Reuse of Concrete Waste Powder (CWP) from Construction and Demolition Waste in Egypt as a Partial Cement Replacement to Reduce Carbon Footprint

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Abstract - *Concrete waste powder (CWP), derived from construction and demolition waste (CDW), is a promising supplementary material for sustainable cementitious applications in Egypt. This study investigates the feasibility of using untreated CWP with particle sizes below 150 µm and 75 µm as a partial replacement for ordinary Portland cement in mortar mixtures. A total of 252 50-mm mortar cubes were cast with replacement ratios from 0% to 40%. Sodium silicate (Na_2SiO_3) was used as a chemical activator at dosages of 0.5% to 2% by weight of CWP. Density and compressive strength were measured at 7 and 28 days. Results show that increasing CWP content without activation reduces compressive strength. However, acceptable mechanical performance was achieved at replacement levels of up to 10% for CWP <150 µm and up to 20% for CWP <75 µm when appropriate activator dosages were used. All mixtures remained within the normal-weight classification. A carbon reduction assessment indicates that 10–20% cement substitution could reduce CO_2 emissions by approximately 85–170 kg per ton of cement replaced. The findings demonstrate that CWP can be used in cement-based brick production, reducing cement consumption and lowering carbon emissions in the Egyptian construction sector.*

Key Words: **Concrete waste powder, Cement replacement, Carbon reduction, Construction and Demolition Waste, Sustainability.**

1. INTRODUCTION

Concrete is the most widely used construction material worldwide and ranks second only to water in total consumption. The production of Portland cement, its primary binder, accounts for approximately 8% of global CO_2 emissions. In Egypt, large-scale infrastructure development is increasing both cement demand and the generation of construction and demolition waste (CDW). Recycling CDW into valuable construction materials is an essential pathway toward sustainable development.

Concrete relies on non-renewable resources, primarily fine and coarse aggregates derived from crushed stone, limestone, and clay, essential raw materials for the cement industry. Additionally, it is considered environmentally unfriendly not only because of resource waste but also because it significantly contributes to rising atmospheric carbon dioxide levels. The adverse effects of concrete include global warming, soil erosion, depletion of natural resources, dust, noise, waste, emissions, and air pollution [1,2]. Furthermore, pollution from concrete persists throughout its lifecycle, beginning with the extraction of materials from quarries and crushers, continuing through the production of clinker and the construction of concrete structures, and extending to the end of a structure's life and subsequent demolition. The latter aspect is the focus of the current research, as demolition waste presents a substantial burden on the solid waste collection and disposal systems in any country. Fig. 1 illustrates the average global municipal solid waste generation per capita, with Egypt averaging 255.6 kg per capita per year. Fig. 2 further indicates that Egypt ranks among the top 20 countries by municipal solid waste generation, producing approximately 21,100,000 tons annually. Demolition waste constitutes a significant volume in any sanitary landfill or open dump and is non-degradable. The presence of such waste in sanitary landfills results in the loss of investments made in landfill construction, escalating waste disposal costs, and shortening the landfill's lifespan. Much research indicates that demolition and construction waste account for approximately 50% of solid waste [4,5], suggesting that demolition and construction waste in Egypt amounts to approximately 11,000,000 tons annually (this estimate is based on the lack of accurate data on this waste in Egypt).

Soo et al. [6] noted that the construction industry accounts for 18% of greenhouse gas emissions, 40% of natural resource consumption, and 25% of global waste. This prompted researchers in concrete to explore the potential of reusing demolition concrete to produce new concrete. They questioned the specifications and quality of these materials: Do different codes accept them, and does the component extraction method affect their properties? This line of inquiry has led to a wealth of published research, yielding numerous answers, though many questions remain.

Daoud et al. [7] addressed the amounts of CDW produced by various construction projects in Egypt, noting that cement and concrete waste constitute approximately 12% of the total CDW in infrastructure projects. Parween and Mohammed [8] examined the mechanical properties and flexural stress of reinforced concrete (RC) beams created from demolition waste as a partial substitute for coarse aggregates. Concurrently, Lamen and Forth [9] investigated the long-term flexural behaviour of RC beams incorporating recycled aggregates.

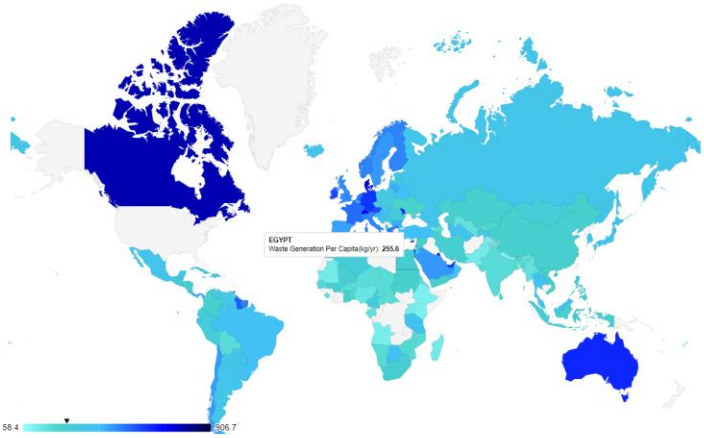


Fig -1: The average amount of Municipal Solid Waste (MSW) generated annually per capita (kg/year) [3]

Concrete waste powder (CWP), obtained by crushing demolished concrete, has been investigated as a supplementary cementitious material. Previous studies have reported varying replacement ratios depending on particle size, treatment method, and activation technique. However, limited research has examined untreated CWP from Egyptian CDW sources and its potential contribution to carbon reduction in the local construction industry.

CWP has recently been utilized by researchers in various forms and through different treatment methods [10], including: a) as received [11,12,13,14,15], b) chemical treatment [16,17], c) thermal treatment [18,19], and d) the addition of other cementitious materials [20,21,22,23]. CWP has been employed in its received state for applications such as grouting for soil stabilization, as a cementitious material due to its calcium and silica content, in concrete pavements, and brick manufacturing. Some studies recommend using CWP in proportions not exceeding 15% [24,25,26], while others have increased this proportion to 20% by incorporating red clay brick residue (RCB) into the mixture [11]. Topic et al. [12,13,14] conducted three successive studies on CWP and initially recommended a rate of 30%, which they later raised to 30%-50%. In their final research, however, they returned the rate to 30% because of the non-hydraulic nature of this waste.

Due to WCP's inability to demonstrate high specifications when used as received, the potential for chemical treatment of the powder before use with ordinary Portland cement was explored. The treatment involved adding an activator to the powder, with Na_2SiO_3 and NaOH used at an optimal concentration of 1% of the CWP [16]. It was observed that replacing 10% of the cement with alkali-activated CWP significantly increased compressive strength. XRD and SEM tests indicated that using activators with CWP enhances late-strength relative to early-strength, due to the formation of substantial amounts of calcium silicate hydrates (C-S-H) and aluminium hydrates at later stages [10].

Others employed thermal treatment, studying the effects of temperatures ranging from 200 to 800 °C. It was found that temperature affected particle size, with size increasing at 600 °C and decreasing again after 700 °C [18]. The results also indicated that CWP reactivity increased with temperature, with the highest reactivity observed at 800 °C. A 30% replacement ratio of CWP thermally treated at 700 °C was optimal for the mixture's mechanical performance. Qian et al. [19] demonstrated that a replacement ratio of 25% at 650 °C yielded the best results, producing ultra-high-performance concrete (UHPC) without compromising the control mix specifications.

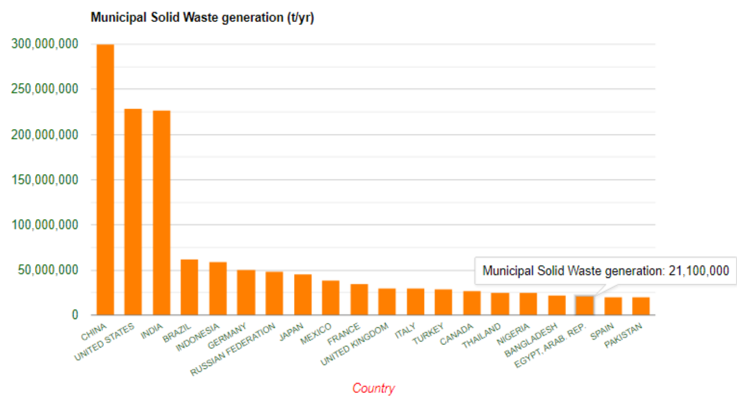


Fig -2: Municipal solid waste generation for the 20 top countries (ton/year) [3]

Let us acknowledge that concrete is the primary construction material globally due to its low cost compared to steel, ease of shaping, and durability. Given the serious environmental issues, no one can be certain that the world will cease using this material. Therefore, the construction industry is confronted with the inevitability that concrete will continue to dominate this sector for decades. Amid global inflation, cement prices have risen significantly, creating a substantial burden on poorer countries' budgets. In Egypt, infrastructure is a key factor in the nation's renaissance and the establishment and prosperity of society, emphasizing the pursuit of sustainable and comprehensive development. Egypt has suffered deterioration across all infrastructure sectors, including housing and roads.

There is an apparent conflict between previous research recommendations regarding the appropriate replacement ratios when CWP is used as received. This may be due to the source itself, the particle size, the nature of the mixture and tests, the cementitious materials used, or other factors. This study aims to evaluate the mechanical performance of mortar mixtures incorporating CWP with particle sizes below 150 µm and 75 µm, with and without sodium silicate activation, and to quantify the potential reduction in carbon emissions from partial cement replacement.

2. MATERIALS AND METHODS

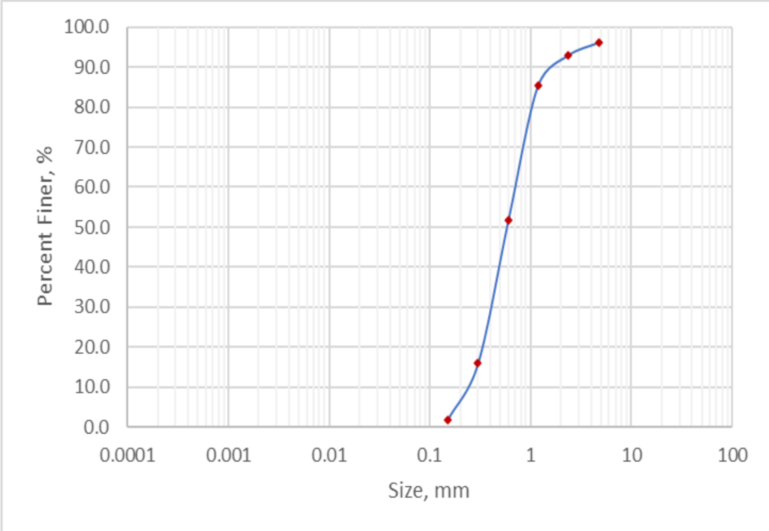
In this research, tests were conducted on 50 mm cement mortar cubes. Ordinary Portland cement (CEM I 42.5N) conforming to Egyptian Standard ES 4756-1 was used. Table 1 presents the standard limits for the chemical components of cement. Yellow siliceous sand grading between 0.15 mm and 4.75 mm with a fineness modulus of 2.56 served as the fine aggregate. Table 2 presents the sand test results. Potable water was used for mixing and curing. The independent variable in the experimental program was the percentage of cement replaced with CWP, with proportions ranging from 0 to 40%.

CWP was produced by mechanically crushing laboratory-tested concrete cubes in a Los Angeles abrasion machine. The material was then sieved to obtain two particle-size fractions: <150 µm and <75 µm. Table 1 presents the XRF analysis for the CWP components for both sizes.

Table -1: ES 4756-1 [10] limits for CEM I cement Vs. XRF analysis for concrete waste powders

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	L.O.I
CEM I						≤5.0					≤3.5	≤5.0
<150µm CWP	19.48	0.25	4.37	2.57	0.07	5.51	41.82	0.11	0.18	0.07	0.88	24.44
<75µm CWP	12.98	0.52	2.23	4.64	0.15	0.54	48.09	0.06	0.32	0.46	0.77	29.01

Table -2: Grading and physical properties of fine aggregate

Particles size	0.15 to 4.75 mm	**Grading**
Fineness modulus	2.563	
Bulk density	1507 Kg/m³	
Specific gravity	2.67	
absorption	1.2 %	
Grading Type	Medium Sand	

A total of 252 50-mm mortar cubes were prepared across 42 mixtures. Cement was replaced with CWP at levels from 0% to 40%. Sodium silicate (Na_2SiO_3) was used as a chemical activator at dosages of 0.5% to 2% by weight of CWP. Specimens were water-cured at 20 ± 2 °C and tested for compressive strength at 7 and 28 days. Tables 3 and 4 present the proportions of ingredients for the mixtures under <150 microns and <75 microns, respectively.

3. RESULTS AND DISCUSSION

The current research focused on using different percentages of CWP as a cement replacement. The results include only tests for density and compressive strength. This limits the application of this waste in structural concrete, except after conducting additional tests that ensure good performance from the plastic stage through to the hardened concrete and the durability of the structures. Consequently, the authors have agreed to explore the use of CWP as a cement replacement in cement bricks.

The density of all samples was calculated as the ratio of sample weight to volume to compare with the values reported in ES 1292-1 [28], ES 1292-2 [29], and ASTM C90-16a [30]. The samples were categorized into three classes based on density: lightweight, medium-weight, and normal-weight, as shown in Table 5. The results indicate that all values fall under the normal weight classification, except for sample 150-40-SS-0.5%, which falls within the medium weight classification. Density ranged from 1.99 to 2.43 g/cm^3, with an average of 2.26 g/cm^3. It can be concluded that CWP or Na_2SiO_3 does not influence the samples' density, and the curves reveal no cause-and-effect relationship between these two independent variables and the dependent variable (density). The curves are not included because they represent 252 samples and provide no additional insights that could contribute to the research.

Table -3: <150 microns mixtures proportioning

CWP Size	Mix No.	Mix Code	Cement	CWP	Sand	Water	Na_2SiO_3
			gm	gm	gm	ml	gm
<150µm	1	150-C	434	0	1302	173.6	0
	2	150-10	390	44	1302	173.6	0
	3	150-20	347	87	1302	173.6	0
	4	150-30	304	130	1302	173.6	0
	5	150-40	260	174	1302	173.6	0
	6	150-10-SS-0.5%	390	44	1302	173.6	0.22
	7	150-10-SS-1.0%	390	44	1302	173.6	0.44
	8	150-10-SS-1.5%	390	44	1302	173.6	0.66
	9	150-10-SS-2.0%	390	44	1302	173.6	0.88
	10	150-20-SS-0.5%	347	87	1302	173.6	0.435
	11	150-20-SS-1.0%	347	87	1302	173.6	0.87
	12	150-20-SS-1.5%	347	87	1302	173.6	1.305
	13	150-20-SS-2.0%	347	87	1302	173.6	1.74
	14	150-30-SS-0.5%	304	130	1302	173.6	0.65
	15	150-30-SS-1.0%	304	130	1302	173.6	1.3
	16	150-30-SS-1.5%	304	130	1302	173.6	1.95
	17	150-30-SS-2.0%	304	130	1302	173.6	2.6
	18	150-40-SS-0.5%	260	174	1302	173.6	0.87
	19	150-40-SS-1.0%	260	174	1302	173.6	1.74
	20	150-40-SS-1.5%	260	174	1302	173.6	2.61
	21	150-40-SS-2.0%	260	174	1302	173.6	3.48

Table -4: <75 microns mixtures proportioning

CWP Size	Mix No.	Mix Code	Cement	CWP	Sand	Water	Na_2SiO_3
			gm	gm	gm	ml	gm
<75µm	22	75-C	434	0	1302	173.6	0
	23	75-10	390	44	1302	173.6	0
	24	75-20	347	87	1302	173.6	0
	25	75-30	304	130	1302	173.6	0
	26	75-40	260	174	1302	173.6	0
	27	75-10-SS-0.5%	390	44	1302	173.6	0.22
	28	75-10-SS-1.0%	390	44	1302	173.6	0.44
	29	75-10-SS-1.5%	390	44	1302	173.6	0.66
	30	75-10-SS-2.0%	390	44	1302	173.6	0.88
	31	75-20-SS-0.5%	347	87	1302	173.6	0.435
	32	75-20-SS-1.0%	347	87	1302	173.6	0.87
	33	75-20-SS-1.5%	347	87	1302	173.6	1.305
	34	75-20-SS-2.0%	347	87	1302	173.6	1.74
	35	75-30-SS-0.5%	304	130	1302	173.6	0.65
	36	75-30-SS-1.0%	304	130	1302	173.6	1.3
	37	75-30-SS-1.5%	304	130	1302	173.6	1.95
	38	75-30-SS-2.0%	304	130	1302	173.6	2.6
	39	75-40-SS-0.5%	260	174	1302	173.6	0.87
	40	75-40-SS-1.0%	260	174	1302	173.6	1.74
	41	75-40-SS-1.5%	260	174	1302	173.6	2.61
	42	75-40-SS-2.0%	260	174	1302	173.6	3.48

Axial compression tests were performed on all samples, with an average of three results taken at 7 and 28 days for all mixtures. Figures 3 to 6 display the overall findings of the research. Excel software was used to illustrate the relationships and determine the best-fit equation between the X and Y values. Some relationships do not provide an equation because the R^2 values are below 0.6 and are therefore excluded from the results.

According to Egyptian specifications [28, 29], load-bearing bricks must have a minimum compressive strength of 13.1 MPa, while non-load-bearing bricks must reach at least 4.14 MPa.

Table -5: Classification of samples according to density values

Classification	Density gm/cm^3	Samples
Lightweight	< 1.68	No samples
Medium weight	1.68 to 2.0	150-40-SS-0.5%
Normal weight	> 2.0	The rest of the samples

Compressive strength decreased with increasing CWP content when no activator was used. For CWP <150 µm, acceptable performance was achieved at up to 10% replacement with 1.0–1.5% Na_2SiO_3. For CWP <75 µm, replacement up to 20% was feasible with 1.0–2.0% Na_2SiO_3. The improved performance of finer CWP is attributed to increased surface area and enhanced pozzolanic reactivity.

The average CO_2 emission factor for Portland cement is approximately 0.85 tons of CO_2 per ton of cement produced. Replacing 10% of cement reduces emissions by approximately 85 kg of CO_2 per ton of cement used, and 20% replacement yields approximately 170 kg of CO_2 reduction per ton. If applied to large-scale cement brick production in Egypt, even partial implementation could significantly reduce national carbon emissions while simultaneously diverting CDW from landfills.

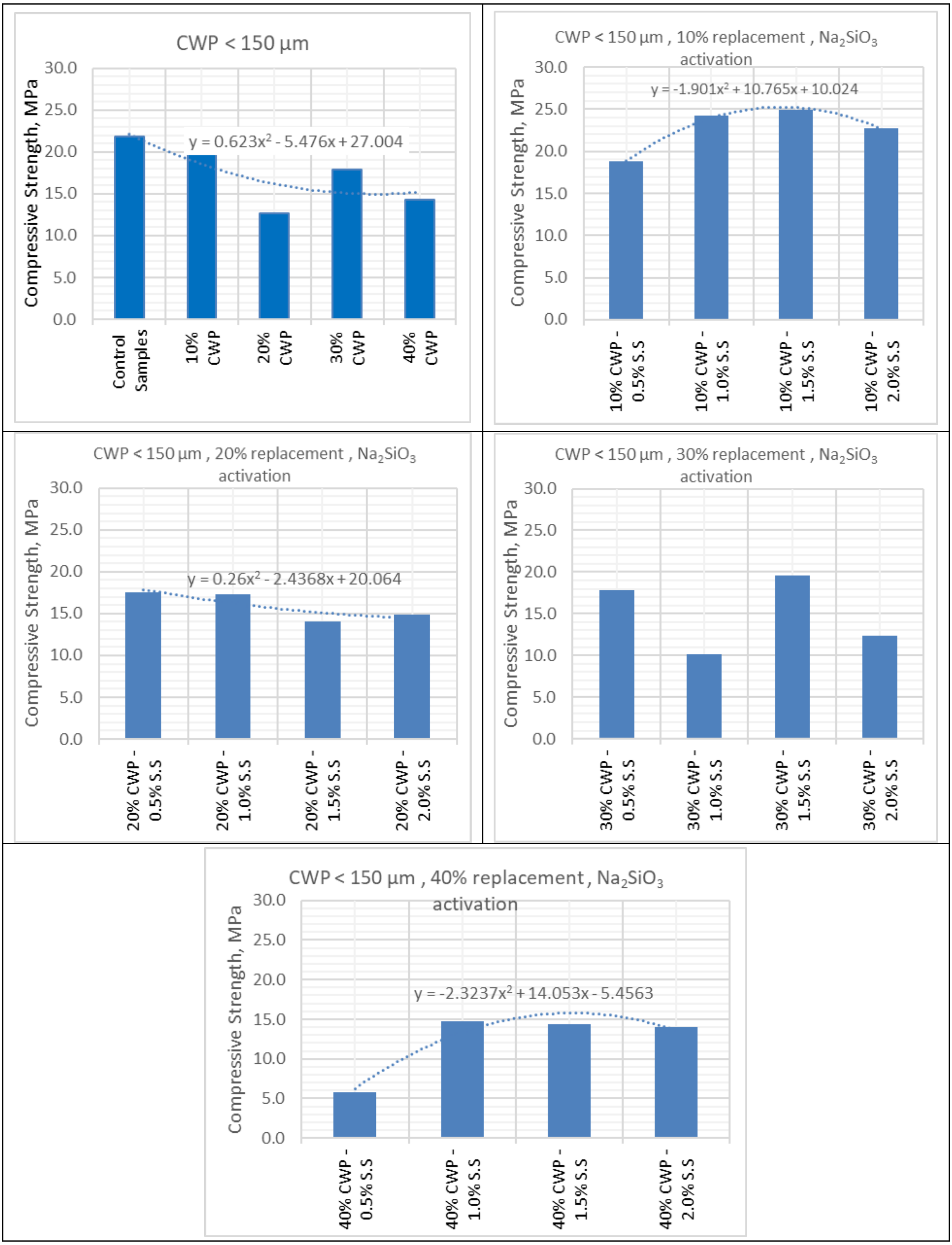


Fig -3: Seven-day compressive strength results for mixtures with CWP <150 microns.

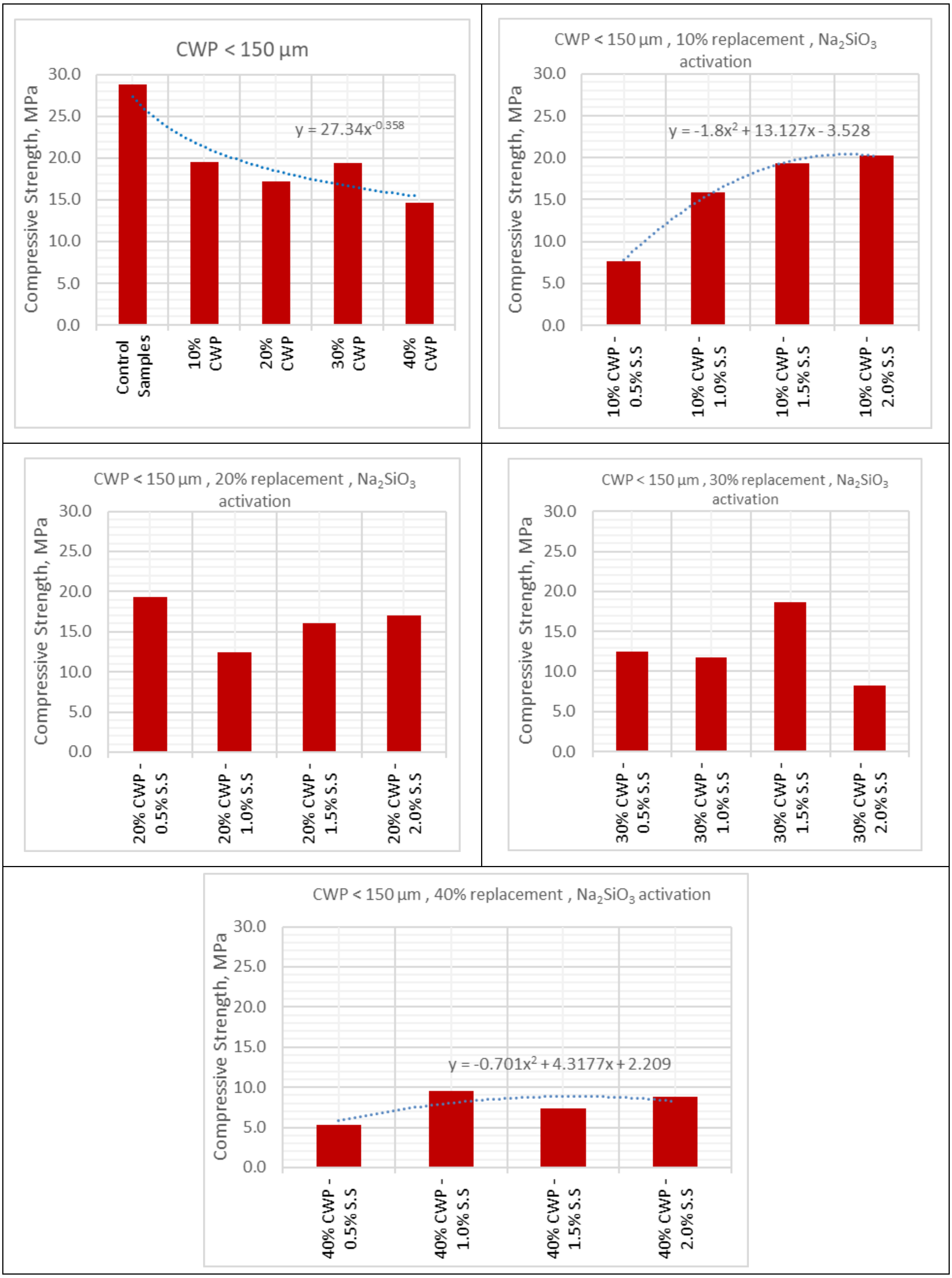


Fig -4: (28 days) compressive strength results for mixtures with CWP <150 microns.

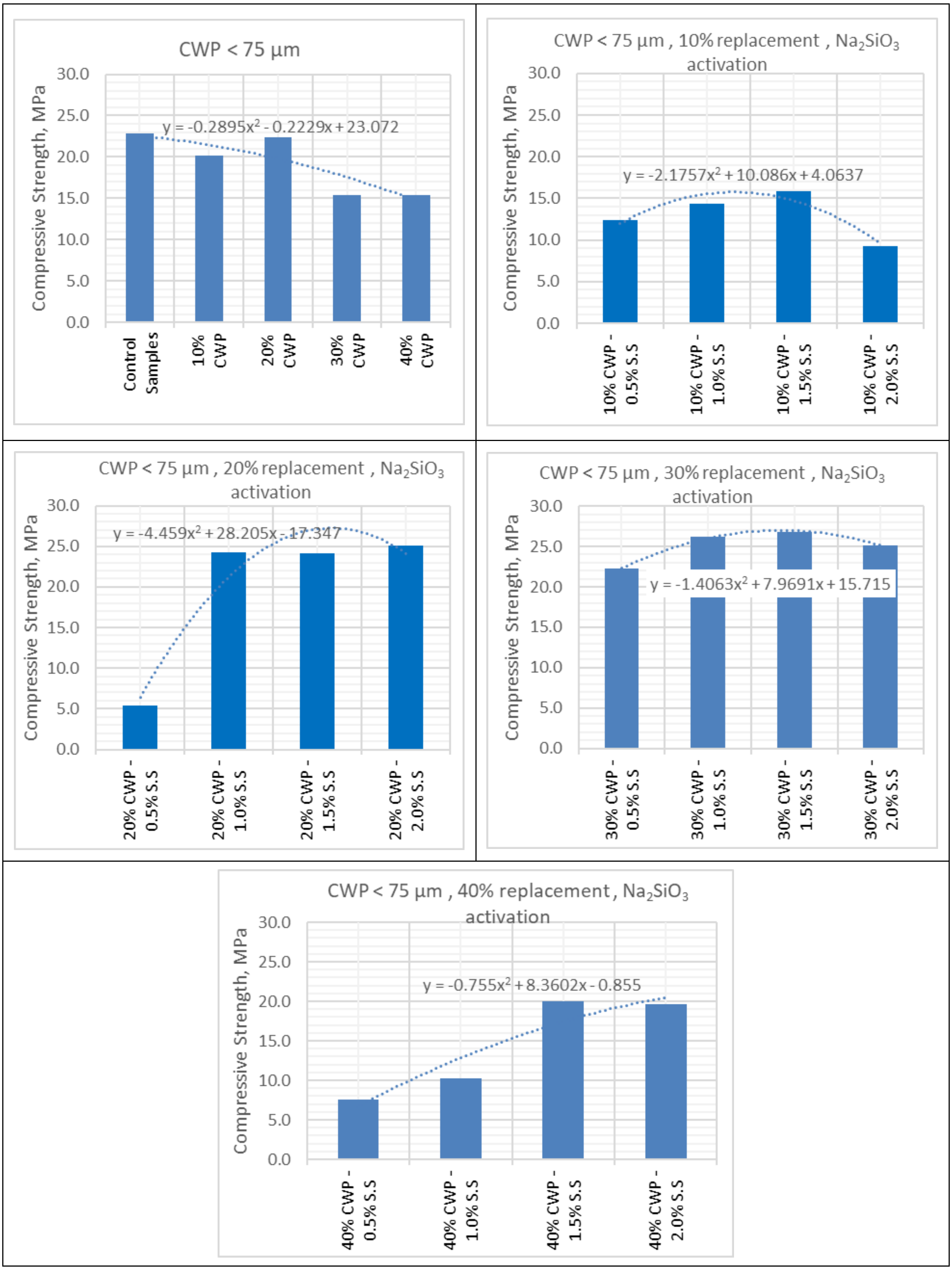


Fig -5: Seven-day compressive strength results for mixtures with CWP <75 microns.

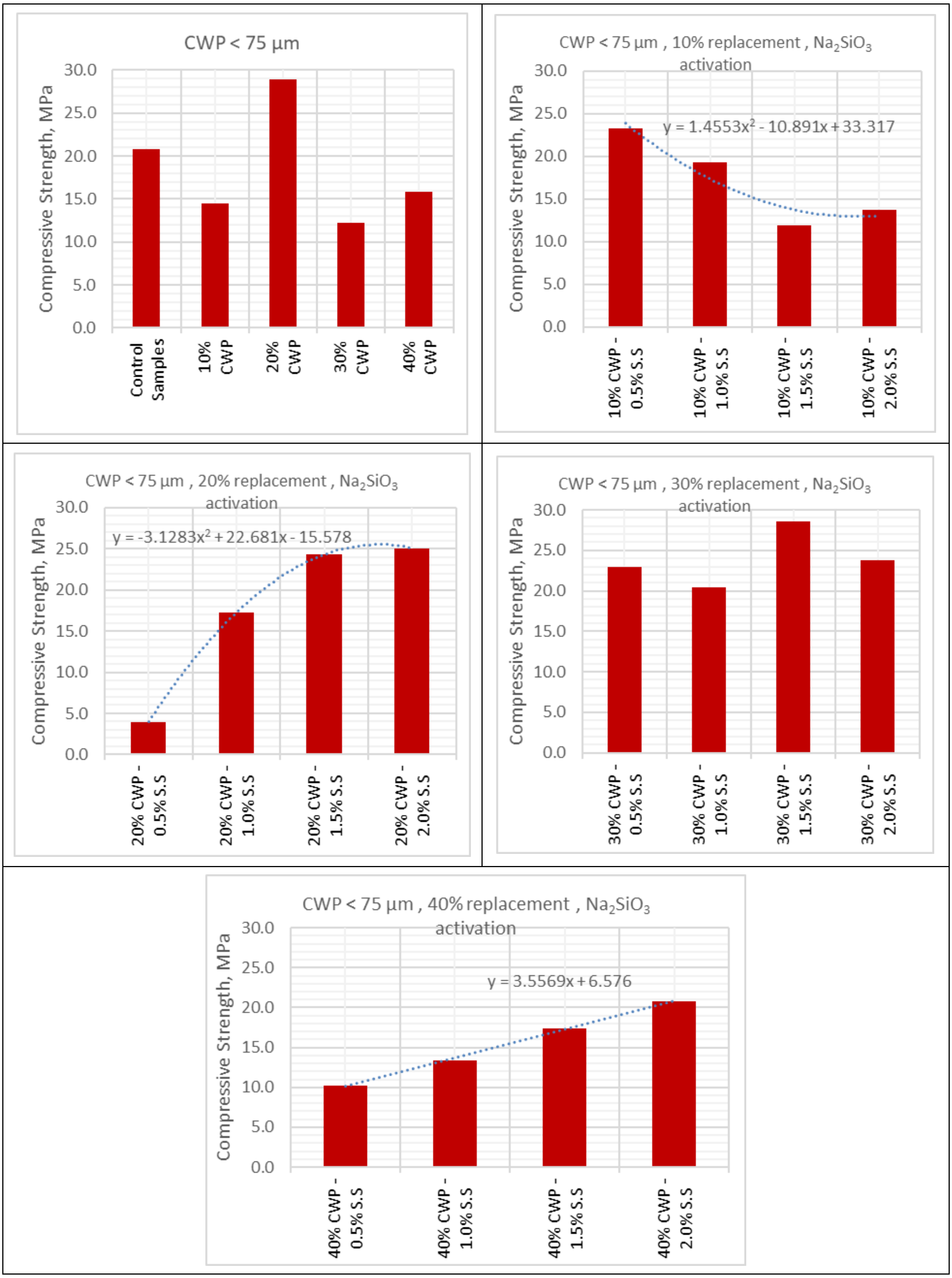


Fig -6: (28 days) compressive strength results for mixtures with CWP <75 microns.

4. CONCLUSIONS

This study investigated the feasibility of reusing concrete waste powder (CWP) with particle sizes below 75 and 150 microns as a cement replacement at various proportions. It evaluated the differences with the control mixture based on compressive strength values. The results obtained are promising and may help reduce environmental pollution from the cement industry, minimize degradation of natural raw materials, and decrease the amount of construction and demolition waste (CDW) sent to landfills. The key conclusions are as follows:

- The results indicated the potential of using CWP as a substitute for cement in producing cement bricks that fulfill the requirements for both load-bearing and non-load-bearing cement brick specifications.
- Density results for all replacement ratios indicated no effect from adding CWP or Na_2SiO_3.
- According to the mixtures used in the study, all replacement ratios resulted in normal-weight samples with densities exceeding 2.0 gm/cm^3.
- Compressive strength decreases with increasing CWP content without activation.
- No statistically significant differences were observed between samples <75 µm and <150 µm across various ratios without the activator.
- The results of the CWP samples below 150 µm with the Na_2SiO_3 activator demonstrated that replacing up to 10% of cement is feasible, combined with an activator percentage of 1.0 to 1.5%.
- It was found that the CWP samples under 75 µm performed better than those below 150 µm, as a replacement rate of 20% could be achieved using the Na_2SiO_3 activator at a concentration ranging from 1.0 to 2.0%.
- Partial cement substitution can reduce CO_2 emissions by 85–170 kg per ton of cement replaced.

The current research involves observing the performance of CWP with different sizes and replacement ratios with respect to density and compressive strength, and comparing these values to those specified in the Egyptian standards for cement bricks. Therefore, the research requires completion, and the samples' durability and water absorption performance must be assessed.

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