increased with moderate levels of replacement, where 1% RCP mix had the highest compressive strength (31–32 MPa), split tensile strength (3.2 MPa) and flexural strength (4.8–5.0 MPa) at 28 days. The addition of RCP in the content to 1.5% led to a decrease in strength caused by cement dilution and the lower dispersion efficiency. The results indicate that recycled cardboard powder (RCP) can safely be used to a

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high degree of cement substitution at 1% of structural-grade concrete, which provides a perspective of low-energy and sustainable waste-valorization.

Keywords: Recycled Cardboard Powder (RCP); Low-Energy SCM (Supplementary Cementitious Materials); Oman Vision 2040; Microstructural Densification; Low-Carbon Concrete

1. Introduction

1.1. International Environment: Cement and Carbon Emissions

Almost 40% of the total greenhouse gas emissions in the world are due to the construction sector, with the cement production alone constituting about 8% [1]. The process of cement production requires not only the calcification of limestone but also the use of energy-consuming kilns when it is necessary to produce almost 0.9 t of CO_2 per ton of clinker [2]. With the increased rate of urbanization and population, especially in developed areas, the demand for cement is expected to grow by more than 25% by 2050 [3]. This expansion is a direct threat to global climate mitigation pledges as a part of the Paris Agreement [4] and the Sustainable Development Goals (SDGs). Efforts to make carbon neutral construction are starting to focus on alternative binders, additional cementitious materials (SCMs), and waste-based additives [5,6]. The substitution of cement with environmentally friendly cement like fly ash, GGBS (Ground Granulated Blast Furnace Slag), silica fume, or agro-industrial waste greatly reduces embodied CO_2 without deteriorating or affecting performance [7–9]. The shift toward low-carbon concrete, in addition to environmental demands, corresponds to the concept of circular economy that emphasizes resources efficiency and waste value creation.

1.2. Waste Valorization and Paper-Based Additives

The packaging sector of the world creates enormous amounts of cardboard and paper waste, which comprises almost 30% of municipal solid waste in certain cities. Traditional methods of disposal such as landfills or burning also add to the greenhouse gas emissions as well as waste of resources. The reuse of these lignocellulosic materials in concrete manufacture is beneficial on two different levels: (i) it decreases the cement production and, consequently, the CO_2 emissions, and (ii) it removes waste from landfills. The paper and cardboard contain high contents of cellulose and hemicellulose, and these provide the ability to enhance micro-fiber reinforcement in the material in case their contents are properly processed [10,11]. The tensile capacity and crack resistance are increased by their fibrous structure, and fine ash, obtained with the use of paper waste, may serve as a micro-filler, which increases packing density and decreases porosity [12,13]. But the majority of the current literature is based on the method of high-temperature incineration to get ash—the method that subsequently cancels environmental advantages to some extent because of energy consumption [14,15]. Therefore, one of the possible directions that could be taken in the reuse of cardboard waste in a sustainable manner is low-energy recycling, including soaking, drying, and grinding. The techniques are especially applicable in the developing and dry areas where a large-scale burning plant is not possible.

1.3. Sustainability Vision and Construction Demand of Oman

The Sultanate of Oman is experiencing a rapid infrastructure development, where residential, industrial, and transport sectors are growing, which is why the cement demand is also steadily evolving. Meanwhile, the municipal waste management systems experience difficulty due to increasing waste streams of paper and packaging [16]. Circular economy, resource efficiency, and green construction materials are clearly encouraged in the Oman Vision 2040 framework [7,8]. One of the pillars directly supported by using cardboard waste as a cement substitute is the use of the waste. It helps to reduce the dependence on imported clinkers, reduces the land use by decreasing the size of the landfill, and complies with the national strategies of reducing carbon footprint and valorizing the waste. Moreover, in the hot-arid environment of Oman, the use of fibrous waste in concrete can provide the benefit of thermal insulation and, therefore, reduce the use of energy in the buildings [17].

1.4. Research Gap and Rationale

Despite a number of research being conducted on wastepaper sludge ash and cellulose fiber addition, only a few are carried out specifically on recycled cardboard powder (RCP) as a partial substitute of cement in structural-grade concrete. Prior experiments with wastepaper sludge ash proved to have high compressive strength (to 7.5% of replacement) [18] but demanded high burning temperatures (>700 ℃) that compromise sustainability. Some of them also found increased tensile strength with paper fiber reinforcement but failed to evaluate its application as a cementitious substitute [19]. In addition, most of the past work had been done in mortar or mini-sized samples, which did not apply to whole structural concrete use [20,21]. Another gap in the literature is the lack of investigations that may relate such materials to the national sustainability frameworks such as Oman Vision 2040 which are region-specific. This study fills those gaps by discussing M25-grade concrete containing RCP which is prepared using a low-energy process, its mechanical behavior, and its implications regarding environmental management.

Research questions and hypotheses:

What is the impact of low RCP dosage on workability and strength at 7/28 days?

What is the ideal dosage capacity between strength retention and workability in the field?

H1. *Low dosage enhances packing, tensile/flexural response through micro-filler/bridging, reduces strength through reducing effective water and compaction.*

1.5. Aim and Objectives

The primary objective of the research would be to design and test low-carbon concrete with the use of recycled cardboard as ash as partial cement replacement and help reduce the amount of waste and mitigate the emission of pollution. Objectives involve:

1. Comparing compressive, tensile, and flexural strength of concrete mixes in the presence of 0%, 0.5% and 1.5% recycled cardboard powder (RCP).
2. To check the workability of these mixes against conventional M25 concrete.
3. To identify the best level of replacement between strength and sustainability.

2. Literature Review

2.1. Waste Materials Used in Sustainable Concrete

Sustainable Concrete refers to waste materials such as wastepaper and cardboard that can be recycled to produce concrete. The amount of wastepaper and cardboard is one of the most widespread urban solid wastes in the world. They have been studied in terms of their incorporation in cementitious materials because of the desirable fiber morphology and renewed nature [22]. The ash and fiber derived out of paper may be used as partial replacements of cement or reinforcing fillers. These materials increase tensile and flexural strength at lower doses (below 2%), fill in microcracks, and elevate water demand and also strength at higher doses [23].

Internal reinforcement in the matrix is represented by cardboard fibers, which feature a honeycomb microstructure and a remainder of the lignocellulose [24]. They enhance microcrack resistance to cracks and minimize microcracks caused by shrinkage, which leads to ductility when distributed appropriately. On the other hand, over addition leads to low compaction and porosity.

2.2. Wastepaper Sludge Ash Studies

Initial research of wastepaper sludge ash (WPSA) determined the possibility of utilizing paper-derived residues as SCMs. Poloju et al. [24] showed that compressive strength was not affected by a replacement of up to 7.5% of cement using WPSA, but preparation involved calcification at temperatures of 700 to 800 ℃. Poloju [25] tested 0.5–1.5% paper ash in cement mortars and found that there was a decrease in permeability but a moderate loss in strength.

2.3. The Mechanisms of Recycled Cardboard Powder (RCP) in Concrete

The mechanism of cardboard powder is mainly micro-filler and fiber-bridging as opposed to pozzolanic SCM which reacts with calcium hydroxide chemically. Its fine particles occupy interstitial spaces of the cement matrix causing a high packing capacity and low permeability [26]. Furthermore, the leftover trace cellulose fibers in the ash produce mechanical interlocking in the microcrack locations to improve tensile performance. The high ability of the cellulose to hold water, however, may modify the effective water-cement ratio, and so, it affects the workability and the hydrostatic kinetics. Similar phenomena were found by Onyejekwe and Ghataora [19] in the paper ash-modified concretes where moderate concentrations enhanced the slump consistency, whereas excess fiber content caused loss of water and segregation. Therefore, dosage optimization will be required to make use of filler and fiber benefits without creating an imbalance of moisture.

2.4. Comparison with Other Industrial and Agricultural Wastes

In comparison to the traditional SCMs, i.e., fly ash, GGBS or rice husk ash, recycled cardboard powder (RCP) has lower pozzolanic activity and higher fibrous contribution. Fly ash and slag are either siliceous or alumina which form more calcium silicate hydrate (C–S–H) phases, whereas RCP improves the physical packing and microstructural densification An example of such is rice husk ash which enhances the compressive strength because of the high amorphous silica content [2], it has a low reactivity which limits its performance. However, it has a beneficial impact on the environment due to low-temperature processing and the absence of waste valorization. Hybrid mixtures can be used with reactive SCMs, and they can have synergistic mechanical and environmental advantages [12].

2.5. Durability and Impact on the Environment

Although not much literature evaluates the structural permanence of the paper-based concrete, available findings indicate that the low ash content decreases the porosity and water absorption and thus enhances the resistance to chloride intrusion [26]. Nevertheless, in the alkaline cement, natural fibers can deteriorate, and voids develop over time [27–31]. Such effects can be countered by stabilization techniques such as silica coating or mixing with mineral SCMs. Regarding the environment, partial replacement of cement has real carbon savings. The amount of emissions of CO_2 saved by replacing each ton of cement is about 0.9 t of CO_2 [1]. In addition, the reuse of cardboard waste will decrease the release of methane in anaerobic waste in landfills, which is a direct contribution to United Nations (UN) SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Consequently, low rates of substitution (0.5–1.5) have potential to lead to significant emissions cuts even when implemented on a large-scale infrastructure construction. Recent literature has demonstrated an increasing interest in the recycled paper/cardboard cellulose fibers as a low-carbon reinforcement in cementitious composites primarily to enhance crack-bridging/toughness and convert waste streams into useful products. A multi-dimensional study by Patrisia et al. [27] specifically utilized cellulose fibers of paper and cardboard and tested both strength and durability and microstructure, which appear to be highly controlled by (i) the variability of the fiber source, (ii) dispersion quality and fiber-matrix interface, and (iii) the transport durability indicators, which may change over mix design and processing. To this end, more general synthesis papers on wastepaper-based cellulose fiber-cement composites indicate that the chemistry of the raw material and a processing regime influence the binder formation, pore architecture and durability behavior. In a further move towards boosting durability positioning, evidence suggesting the practice of framing cellulose-fiber composites around a basal expected durability test suite that underlines transport properties has been advanced in the recent past. One such study is by Yuvaraj et al. (2026) [28], which determined durability by rapid chloride permeability testing (RCPT), water absorption, and porosity, as well as microstructural Scanning Electron Microscopy (SEM), which showed an applied template of durability evaluation by transport that can be applied and extended to cellulose/cardboard research. The current research paper will use recycled cardboard powder (RCP) of M25 structural concrete and assess fresh and hardened properties under controlled cured conditions.

3. Materials and Methods

3.1. Research Design

This research adopted a quantitative experimental design which was geared towards assessing the impact of a partial substitution of Ordinary Portland Cement (OPC) by recycled cardboard powder (RCP) on the fresh and hardened properties of concrete (M25) of structural grade. Four mix proportions were made with 0%, 0.5%, 1%, and 1.5% to the weight of cement as shown in **Figure 1**. The experiment concerned workability, compressive, split tensile and flexural strengths at 7 and 28 days of curing. The design was designed according to the ASTM (American Society for Testing and Materials) and ACI (American Concrete Institute) to get reproducibility and comparison with conventional concrete (ASTM C39 2021; ACI 211 1991) [32,33]. The independent variable was the proportion of cement that was substituted and assessed slump, compressive, tensile and flexural strength were the dependent variables. The control mix (0%) was used as a benchmark in performance comparison.

3.2. Materials

Each of the constituent materials meets the required ASTM specifications as shown in **Table 1** below.

The obtained ash still contains remnants of cellulose fiber, which can possibly serve as micro-fillers and crack-bridging structure [34,35]. The current investigation did not assess loss on ignition (LOI), the elemental oxide composition using X-ray fluorescence (XRF), or the carbon/organic content analysis using CHNS (Carbon–Hydrogen–Nitrogen–Sulfur Analysis). Such characterizations will be done in the future to allow material fractionation and a more explicit separation of the respective contributions of filler effects and fiber-reinforcement mechanisms.

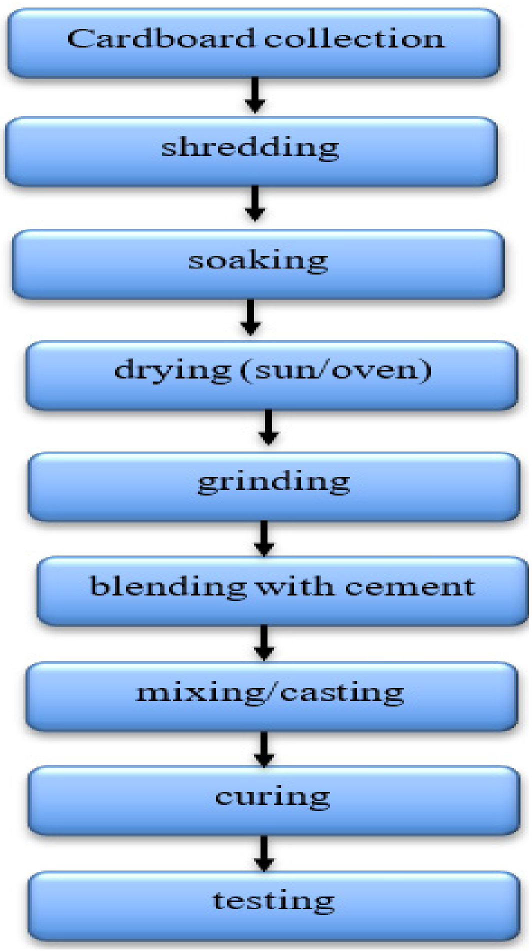

Figure 1. Experimental flowchart.

Table 1. Material and description.

Material	Specification	Description
Cement	ASTM C150/C150M (2020) ASTM C150/C150M	43-grade; specific gravity 3.15
Fine Aggregate	ASTM C33/C33M (2018)	Natural river sand, fineness modulus 2.65, clean and well graded.
Coarse Aggregate	ASTM C33/C33M (2018)	Crushed granite, nominal max size 20 mm
Water	ASTM C1602/C1602M (2018)	Potable tap water without harmful components
Recycled cardboard powder (RCP)		Local product or recycled Shredded, soaked, dried and ground recycled packaging cardboard less than 75 µm.

3.3. Mix Proportion

Concrete proportions were established according to the ACI 211.1 [36] method of normal-weight concrete that was aimed at obtaining a 25 MPa characteristic compressive strength with a water-cement ratio of 0.50. No water correction or pre-saturation was implemented since the purpose of the research was to test practical feasibility under constant w/c = 0.50 but this is recognized to be one of the factors that affect slump at high RCP concentration.

The initial mix ratio (by weight) consisted of 1:1:2 (cement: sand coarse aggregate) as shown in **Table 2**.

Table 2. Description of different percentages.

Category	Description
Independent variable	RCP dosage (0%, 0.5%, 1.0%, 1.5%)
Dependent variables	Slump, compressive, split tensile, flexural
Constants	w/c = 0.50, specimen types/sizes, curing 23 ± 2 °C, test ages 7 & 28 days.

At 0.5%, 1.0% and 1.5% cement was substituted by recycled cardboard powder (RCP) keeping the total binder mass constant.

Specimens cast per mix:

Cube molds (150 × 150 × 150 mm) for determining Compressive strength ASTM C39 [36].

Cylinders (150 × 300 mm) → Split-tensile strength.

Beams (100 × 100 × 500 mm) → Flexural strength.

In both tests, three replicas were used to obtain the mean values and standard deviations.

3.4. Mixing, Casting, and Curing

The dry material (cement + ash, sand, aggregates) was combined using a mechanical pan mixer for approximately 3 min, and water was slowly added until the consistency was produced. The recycled cardboard powder is prepared as shown in **Figure 2** and cast concrete specimens using respective moulds as shown in **Figure 3**. Later, the specimens were demoulded after 24 h as shown in **Figure 4** and kept for curing in water at 23 ± 2 °C and tested at different ages (7 and 28 days) as shown in **Figure 5**. Representative hydration and early age development of strength were made possible by this curing regime. No batches were lost or recast; all specimens were done using the same procedure, that is, uniform mixing, casting and demoulding after 24 h.

Figure 2. Recycled cardboard powder.

Figure 3. Preparation of samples.

Figure 4. Demoulded specimens.

Figure 5. Samples immersed in water for curing.

4. Results

4.1. Workability (Slump Test)

Figures 6 and **7** and **Table 3** show the preparation and finding the workability of fresh concrete using the sump cone apparatus. It is revealed that the decrease in the concrete was gradual with the percentage of RCP to be added. Control mixes were the most workable even though mixes containing RCP were less slumping due to the ability of cellulose-based particles to hold a lot of water. However, this concrete which was mixed up to 1% with RCP could still be cast without any chemical admixtures.

Standard vibration practice had been used to consolidate the mixes and was workable when it was possible to place and compact without appreciable surface segregation/honeycombing.

4.2. Compressive Strength

The compressive strength grew at an intermediate level of replacement and decreased beyond the optimum as presented in **Table 4** and **Figure 8**. The maximum mean strength of the material at both ages was recorded in the recycled cardboard powder (RCP) mixture (1%) which demonstrates that it has good particle-packing and filler characteristics.

The compressive strength outcomes also indicate that apparent age is dependent on the strength development of all mixes with 28-day strengths that are superior to those of 7-day strength as anticipated of normal-weight concrete. After 28 days of life, the compressive strength of the control mix was approximately 28 MPa which met the grade of M25. RCP concentrations of 0.5% and 1% enhanced compressive strength and the highest compressive strengths of approximately 31–32 MPa were achieved in 1% RCP mixture. However, the value was lower than the characteristic strength requirement as the content of RCP was raised to 1.5%, at which the value had been weaker. The increase in M1.5 is also greater at 28 days, which is in line with hydration persistence, although the decrease with early age is probably indicative of less sensitivity to effective water and compaction at higher RCP content (trace back to slump) [37].

Figure 6. Preparation and testing workability using slump cone apparatus.

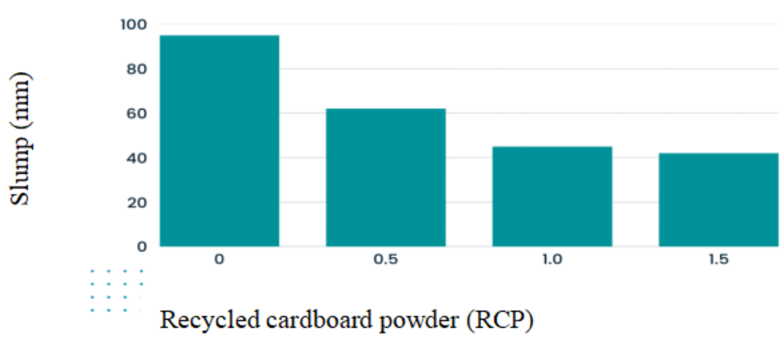

Figure 7. Slump vs. replacement level plot.

Table 3. Slump values.

Mix ID	Recycled Cardboard Powder (RCP)	Slump (mm)
M0	0	95 mm
M0.5	0.5	62 mm
M1	1.0	45 mm
M1.5	1.5	42 mm

Table 4. Results for Compressive strength (MPa) after 7 and 28 days.

Mix ID	7 Days	28 Days
M0 (0%)	18.3	27.9
M0.5 (0.5%)	19.5	29.5
M1 (1%)	21.2	31.5
M1.5 (1.5%)	16.9	26.3

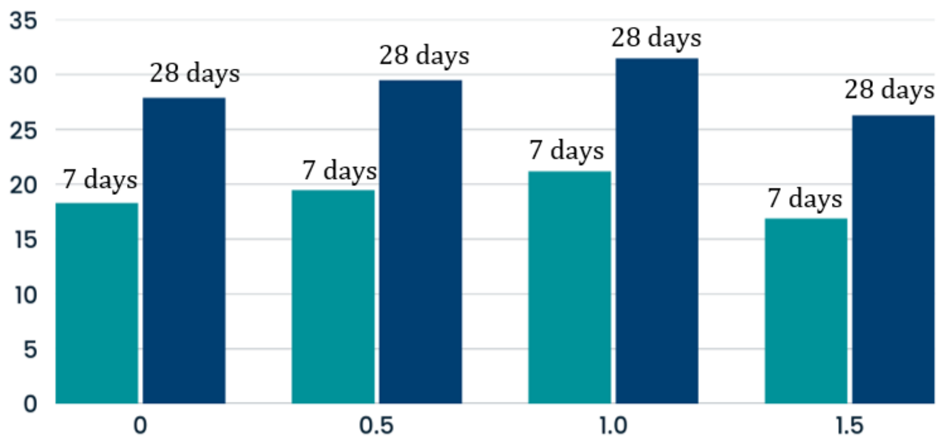

Figure 8. Results for compressive strength (MPa) after 7 and 28 days.

4.3. Split-Tensile Strength

Table 5 and **Figure 9** show the trend of tensile strength whereby 0.5% and 1% mix showed slight improvement as a result of the fiber-bridging of the left cellulose. The tensile capacity was low due to the low dispersion of the 1.5% mixture.

The split tensile strength and compressive strength showed a similar trend as **Table 5**. At 7 days, tensile strength ranged between 1.9 and 2.4 MPa which corresponds to 70% to 75% of tensile strength at 28 days. The tensile strength of the control mix stood at about 2.6 MPa in 28 days' time, and the tensile strength of 1% RCP mix was at its highest and stood at 3.2 MPa. The reduced percentage of 1.5% RCP replacement has been observed to be caused by dilution of cementitious material and decreased efficiency of transfer of stress [38].

4.4. Flexural Strength

Table 6 and **Figure 10** indicate that the flexural strength also increased when the percentage of RCP was added up to 1% replacement with values of 28-days falling between 4.6 and 5.0 MPa, which are normal in M25 concrete. The fact that the moderate RCP levels had increased would suggest that the resistance to crack initiation under bending loads was also increased. It showed a slight reduction in flexural strength at 1.5% of RCP content and that also indicates that it is less efficient at a high level of replacement.

Table 5. Results for split tensile strength (MPa) after 7 and 28 days.

Mix ID	7 Days	28 Days
M0	1.9	2.6
M0.5	2.1	2.9
M1	2.4	3.2
M1.5	2.0	2.7

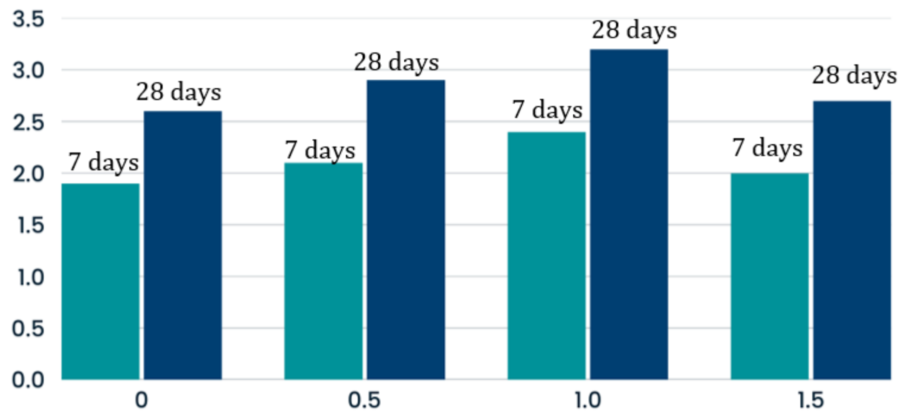

Figure 9. Results for split tensile strength (MPa) after 7 and 28 days.

Table 6. Flexural strength (MPa).

Mix ID	7 Days	28 Days
M0	4.16 MPa	4.63 MPa
M0.5	4.26 MPa	4.49 MPa
M1	4.29 MPa	4.03 MPa
M1.5	3.74 MPa	4.43 MPa

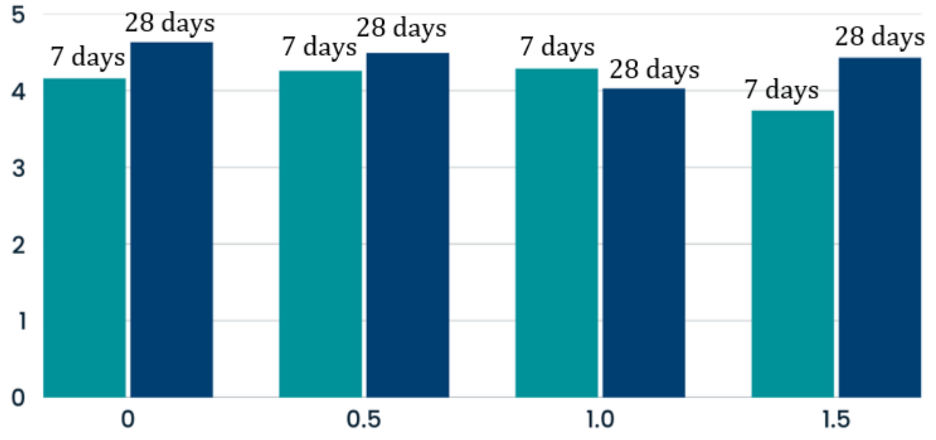

Figure 10. Results for flexural strength (MPa) after 7 and 28 days.

Risks of Durability and Service-Life of Cellulose-Containing Cementitious Systems

One of the main durability issues in cellulose-reinforced cementitious composites is that alkaline degradation of cellulose in the presence of very high alkalinity of pore solution (pH 12.5–13.5) can gradually depolymerize the cellulose polysaccharide backbone and reduce tensile strength of the fibers and the bond between the fibers and the matrix. The key degradation mechanisms, which take place both in the amorphous and crystalline regions of cellulose and involve a peeling and chain-scission reaction, have been elucidated mechanistically and this has provided a solid chemical foundation to predict durability risks of cementitious environments with time [38]. Also, the void formation can be caused by the swelling-shrinkage cycles of fibers, low dispersion, or interfacial debonding, which results in a greater number of permeable pore structures and localized microcracking; this risk is especially significant in waste-based cellulose fiber systems, where the composition of the source has variable effects on durability indicators such as absorption and porosity [11]. Moreover, the hygroscopic cellulose character also leads to sensitivity of moisture transportation, which may change sorptivity, internal curing characteristics, as well as long-term permeability behaviors. As such, in line with the current durability assessment models suggested by ASTM C1585 and ACI 211.1, future research must also include an anticipated durability test battery that, in admiration of the collected durability assessment models, incorporates rapid chloride permeability testing (RCPT), water absorption, and total porosity tests to objectively assess transport-controlled deterioration controls and benchmark mix optimization approaches.

4.5. Mechanistic Interpretation Founded on Microstructural Evidence Based on Literature

Though no experimentally conducted direct microstructural characterization methods like Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), or isothermal calorimetry were carried out as part of the present study, the trends in observed mechanical performances can be discussed in terms of already established literature in the context of hydration and filler-mechanism of inert and cellulose-based additions to cementitious systems. The increase in strength at 1% RCP replacement is also in line with the well-recorded micro-filler and nucleation-assisted hydration processes of fine inert particles in cement matrices [39]. Even non-pozzolanic ultrafine particles can enhance the particle packing density, optimize the distribution of capillary pores, and offer other nucleation sites on which C–S–H precipitation takes place early. This is commonly known as the filler effect or the seeding effect and has been actively reported in limestone powder and other mineral non-reactive additions.

In these systems, fine particles enhance the surfaces open to hydration, which are able to quickly react to hydration, improve the densification of matrices, reduce interfacial transition zone (ITZ) porosity and enhance moderate replacement levels of compressive strength.

The compressive strength increase at 1% RCP replacement in the current study is in line with this nucleation-dominated regime. Besides the filler densification, the leftover cellulose level of recycled cardboard powder can also be a contributor to the crack-bridging and redistribution of stresses mechanism at low dosages. Past researchers have found that low fiber content (less than 2%) can be used to improve tensile and flexural properties by hindering the propagation of cracks, increasing fracture energy and fostering false-ductile behavior.

This has been witnessed in cellulose fiber-cement system and microcrystalline cellulose-modified mortars [40–44]. The present work finding improvement in the split tensile and flexural strength at 0.5–1% replacement of RCP is thus in line with the literature backed fiber-assisted toughening processes. But strength was found to decrease with an increase in the dosage of RCP to 1.5%. This tendency is in line with two competing processes that can be often found in filler-modified systems, such as cement dilution effect, where the reactive clinker is substituted with non-reactive material, the amount of hydrate that forms per unit of volume decreases and thus ultimate strength is lowered [43,45] and the influences of water intake and dispersion where the cellulose-based ingredients are hygroscopic and can lead to the reduction of the effective free water as well as high internal friction in the mixing. Fiber agglomeration can also result in localized weak spots and void clustering at larger dosages, resulting in a lower mechanical efficiency [41–45].

It has been shown that inert fillers, lignocellulosic fibers and waste-derived cellulose systems of cement composites exhibit an inverted-U strength profile (strength improves with low dosage, strength decreases with high dosage) [41–43].

Regarding phase formation, past XRD studies of related inert or cellulose-based systems in general have reported that no additional crystalline hydration phases were formed, minor changes in peak intensity of Portlandite because of dilution, and the modifications in the amorphous C–S–H hump with densification and not chemical activity.

These observations suggest that these materials work under physical as opposed to pozzolanic mechanisms. RCP has performed in the current study as can best be explained by micro-filler packing of physical type, low dose hydration (assisted by nucleation) and higher dosage dilution not reactive.

The future research will include direct microstructural validation using SEM imaging, XRD phase analysis, mercury intrusion porosimetry (MIP), and isothermal calorimetry to not only give quantitative verification of the proposed mechanisms and correlate transport properties to the mechanical behavior.

4.6. Hydration Kinetics Interpretation

It was not conducted in the present study but the trends in strengths and workability can be explained based on well-known hydration kinetics mechanisms of (i) inert/filler additions, (ii) cellulose-based fibrous additions. Fine inert particles can also co-exist in cement systems to generate (a) nucleation/seeding (enhanced early C–S–H formation) and (b) dilution (lowering clinker content, and overall volume of hydrate at increased replacement) effects. This dichotomous behavior has been frequently documented in limestone and other non-reactive fillers, where the fineness of particles controls whether the acceleration process (nucleation) or the retardant/weakening process (dilution) prevails [43–45].

At low RCP dosage (1%), the increase in performance is consistent with a regime in which the micro-filler/nucleation contribution is dominant: fine RCP particles have the potential to offer more surfaces on which hydrate can be precipitated, and to facilitate the early formation of a connected C–S–H network, which can be observed in calorimetry as a small enhancement in the intensity of the main hydration peak and/or a slight leftward shift of the main peak to earlier times, accompanied by enhanced early densification of the matrix. The same trends of acceleration by surface are claimed in calorimetry of ultrafine fillers and nucleation promoters [40,41]. In the case of increased RCP dosage (1.5%), two processes may be used to oppose the nucleation advantage:

(i) Cement dilution, which decreases the amount of total heat released and hydrate generated/unit volume.

(ii) Dispersion/absorption due to cellulose-containing constituents, which may momentarily tie up mixing water and/or react with ions, may tend to give rise to a longer induction period or slow heat evolution based upon dosage and surface chemistry. Investigations of cellulose nano/micro additives and microcrystalline cellulose in cementitious matrix show that the addition of cellulose has dose-dependent effects on calorimetry, i.e., it accelerates the process when dispersed well and sufficient water is present (absorption/interaction) and retards it when dispersed poorly and when water is not adequate (absorption/interaction).

The hypothesis to which the proposed mechanism is applied is, therefore, as follows: 1% RCP is placed in an optimal position: there is sufficient fine solid surface to promote nucleation/packing, and, at the same time, the binder is available and dispersed in sufficient amounts. Also at 1.5% RCP, the dilution and clustering/dispersion inefficiency begins taking more effect and hence would be predicted to cause a decrease in cumulative heat and decrease in the later-age hydrate volume required to provide strength. [40–43].

5. Discussion

This experiment can ascertain that recycled cardboard powder (RCP) does play an important role in determining both fresh and hardened strength properties of M25 concrete and its behavior highly depends on the extent of substitution. The observed reduction in the slump with the rise in the RCP content correlates to the hygroscopic nature of the cellulose-based residues which absorb part of the mixing water and raise the internal friction of the fresh matrix gradually. Other forms of workability decreases have been widely noted in concretes that have wastepaper ash and cellulose-based additives [6,23]. Despite such a tendency, even 1% of RCP mixes were decently working, which implies that even low doses do not possess a critical value of disrupting fresh-state performance.

Recycled cardboard powder (RCP) was of hygroscopic and fibrous nature, with residual cellulose particles included in the powder which primarily contributed to the progressive reduction of slump with increasing recycled cardboard powder (RCP) content. As compared to the traditional mineral SCMs, RCP also incorporates those lignocellulosic residues that have a high-water absorption capacity that reduces the free mixing of water and increases internal friction within the fresh matrix. A proportional decrease in workability has been positively reported with concrete containing wastepaper sludge ash and cellulose fibers whereby the water sorptivity together with angular particle morphology increased in either mix viscosity and slump flow reduced [19,20]. The outcomes of strength tests indicated that the optimum RCP replacement level is 1% because it registered the highest compressive, split tensile as well as flexural strength. Such action can be attributed, primarily, to physical processes rather than the chemical activity of pozzolana since recycled cardboard powder (RCP) is also reported to have traces of reactive silica in small concentrations and is evidenced by observations made from SEM.

Low replacement level RCP finely ground particles can be used as micro-fillers in facilitating the improvement of the particle packing (reducing interior void) and the transfer of stress in the cementitious matrix [14]. This is what explains the increase in compressive strength with the 1% replacement being put into consideration in comparison to the control mix. The growth of split tensile strengths and flexural strengths of the 0.5–1% RCP replacement also suggests the existence of residual cellulose fibers which contributed to the closing of the microcracks and to the slowing down of the crack propagation.

Previous researchers have reported similar enhancement in tensile-related properties in paper- and cellulose-modified concretes by maintaining the fiber content at a low level and dispersed well even when keeping the fiber content at a low level [24]. The same interpretation can be justified by the reduction in crack propagation rate and an increase in ductility in RCP-modified specimens.

A weakening of 1.5% was achieved. This diminution is normally associated with cement dilution and poor dispersion of fibrous particles that might form zones of weakness and reduce the bond strength of the paste and aggregates. The excessive presence of cellulose also increases the uptake of water which in effect decreases the water available to hydrate cement and thus leaves the topography of cement incomplete [15]. The same strengths have been shown to decrease with dosage with wastepaper sludge ash and additional waste-based lignocellulosic concrete [31].

In general, the trends of the strength of the additives of paper and cardboard in the given paper can be considered as similar to the existing literature, which suggests the fact that paper- and cardboard-based additives can be used with the minimal level of substitution, when the filler action and micro-reinforcement work predominantly, and when the forces of dilution are not predominant. The findings of the test prove that the recycled cardboard powder (RCP) can be a viable additive to a structural-grade concrete up to 1% of cement replacement with no significant impact on the strength of the product and, therefore, as a low-carbon substance, there is a chance it can be used in waste-valorization, which is low dosage (around 1%), it could lead to the cohesion of particles, and the reduction of micro-voids, and in high dosage, the absorbed water in the product will lower effective w/c. **Table 7** demonstrates the durability structure.

Table 7. Proposed Durability Evaluation Framework.

Test	Standard	Purpose
Water absorption	ASTM C642	Porosity evaluation
Sorptivity	ASTM C1585	Capillary suction
RCPT	ASTM C1202	Chloride permeability
SEM	—	ITZ + fiber-matrix bonding
XRD	—	Phase identification

5.1. Strength Development and Optimum Replacement Level

The results of strength test show in a decisive manner that there is an optimum level of RCP replacement of 1 above which there is a decline in the mechanical performance. At this dosage, compressive and split tensile as well as flexural strength were higher than the control mix at 7 days and 28 days. This is largely governed by physical processes rather than chemical ones as RCP is not pozzolanic as fly ash or GGBS. Finely ground RCP, at low replacement levels, is a micro-filler, that improves the particle packing density and fineness in capillary pore structure particularly in an interfacial transition zone (ITZ). This presence of fine particles provides additional sites of nucleation in the C–S–H precipitation that enhances the fast hydration and better densification of the matrix [14]. Simultaneously the left-over cellulose fibers assist in sealing the micro-cracks and redistribute the tensile stresses as well as avert the localization of cracks in that sense, credited to the gains in the split-tensile and flexural strengths realized. The 1.5% replacement loss is also consistent with a disadvantage coupled of dilution and clustering effect where excess non-reactive material replaces cement clinker and fiber agglomeration forms weak spots and trap voids. Other involved inverted-U strength trends have been observed on wastepaper sludge ash, bamboo fiber and other lignocellulosic additives where strength increase is restricted to smaller dosage levels (<2%) [17].

5.2. Mechanisms of Tensile and Flexural Performance Enhancement

The great improvement of both split-tensile and flexural strength with 0.5–1% RCP replacement is telling of the relevance of the mechanism of fiber-induced toughening. Remnants of cellulose hinder the crack propagation since under tensile and bending forces they bridge the microcracks and dissipate the fracture energy, preventing further propagation of cracks and showing pseudo-ductile behavior. The latter observation is supported by the altered failure modes that were exhibited in the RCP-modified specimens in which smaller and distributed cracking modes were found as opposed to the brittle failure of the control mix. The previous literature on paper-fiber-reinforced concrete had previously achieved similar gains in modulus of rupture and post-cracking behavior, and in particular cases where fiber dispersions were smooth and volume proportions were controlled [24]. However, with the increased levels of RCP content to 1.5%, fiber agglomeration and undercoating of pastes will render the effective transferring of stress ineffective which explains the minor drop in flexural strength and early cracking that is being experienced in the present experiment.

5.3. Hydration Microstructure Interactions

The mechanical trends of this research are more or less similar to those which were recorded for SEM, XRD, and MIP of cellulose based cementitious systems although no microstructural characterization was made in this study. The literature has demonstrated that the ideal paper-based additives can densify the ITZs, reduce the size of the portlandite plates in addition to refining the pore structures by transforming the predominant pores to those of gel scales [13]. This 1% enhancement in the replacement of RCP could be attributed to nucleation-assisted hydration, i.e., fine ash particles are employed as growth centers of hydration products, without consuming $Ca(OH)_2$ in a significant amount. At greater replacement, the role of dilution dominates and ensures that not all hydration occurs and that the porosity increases which is similar to the findings of XRD and calorimetry of both low-reactivity bio-ashes [2].

5.4. Environmental/Sustainability Implications

In terms of sustainability, the implementation of RCP has two environmental positives: the reduction in the amount of cement used and the prevention of cardboard waste in the landfills. Moreover, even a minor 1% cement replacement in 1 m^3 of concrete (300 kg cement). CO_2 saving: 0.01×300 kg $\times 0.9 = 2.7$ kg CO_2 per m^3. National extrapolation (10 million m^3): = 27,000 t CO_2/year. This has a great potential of mitigation particularly when it is extrapolated to the national levels of concrete production in such booming regions like Oman [45].

6. Conclusions

According to the experimental study on workability and strength properties of M25 concrete by adding recycled cardboard powder (RCP), the following conclusions are made:

1. Recycled cardboard powder (RCP) that is produced by a low-energy soaking-drying-grinding method can be used successfully as a partial cement replacement in construction grade concrete.
2. Workability reduces as much as possible with rise in RCP content, as cellulose residues absorb water but still, the mixes with RCP as much as 1% can still be practically worked.
3. An ideal RCP replacement ratio of 1% increases compressive, split tensile and flexural strengths and even 28-day strengths are better than normal M25 concrete.
4. Greater replacement levels (1.5) cause loss of strength because of the cement dilution and dispersion efficiency decreased, but characteristic strength requirements are still achieved.
5. Ash of the recycled cardboard can thus be safely used up to 1% cement replacement in M25 cement concrete as a sustainable and low energy source of waste valorization, and structural reinforcement.

7. Limitations and Future Work

Even though the current research paper shows that there is a mechanical possibility of integrating fibers using cellulose in cementitious composites, there has been minimal long-term durability confirmation. Subsequent research will thus implement an orderly framework of durability and microstructural analysis, consistent with recent high impact research on sustainable fiber-reinforced systems [11,12].

To measure the permeable void content and determine the variations in the densification of the matrices with respect to the additions of fiber, first water absorption (ASTM C642) will be done. The improved absorption can be an indicator of interfacial void development or fiber degradation during the exposure to alkali which is emphasized in waste-derived cellulose systems [12].

Second, sorptivity testing (ASTM C1585) will be conducted in order to determine capillary suction and sensitivity to moisture transport. Since the fibre of cellulose is hygroscopic, the sorptivity test is necessary to ascertain whether internal curing advantages surpass any increase in the capillary porosity [19].

Third, the drying shrinkage (ASTM C157) will be evaluated to learn about dimensional stability and the vulnerability to microcracks. The cycles of fiber swelling-shrinkage can affect restrained shrinkage and observing long-term deformation will explain the efficiency of crack-control in comparison with the risk of degradation.

Fourth, resistance to chlorides will be tested by Rapid Chloride Permeability Testing (RCPT, ASTM C1202) and/or chloride migration testing (NT Build 492). These tests are essential to benchmark the transport-controlled durability performance and are suggested in the context of the recent frameworks of durability assessment of sustainable composites [10]. Lower charge passed values or lower migration coefficients would be indicative of effective pore refinement whereas higher values would indicate interfacial degradation or void connectivity.

Lastly, microstructural characterization will be done in detail using Scanning Electron Microscopy (SEM) of fiber interfaces between fibers and matrices to analyze fiber (ITZ), debonding and the development of microcracks.

X-ray Diffraction (XRD) to identify the changes in phase and the potential variation in hydration products that could result because of the interaction between the fibers.

This combined mechanical-durability-microstructural structure will allow the linking of transport properties, chemical stability and long-term performance. A structured durability package like this is aligned with the new requirements of an environmentally friendly cementitious system and is essential to confirm the service-life implication before its use on a large-scale basis [10,11].

Isothermal calorimetry (according to standard practice) of Control, 1% RCP and 1.5% RCP should be performed to obtain quantitative data to prove hydration kinetics and meet the requirement of the link between microstructure and mechanism: (a) duration of induction period, (b) time-to-main-peak, (c) magnitude of main-peak, and (d) cumulative heat at 24–72 h. Quantitative analysis procedures to interpret the curves and extract the parameters of the calorimetry are properly developed and can be directly utilized in the subsequent experiments [44,45]. The current study has no direct microstructural characterization; hence, the experimental phase analysis is not done but instead the correlations are made based on existing literature.

Author Contributions

Conceptualization, A.A.N.A.S., K.K.P., B.S.N.A.M., M.A.A.A.A., U.M.S.A.S., and Z.S.S.M.A.M.; methodology, A.A.N.A.S., K.K.P., and B.S.N.A.M.; validation, A.A.N.A.S., K.K.P., and B.S.N.A.M.; formal analysis, M.A.A.A.A., U.M.S.A.S., and Z.S.S.M.A.M.; investigation, A.A.N.A.S., K.K.P., and B.S.N.A.M.; resources, M.A.A.A.A., U.M.S.A.S., and Z.S.S.M.A.M.; writing—original draft preparation, M.A.A.A.A., U.M.S.A.S., and Z.S.S.M.A.M.; writing—review and editing, A.A.N.A.S., K.K.P., and B.S.N.A.M.; visualization, K.K.P.; supervision, K.K.P; project administration, XA.A.N.A.S., K.K.P., and B.S.N.A.M. All authors have read and agreed to the published version of the manuscript.

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