Chapter 7
Contribution of Waste Paper Sludge on the Mechanical and Durability Attributes of Concrete: A Review

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Abstract Almost every developed and non-developed country struggles to tackle the problems caused by the generation of various types of wastes from the agricultural and industrial fields through natural and human-made activities. Waste paper sludge (WPS) is one of those industrial wastes which are being produced in massive amounts. It is the final of the paper production process that has issues related to health and the environment as it consists of heavy metals. Many researchers have attempted to use WPS in the construction field by converting it into a useable form (ash) to mitigate the problems associated with it. Studies have revealed that the addition of WPS ash as supplementary material in cement can be subjected up to a certain limit that alters the mechanical and durability characteristics of concrete. The present article also reviews the physical and chemical attributes of waste paper sludge ash (WPSA) while discussing the environmental concern of this waste.

Keywords Waste paper sludge · Cement replacement · Concrete production · Heavy metals

7.1 Introduction

Concrete is one of the most used construction materials around the globe due to its easy fabrication, versatility and durability aspects. Cement is the main ingredient of concrete that helps to bind the fine and coarse aggregates with the help of water. Globally, because of the increase in urbanization and development, the rate of consumption and production of cement has also increased drastically. Several types of processes from the collection of clinkers to the packaging of cement bags are

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involved in the production of cement. Although cement has many benefits to the construction sector at the same time, a massive quantity of raw material and energy is required for its production that emits greenhouse gases to the atmosphere [1, 2]. According to a report, around 1.35 billion tons of carbon dioxide is emitted into the atmosphere, annually [3]. In previous years, many researchers have attempted to lower the consumption of cement through various practices such as the integration of another material that has similar properties as cement. Researchers have found that it is possible to utilize some of the industrial and agricultural wastes as a substitution material for cement, which further can be used for the production of concrete. Industrial wastes such as copper slag [4], electric arc furnace dust [5] and silica fume [6] and agricultural wastes such as rice husk ash [7], sugarcane bagasse ash [8] and corn cob ash [9] have been successfully used to replace some portion of cement for the production of cement. The present approach has led to lower the usage of cement which has not only resulted in lowering the overall cost of construction but also results in utilization of waste and reduction in the greenhouse gases.

Waste paper sludge is also one of the industrial wastes which are being produced during the processing of paper. It is produced during the dewatering process of waste material. It has been reported that around 204 million tons of paper are produced each year in the paper and pulp industries [10]. Moreover, each unit of manufactured paper generates around 24% of waste paper sludge [11]. Being a by-product, it is commonly disposed into the landfills for its disposal which caused many health and environmental problems [12]. Studies have been reported on the application of this waste in concrete by incinerating it at a particular temperature to get the final by-product as ash [13, 14]. Apart from the landfilling [15], the WPS is subjected to land spreading [16, 17] and composting [18, 19] as a fertilizer [20] and as an absorbent material [21] for the elimination of heavy metals and phenols [22, 23]. In addition, the waste paper has also been reported to be used to produce lightweight building blocks for the construction purposes [24–27].

The present review paper focuses on previous studies conducted on the utilization of WPS in concrete by replacing the cement with the ash produced after incinerating the WPS at elevated temperatures. A brief discussion has also been provided on the physical and chemical characteristics of WPS along with the effect of this waste on human health and the environment.

7.2 Physical and Chemical Properties of WPSA

7.2.1 Physical Properties of WPSA

The physical properties of WPSA such as texture, shape, specific gravity, bulk density, water absorption and fineness modulus used in previous studies were reviewed thoroughly. The particles of ash have small-sized fibres and rough textures having some organic and inorganic contents. The specific gravity of ash ranges from 2.40

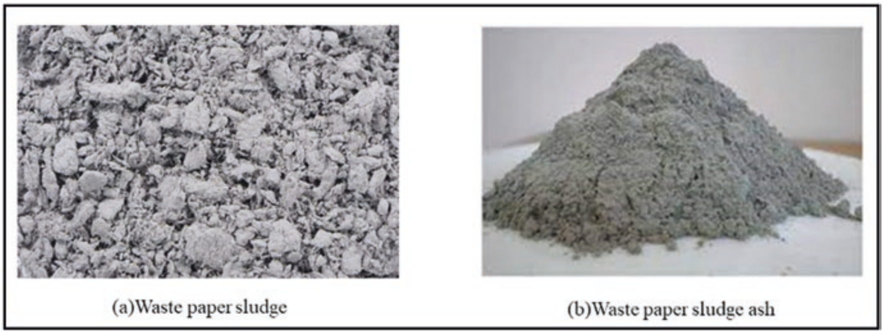

Fig. 7.1 (**a**) Waste paper sludge. (**b**) Waste paper sludge ash

Table 7.1 The composition of oxides present in the WPSA

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	L.O.I
[36]	23.3	5.3	0.8	0.5	2.5	62.4	0.4	0.4	0.5	0.6	4.5
[37]	15.1	6.06	1.11	0.45	2	72.1	0.19	0.34	0.48	0.7	17.51
[38]	30.2	18	0.7	0.35	3.7	31.4	0.21	0.32	–	0.2	14.53
[39]	27.8	13.79	4.94	0.73	3.92	44.5	0.33	0.28	–	–	–
[40]	10.7	6.82	0.46	0.28	0.86	25.4	0.13	0.24	0.13	0.3	54.34
[41]	18.0	10.14	0.55	0.26	2.58	19.8	0.25	0.21	0.1	0.3	47.62
[42]	10.8	6.8	0.5	0.3	0.9	25.4	0.1	0.2	0.1	0.3	54.3

to 2.99 [14, 28–30], and bulk density ranges from 1200 to 1435 kg/m^3 [30, 31]. The pH of the ash varies from 7 to 12 in accordance with the composition of WPS and the packing density of particles [32]. The water absorption capacity and fineness modulus of ash are around 25% [33] and 3.82% [29], respectively. If the calcination temperature is in the range of 850–1200 °C, then the produced waste paper sludge ash (WPSA) will not be able to produce a sufficient amount of metakaolinite, and thus the WPSA will act as a hydraulic by-product [34, 35]. Figure 7.1 shows the texture and colour of waste paper sludge and its ash.

7.2.2 *Chemical Composition*

The chemical compositions of WPSA used by the various researchers in the previous studies are given in Table 7.1.

Table 7.1 provides information about the presence of oxides in the WPSA. It can be clearly observed from the table that ash consists of the major share of oxides of calcium and silica.

7.3 Generation and Environmental Significance of WPS

During the production of waste paper sludge, several basic steps are involved. In the beginning, the raw material in the form of wood is collected and transported to the pulp industry. Followed by that, the refining and bleaching procedure loosens the wood-based fibres resulting in its easy and rapid digestion for the production of paper. In the course of refining and bleaching processes, a massive amount of wastewater is generated that is handled and treated carefully within the industry through the wastewater treatment facilities. The sludge generated from the treatment facilities is subjected to the dewatering process allowing the formation of waste paper sludge [43, 44]. Figure 7.2 illustrates the processes involved in the production of waste paper sludge.

Studies have revealed the toxic nature of WPS as it contains chemical compounds and dyes which possess a threat to human health and the environment. The major problem related to the WPS is its handling and safe disposal. Most paper production industries dispose of the WPS generated from the wastewater treatment plant on nearby lands which increases the pH and number of organic compounds in the soil [45], whereas the direct discharge of effluent produced from water treatment plants in the natural streams causes an adverse effect on the population and reproduction process of the fishes [46, 47].

7.3.1 *Concentrations of Heavy Metals*

Apart from the above-mentioned problems, it has been reported that the WPS consists of heavy metals; however, their concentrations were reported to be within the specified permissible limits. Earlier conducted studies have suggested that high concentrations of heavy metals such as chromium, copper, lead and zinc have been detected [48, 49]. But in some of the studies, the amount of the heavy metals detected is less than the permissible limits suggested by the Environmental Protection Agency (EPA), Taiwan [50]. The source of the heavy metals is the different types of inks used during the processing of the paper [51, 52]. Table 7.2 represents the heavy metal concentration present in the WPSA.

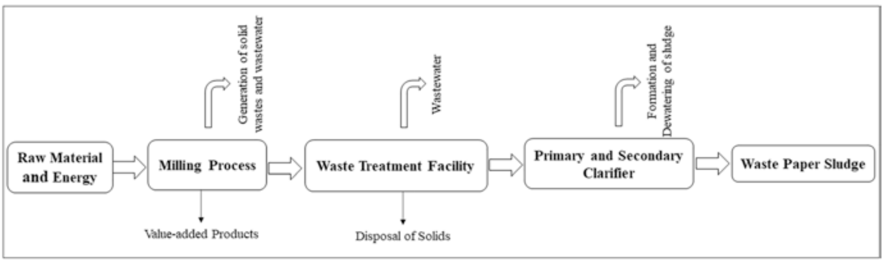

Fig. 7.2 Steps involved during the formation of WPS

Table 7.2 The concentration of heavy metals detected in WPSA (mg/l)

	[50]	[53]	[54]
Ba	–	0.75 ± 0.02	123.9
Zn	1.4–1.6	1.23 ± 0.06	101.1
Ni	–	1.05 ± 0.003	–
Pb	0.41–0.96	<0.05	62.2
Cu	0.01–0.03	0.31 ± 0.07	210.3
Mn	–	0.23 ± 0.01	–
Cd	0.02–0.03	<0.01	0.11
Cr	0.11–0.21	0.05 ± 0.01	23.6
As	–	<0.1	0.01
Se	–	–	0.38
Ag	–	–	0.14

7.4 Characterization of WPS and Its Effects on Concrete

7.4.1 Characterization of the Waste Paper Sludge

X-Ray Diffraction (XRD) and Thermogravimetric Analysis (TGA) The XRD spectra represent that when the sludge is subjected to the calcination at 700 °C for 2 h, some of the kaolinite gets remained which further on increasing the calcination time to 5 h gets completely dehydroxylated. The majority of the compounds were found to be calcite and kaolinite. It was found that there was no effect of the calcination on the talc and muscovite. The organic content of the sludge depends on the types of used raw constituents, process, time and temperature at which the calcination was performed. Most of the studies reported that the loss during the ignition is more than 40 [55–58]. The TGA analysis shows that there is a noticeable amount of loss of weight and the transformation of the sludge to the non-crystalline phase [59]. XRD image of WPSA is illustrated in Fig. 7.3.

Mineralogical and Morphological Texture The significant changes in the mineralogical and morphological properties were occurred in the waste paper sludge, because of the variation in the calcination temperature and time which changes it to the gel phase type. The products formed were found to be kaolinite, amorphous and spongy structure and the compounds which were close to different degrees of hydration of the cement. The higher temperature of the furnace for the calcination altered the process of reaction and activity of the sludge [61, 62].

Scanning Electron Microscope (SEM) Analysis The SEM analysis of the samples consisting of the WPSA done in the previously conducted studies revealed that the deposit materials on the calcite and quartz are amorphous and possess higher concentrations of the chromium, lead and barium sulphate in comparison to the ordinary Portland cement [63, 64]. Figure 7.4 represents a SEM image of WPSA.

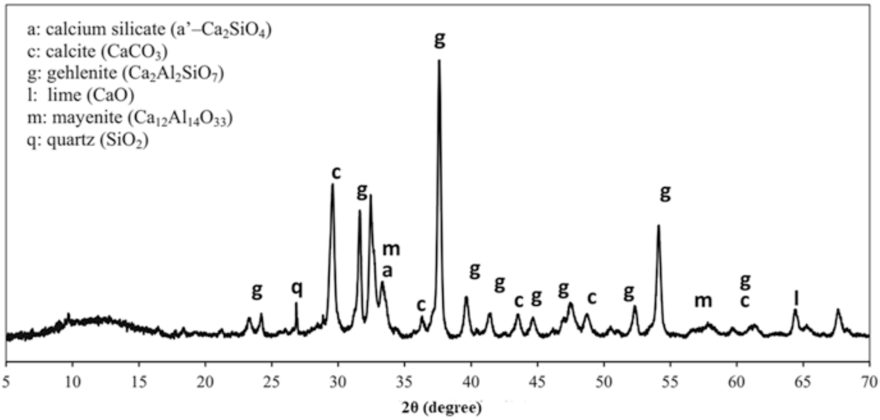

Fig. 7.3 XRD pattern of WPSA [60]

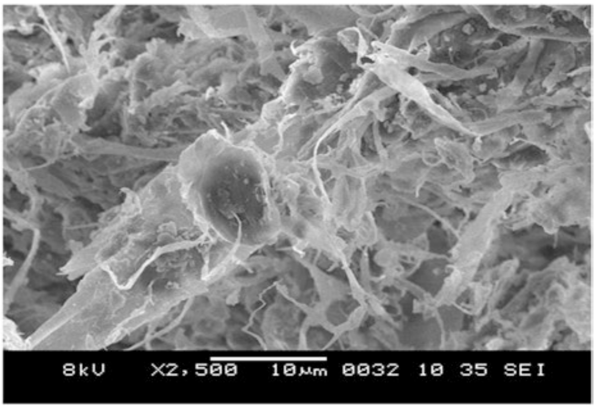

Fig. 7.4 SEM image of WPSA [13]

7.4.2 Influence of WPSA on the Properties of Cement Blended Paste and Concrete

Initial and Final Setting Times Based on the previous studies, it has been revealed that as the amount of substitution of an amount of cement with WPSA is increased, the setting times of the blended cement paste get extended. This could be due to the internal chemical reaction of C_3A with water in the presence of gypsum. The presence of C_3A in the WPSA is low in comparison to the OPC which causes the retardation in the setting time of the cement paste blended with the WPSA [65].

Pozzolanic Activity Many researchers have conducted experimental work on the effect of variation in the calcination temperature and time on the WPS, and it has been noticed that as the calcination temperature and time rise beyond 700 °C and 2 h, respectively, the pozzolanic activity of the formed ash decreased significantly. When the calcination of the sludge is done at 500 °C for 2 h, the ash consists of a higher amount of talc, dolomite, calcite and quartz. With the increase in the temperature, the formed kaolinite gets transformed into metakaolinite. The most reliable temperature for the calcination of WPS was found to be 500 °C for 2 h to get highly active ash, where the least activity of the ash was found to be over 800 °C for a longer period [40, 42, 55, 61, 66]. The surface and fracture in the geopolymer made with the different dosages of NaOH (5, 10 and 15 mol/l) showed that when a higher dosage of NaOH was used, more amount of raw material was reacted and the formed matrix showed a higher degree of geo-polymerization and denser structure [58].

Hydration Test The results of the hydration test represented that when the higher content of WPSA is used as a replacement material for the cement, the temperature values of the blended cement paste increase in the first 10 h. But beyond that period, a significant reduction in the temperature values has been noticed, which means the hydration process gets retarded [55, 67].

Compressive Strength The addition of another mineral admixture (GGBFS or metakaolinite) along with the WPSA has also been reported to influence the performance of the concrete at 28 days of curing [28]. The results of compressive strength of the different mix proportions consisting of the varying amounts of WPSA and recycled aggregates showed a noticeable influence on the strength of the concrete. The maximum increase in the compressive strength has been noted at 5% replacement of the cement with the WPSA without the addition of recycled aggregates. Similar results were found when 25% addition of recycled aggregates along with 5% of WPSA has been incorporated to manufacture the concrete. The obtained results were much higher than the reference concrete mix [68]. The application of the mineral admixtures in the recycled aggregate concrete has shown an improvement in the results because of the filler behaviour and the pozzolanic reaction of the mineral admixtures, therefore improving the inter-transition zone in the concrete mix [69, 70]. At 7 days, it has been noticed that the increase in the compressive strength of recycled aggregate concrete was more when the mineral admixtures such as WPSA and the metakaolinite have been taken under consideration as compared to the silica fume and fly ash [71]. The improvement in the compressive strength during the early days could be due to the chemical composition of WPSA, which consists of a higher content of CaO and a smaller amount of SiO_2 as compared to the other available mineral admixtures. The CaO content of the WPSA would react more rapidly to the water and develop the strength in the initial days of the curing. As found in the previously available literature, the CaO plays a vital role in developing the early day's compressive strength of the concrete [72]. Figure 7.5 shows the effect of the addition of WPSA on the compressive strength of concrete.

The effect of the application of calcinated WPSA along GGBFS with the activator (NaOH) was checked after 7, 28 and 50 days. Five different mixes containing the varying percentages of WPSA and GGBFS had been taken into consideration, and

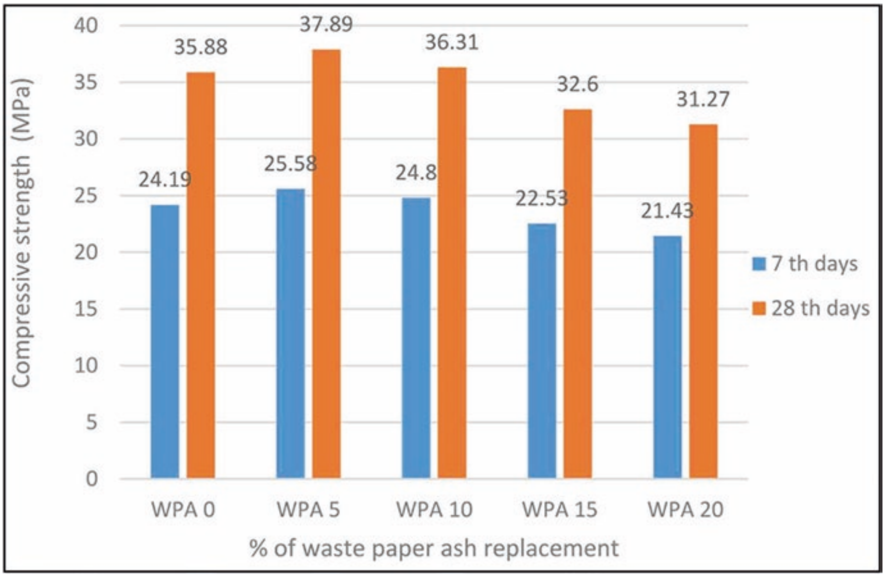

Fig. 7.5 Influence of the addition of WPSA on compressive strength [75]

it was found that the blended mortar mix containing the least amount of WPSA and GGBFS showed better results in comparison to the other mixes. The integration of WPSA causes a delay in the development of strength. Whereas the gain in the strength at later stages may be related to the dissolution of the $CaCO_3$ led to an increase in the pH of the mix, the free Ca^+ ion would show the reaction with the silica content of the GGBFS. Further, the reaction causes the formation of C-A-S-H which is responsible for the increase in the strength of the later stages [57]. Another study has also shown similar satisfactory results for the production of the geopolymer formed with the WPS and coal bottom ash [58]. It has been noticed that temperature causes a significant effect on the mechanical strength of the geopolymers [73]. The strength properties like the compressive strength of the geopolymers may depend upon the used raw material and manufactured conditions [74].

Split Tensile Strength The reason behind the increase in the strength can be linked to the chemical reaction of the pozzolanic materials (mineral admixtures), which has successfully reduced the porosity of the mix and influences the overall gain in the strength of the specimens. Some of the studies have also indicated that the maximum substitution of cement can be done up to 10–20% which has caused a positive impact on the strength properties of the concrete [39, 43, 76, 77]. Figure 7.6 shows the effect of WPSA on split tensile strength of concrete.

Sorptivity Based on the available results, the integration of WPSA has caused to gain in the sorptivity of the concrete samples when compared to the reference mix. As the amount of the replacement of WFSA has been increased in the mix, the sorptivity of the concrete also gets increased [78, 79].

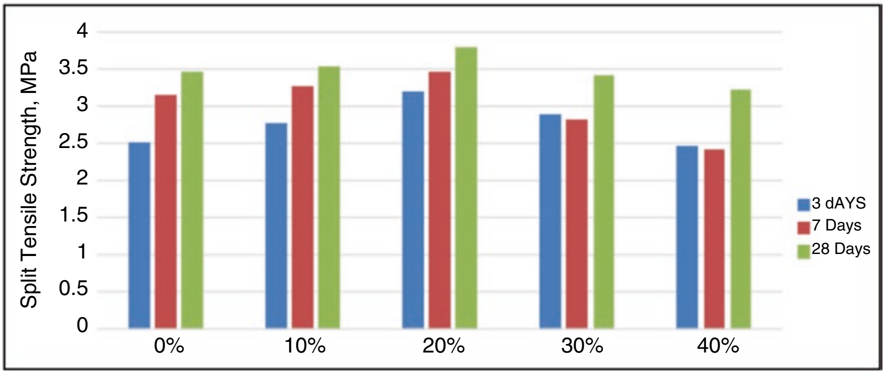

Fig. 7.6 Influence of the addition of WPSA on split tensile strength [77]

Density The study revealed that the integration of the WPSA as a substitution material for the cement and sand has caused a reduction in the density of the concrete. It has been found that as the amount of addition of WPSA to the cement is inversely proportional to the density of the concrete [66, 68, 80, 81], a similar pattern of the reduction in the density of the concrete has been observed when the WPSA has been used to substitute the sand for the concrete production [82].

Acid Resistance The loss in the compressive strength of the concrete, when dipped in the solution of 3% H_2SO_4 for an extended period, has been noticed in the previous studies. It has been found that WPSA has been successfully reported, providing the acid attack resistance to the concrete [39]. For both addition and replacement methods, better performance has been obtained at the usage of 5% of the WPSA; beyond that, content noticeable reduction in the strength of concrete has been observed. The gain in the acidic resistance could be credited to the filling activity of the mineral admixture which clogs the pores or cracks and makes the concrete denser in order to reduce the penetration of the acids. Researchers have also suggested using the recycled aggregates along with the mineral admixtures to lower the deterioration of the concrete because of the acid attacks [83–85].

The chemical reaction between the hydration products and sulphate in order to form the gypsum which further reacted with the tricalcium aluminate (C_3A) to manufacture the ettringite causes the occurrence of the sulphate attack. When the compressive strength of the concrete containing the varying percentages of the WPSA was tested after the immersion in the 5% Na_2SO_4 mixture, it was found that the integration of the WPSA has resulted in to increase in considerable resistance to chemical attack of the concrete. After the immersion of the concrete in the solution, the cement matrix gets closely packed due to the production of ettringite. The increase in the strength after the immersion in the Na_2SO_4 has also been reported in the previously conducted studies [72, 86, 87]. The reason behind the increase in the resistance could also be due to the chemical composition of the WPSA, as it possesses a higher content of the CaO in comparison to the SiO_2; therefore, the amount of the formation of $Ca(OH)_2$ will also be much high. The chemical reaction between the $Ca(OH)_2$ and 5% Na_2SO_4 may have led to cause an influence in the rate of the pozzolanic reaction which ultimately results in the gain in the strength of the concrete when tested after 90 days [39, 88].

Drying Shrinkage The drying shrinkage of the blended cement mix gets increased as the content of the WPSA is increased. It has also been noticed that when the replacement of the cement is done up to 20%, the amount of the shrinkage is approximately three times the control mix. The rate of drying the mixture increases due to the nucleation of the hydration materials on the external surface of the particles of WPSA and the chemical reaction between $Ca(OH)_2$ and metakaolinite which demands a higher amount of water [40, 41].

7.5 Conclusions

After thoroughly reviewing the effect of WPSA on the mechanical and durability characteristics of concrete, the following conclusions have been drawn:

- The optimum dosage of WPSA that can be used as a substitution material for cement for concrete production is 5%. However, beyond that limit, a significant reduction in the concrete attributes has been noticed.
- Better results have been observed when waste paper sludge ash has been used to manufacture geopolymer concrete while using recycled coarse aggregates in comparison to the plain concrete produced through the waste paper sludge ash.
- Incorporation of the waste paper sludge in the construction sector can reduce the health and environmental problems associated with it.

The readers are recommended to explore the integration of waste paper sludge, and its by-product in the concrete matrix can be explored by varying its dosage along with the use of another mineral admixture to measure the overall effect on the mechanical and durability attributes of produced concrete. The studies on leaching of heavy metals and effect of WPSA on other types of concrete such as self-compacting and high-performance concrete haven't been carried out in the literature. The findings on the addition of microbes in the concrete manufactured by integrating WPSA can also be evaluated.

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