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Review Article

Effect of Natural Pozzolana on Physical and Mechanical Properties of Concrete

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Construction industries are rapidly growing, sacking high amounts of concrete which has a highly dense microstructure with excellent mechanical properties, more durable, and highly eco-friendly materials. Hence, many of the researchers are interested in solving this problem with replacing concrete by natural pozzolana (NP) which is a supplementary cementitious material mostly from volcanic sources having much active silica content that can improve the durability and mechanical properties of concrete. However, it is not well-known which common optimum replacement range can give the most desirable concrete properties. So, the present study sought to review the effects of replacing NP from volcanic sources on the durability, physical, mechanical, and microstructural properties of concrete, also, to identify the most common dose of a positive effect as a replacement in concrete. The review shows that many of NP used by different literature from different places satisfy ASTM replacement standard in concrete, especially, based on its chemical compositions. Also, the review observed that employing NP in concrete significantly improves concrete workability, lengthens setting time, and reduces bulk density, porosity, water absorption, and chloride ion migration by making denser concrete microstructure. In general, adding 5%–20% of NP in concrete significantly improves compressive strength, split tensile strength, and flexural strength. Specifically, most of the studies found 15% replacement of NP having volcanic sources can give optimum strength. Besides these, most of the studies indicated that the improvement of the strength was more visible at the concrete age of 7–28 days.

1. Introduction

Currently, construction industries are rapidly growing sacking high amounts of concrete consumption which has highly dense microstructure with excellent mechanical properties, more durable, and highly eco-friendly materials [1, 2]. Hence, the use of supplementary cementitious materials commonly reached by SiO_2, Al_2O_3, and Fe_2O_3 are mostly recommended to be added in concrete for minimizing cement content, to achieve good concrete properties, cost reduction, and reduce environmental pollution coming due to ordinary Portland cement production [3].

Supplementary cementitious materials in concrete mixtures contribute a lot of significance to the fresh and hardened properties of concrete like enhancing workability, reducing the heat of hydration, lowering permeability, improving ultimate strength, and durability [4–19]. Hence, construction industries are potentially using one or another supplementary cementitious material commonly identified as pozzolana [8, 20]. Pozzolana is mostly from natural volcanic ashes, scorched lands, or wastage of different product that mainly consists of siliceous and aluminous materials which can actively react with water and calcium hydroxide compounds to possess cementitious properties commonly known as calcium silicate hydrates (C–S–H) and calcium aluminate silicate hydrates (C–A–S–H) [21, 22].

Pozzolana has two types which are artificial and natural pozzolana (NP) [21, 23, 24]; artificial pozzolanas are mainly from the combustion of the furnace, and the utilization of waste that can be decomposed into ash which contains reactive silica such as fly ash, rice husk ash, and silica fume. Whereas, NPs are from the natural sedimentation of volcanic ash or lava that involves active silica, used as cementitious materials when combined with free lime [23, 25, 26]. Also, NP is categorized into two; NP from natural rocks that require grinding other than calcinations such as volcanic ash and pumice. The other NP is the one that requires thermal treatment to activate its reactivity with free lime from clinker, like calcined clay, bentonite, and meta-kaolin [27].

NPs are widely used as a supplementary cementing materials which can establish promised outcomes in grasping the expansion of cementitious materials [28, 29]. That is through using as a partial substitution of cement by NP to reduce cement consumption and at the same time improve concrete performance [30–38]. Besides these, the employment of NP is beneficial in the reduction of deformations while improving the compressive strength of concrete [14, 30, 35, 39–53]. Also, NP can improve concrete resistance to chloride ion penetration which is directly indicated by electric resistivity and durability of concrete by reducing shrinkage cracks and significantly reducing crack width of concrete matrices [1, 12, 54–56]. In addition to these, increasing the content of NP in concrete increases resistance of chloride ion migration [57], and decreases permeability and water absorption which can improve the long-term strength gain of concrete [1, 36, 58–60]. That is due to natural pozzolanic powder can higher the tortuosity of the pore thereby preventing the permeability or absorption of water into the concrete matrix [61].

Furthermore, increasing the fineness of NP in concrete decreases the slump flow and increases the viscosity [50, 62]. However, it can improve the flow ability, passing ability, and place ability of concrete [63, 64]. In addition to these, incorporating NP in concrete significantly lowers the heat of reactions which can give an enormous advantage in mass concrete production by making a denser microstructure of concrete [51, 65–67]. Also, Paiva et al. [29] reported the denser microstructure of concrete protects chloride ion diffusion. This is mostly due to the pozzolanic reaction of NP which can promote the binding of chloride ions. Hence, the replacement of NP in concrete highly improves concrete durability [68, 69], and also it appears beneficial in technical, economical, and environmental protection compared to traditional concrete [70–78].

Generally, NPs are abundant material in most countries; hence, many researchers are interested to use it in concrete and found different beneficial effects on the physical and mechanical properties of concrete suggesting different doses for the users. However, it is not well-known which common optimum replacement range can give the most desirable concrete properties. So, the present study reviewed different studies on NP and drawn an important conclusion on which common contents of NP most positively affect the physical, mechanical, durability, and microstructural properties of concrete. Besides these, the study can contribute to good implementation of NP mainly from volcanic sources in concrete for its sustainable use for the improvement of mechanical, physical, durability, and microstructural properties of cement composite materials in addition to its eco-friendly and cost-effective concrete productions within a safe environment.

2. Chemical Composition of Natural Pozzolana

Chemical compositions of NP vary from batch to batch depending on the geological location of the deposit but commonly NP is rich in silica [79]. The pozzolanic reaction of NP mainly depends on its chemical composition, chemical reactivity index, and mineralogical composition [80]. Also, Setina et al. [81] reported pozzolanic activity of pozzolana is strongly dependent on their chemical composition mostly on the amounts of reactive silica. As presented in Table 1, all sampled NP satisfies ASTM C618 [105], requirements of sulfur dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) addition have to be greater than 70% for natural pozzolanic materials added to concrete productions. In addition to that, Cavdar and Yetgin [106] reported that increasing the sum of those three oxides increases the strength, mostly increasing strength can mainly depend on the content of active SiO_2. That is because SiO_2 is the most crucial oxide which can improve the pozzolanic reaction in pozzolana. However, as Table 1 shows most of the literature has not tested the contents of chloride ions in NP which can cause corrosion of reinforced bars in concrete.

3. Effects of Natural Pozzolana in Concrete

3.1. Effects on Physical Properties

3.1.1. Workability. Workability of concrete is the degree of fresh mixed concrete that shows homogeneity within the mechanism of mixed, placed, consolidated, and finished state which is mostly measured by slump test for concrete [107]. Hence, the partial replacement of NP by cement weight in concrete significantly improves workability [6, 47, 108–110]. This is shown in Figure 1, as the concrete incorporated with NP increased workability compared to conventional concrete. That is due to NP reduces the amount of hydration product that can occur during the early hydration process [95, 101, 111].

Also, Celik et al. [96] and Xu et al. [112] found that the employment of NP increases the flow ability of concrete, but increasing the fineness of NP, especially volcanic pumice lessens the flow ability of fresh cement composite [50, 62, 85]. That is mainly due to the fine NP starts to more take the place of cement particles which can reduce the workability. For the same reason, employing NP more than 15% by mass of cement can lessen the workability of concrete [102].

3.1.2. Setting Time. Initial and final setting time is used to know the rate of concrete hydration which is crucial in concrete strength development [107]. The employment of NP in concrete increases initial and final setting time with increasing the percentage content of pozzolana [99, 113–115]. That is due to prolonging the hydration process that can cause

Table 1: Chemical composition of natural pozzolana of volcanic rock and ash used in various researches.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	Cl^-	LOI	M	References
43.9	16.2	11.6	9.4	8.8	—	3.1	0.8	—	—	—	1.4	71.7	[82]
71.31	10.81	4.76	4.42	—	—	—	7.74	0.73	—	—	3.37	86.88	[83]
46.8	17.5	8.4	9.4	3.9	0.4	4.32	1.40	—	—	—	4.8	72.7	[84]
47.40	18.52	10.04	7.90	6.04	0.34	2.58	1.07	1.62	0.64	0.01	2.21	75.96	[85]
40.48	12.90	17.62	11.83	8.33	—	3.60	1.67	—	1.37	—	1.60	71	[86]
73.68	14.69	2.63	2.02	0.28	0.03	2.27	3.88	—	—	0.06	2.39	91	[48]
44.95	17.32	9.49	12.36	4.20	0.01	3.0	1.39	—	—	0.0	6.72	71.76	[87]
46.48	14.74	12.16	8.78	8.73	—	3.39	1.27	2.31	0.63	—	1.32	73.38	[88]
47.40	18.56	10.04	7.90	6.04	0.34	2.58	1.07	1,62	0.64	0.01	2.21	76	[61]
46.96	17.81	9.74	10.97	2.46	0.84	3.29	1.57	—	—	—	—	74.51	[89]
65.20	14.9	3.5	3.20	0.6	0.0	3.80	3.70	0.70	—	—	3.90	83.6	[90]
46.50	19.28	11.22	8.50	5.48	0.14	2.70	3.61	1.88	—	—	0.66	77	[73]
44.95	16.91	9.47	14.59	3.70	0.20	1.34	1.35	—	—	—	4.30	71.33	[91]
46.66	17.74	8.67	11.01	4.14	0.04	5.07	1.10	—	—	—	8.94	73.07	[31]
55.0	15.90	4.20	2.20	1.50	—	4.90	4.60	—	—	—	11.2	75.1	[92]
47.21	18.82	9.99	10.84	4.38	0.50	0.81	0.20	—	—	—	1.70	76.02	[93]
57.10	15.82	6.16	5.95	2.09	0.28	1.10	2.0	—	—	1.40	1.20	79.08	[94]
72.14	12.81	1.25	0.84	0.19	0.02	2.38	4.09	0.13	—	—	5.04	86.2	[95]
46.48	14.74	12.16	8.78	8.73	—	3.39	1.27	2.31	0.63	—	1.32	73.38	[96]
45.67	15.10	10.14	8.98	3.45	0.19	3.0	—	—	—	—	—	70.91	[97]
55.0	15.90	4.20	2.20	1.50	—	4.90	4.60	—	—	—	11.2	75.1	[98]
47.21	18.85	9.99	10.84	4.38	0.50	0.81	0.20	—	—	—	3.91	76.02	[99]
59.32	17.50	7.06	6.10	2.55	0.71	3.80	2.03	—	—	—	1.0	83.88	[100]
53.68	12.13	7.04	9.43	9.02	2.52	—	3.05	—	—	—	0.48	72.85	[101]
69.20	13.20	1.70	2.70	0.80	0.10	3.9	3.0	0.20	0.10	—	4.36	84.1	[27]
46.8	18.8	10.5	9.2	3.8	0.2	—	0.5	0.8	—	—	6.5	76.1	[102]
55.8	16.10	6.90	8.60	4.0	0.20	2.20	2.20	0.50	—	—	3.1	78.8	[103]
61.67	15.90	4.32	7.90	2.04	—	3.21	2.12	0.44	—	—	1.85	81.89	[104]

M = Sum (SiO_2, Al_2O_3, and Fe_2O_3).

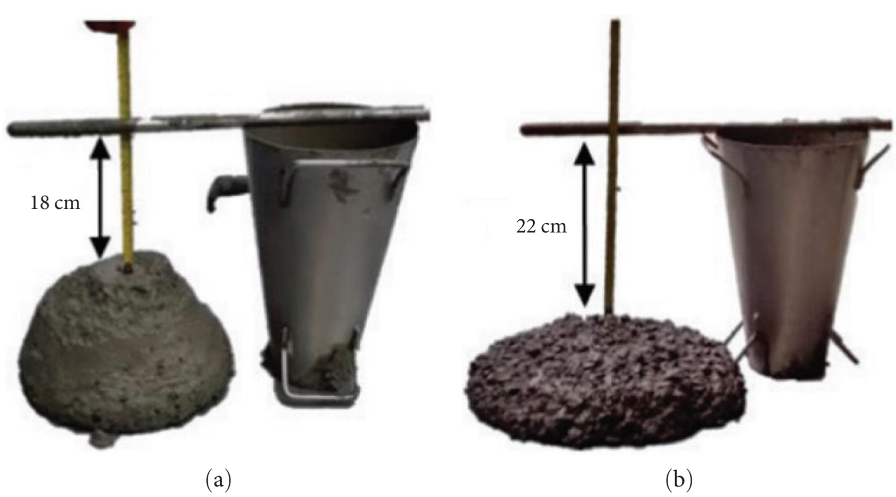

Figure 1: Slump test of concrete mixture (a) only by OPC and (b) OPC + alkali activated by natural pozzolana from Robayo-Salazar et al. [58].

slow stiffening of the concrete mixture [95, 116]. In addition to these, the incorporation of NP in concrete reduces the free lime of cement and C_3A contents in a concrete mixture delay the setting time of concrete [117]. Also, the increase in setting time is considerably due to the employment of NP highly linked with the mineralogical and physical properties of pozzolana that determine the reactivity of NP as well as the setting time of concrete [99, 117]. Also, that is commonly

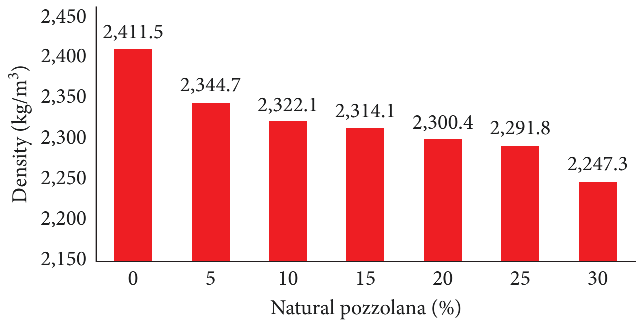

FIGURE 2: Different replacement of NP of calcined kaolin on density at 56 days from Mouanda et al. [118] reproduced.

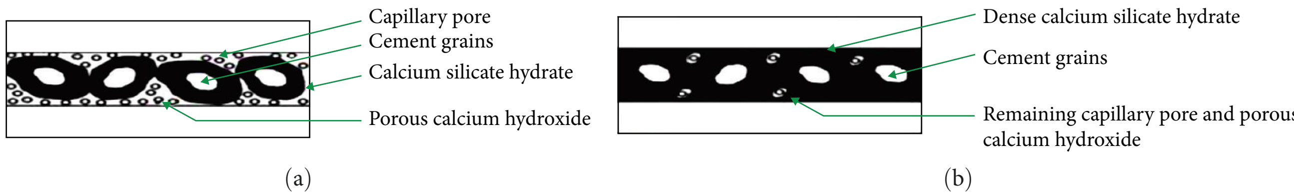

FIGURE 3: Pore-filling ability of pozzolanic materials (a) before adding pozzolana and (b) after the addition of pozzolana from Rathi and Modhera [138].

because NPs that have a higher silica content reflect the higher pozzolanic reactivity in the hydration reactions of cement composite materials.

3.1.3. Bulk Density. Pozzolanic materials are highly reactive with the hydrated calcium hydroxide $Ca(OH)_2$ to form hydrated calcium silicate (C–S–H), which is responsible for the state of fresh bulk density. As shown in Figure 2, concrete samples with NP have lower bulk density than the control mixture without pozzolana, which is due to a result of the dilution action of pozzolanic materials [45, 116, 118–124]. Moreover, increasing NP in concrete significantly reduces the density of concrete. Hence, Ahmad et al. [125] reported that the reduction of density is due to NP having a higher specific area compared to cement. Therefore, lessening of density due to the employment of NP is a crucial consideration for massive concrete construction.

3.1.4. Porosity. The porosity of cement composite materials consisting of pozzolana decreases, which is linked with the ongoing processes of hydration and crystallization of salt in pores [52, 81, 126–129]. Hence, concrete with NP significantly reduces porosity compared with the reference concrete mixture [77, 100, 108, 130–132]. This is because of the pozzolanic reaction between NP and cement hydration which reduces free calcium hydroxide and increases the C–S–H content, hence lower porosity in concrete [15, 27, 77, 84, 133].

Also, pozzolanic particles precipitate calcium hydroxide by early hydration to form C–S–H by pozzolanic reaction. Hence, causes a pozzolanic reaction which consumes free calcium hydroxide and forms cement gel, i.e., C–S–H and C–A–S–H [133], that can reduce the pore size, block capillary voids, and dense concrete matrix; thus improving strength and durability [59, 134–136]. Also, Deboucha et al. [31] confirmed in their report that the durability performance of concrete is mainly dependent on the size of capillary pores in the concrete matrix which is more visible by the water absorption test.

A similar finding with Dembovska et al. [137] found that the hydrated cement reactions of pozzolana give lower density with efficiently filling pores, which decreases porosity by consuming portlandite, as shown in Figure 3. Therefore, the consumption of portlandite in cement gives the improvement of strength, impermeability, durability, and chemical resistance [137]. Also, as the study measured via mercury intrusion porosimetry the smaller size of NP by volcanic ash consumes portlandite which forms secondary calcium silicate hydrate (C–S–H) gels that contribute to the reduction of pore structures of concrete [139].

3.2. Effects on Mechanical Properties

3.2.1. Compressive Strength. The strength development of NP blended cement composite materials is dependent on the size of NP and its reaction capability which highly contribute to the strength development by reinforcing the microstructural matrix and forming binding hydrates that consume portlandite [13, 15, 90, 140–142]. At an early age, NP lowers the strength of the concrete mixture as Senhadji et al. [99], but through longer ages, the pozzolanic reaction aids in more strength development than the control concrete mix [1, 34, 77, 94, 143–149]. The amorphous silicate matrix actively reacts with portlandite to form a secondary C–S–H gel which mainly improves the microstructure and strength of the final hydrated cement matrix, which is mostly dependent on the hydration reaction of NP and cement phase [95, 120, 150].

Besides these, Valipour et al. [124] and Walker and Pavía [22] reported that the compressive strength of concrete with NP increases with decreasing NP particle size. Also, Homayoonmehr et al. [151] and Reddy and Reddy [114]

Table 2: Optimum NP dose recorded for improvement of compressive strength by different researchers.

W/C	Dose range (%)	Curing time (days)	Optimum strength			Type of NP	References
			Age (days)	Dose (%)	Strength (MPa)		
0.40	0,15, 20, 25	2, 7, 30, 90, 365	7, 30, 90, 365	20	88.5, 91.2, 94.3, 105.6	Natural deposited ash	[99]
0.50	0, 5, 7.5, 10, 15	7, 28, 90	90	10	46.1	Diatomite	[13]
0.47	0, 5, 10, 15, 20	7, 28	7, 28	10	22.66, 26.67	Bentonite	[152]
0.55	0, 5, 10, 15, 20, 25	7, 28	7, 28	15	—, 31.65	Kaolin	[153]
0.40	0, 5, 10, 15, 20	7, 28, 56, 90	90	10	101.15	Kaolin	[53]
0.32	0, 5, 10, 15, 20	7, 28	7, 28	15	54.8, 72.7	Kaolin	[39]
0.40	0, 5, 10, 15, 20, 25, 30	3, 7, 28, 56, 90	28, 56, 90	15	—	Bentonite	[145]
0.55	0, 5, 10, 15, 20, 25, 30, 35	7, 14, 28, 56	14, 28, 56	10	32.76, 37.62, 42.67	Kaolin	[118]
0.35	0, 5, 10, 15, 20, 25	3, 7, 28	3, 7, 28	15	110	Natural deposited ash	[154]
0.48	0, 10, 15, 20, 30	7, 28	7, 28	20	22.18, 36.18	Kaolin	[155]
0.43	0, 4, 8, 12, 16, 20	3, 7, 28	3, 7, 28	12	16.83, 29.36, 47.016	Kaolin	[11]
0.50	0, 10, 20, 30	28, 56, 90, 180	180	20	57.5	Volcanic ash	[52]
0.67	0, 20, 30	7, 28	28	20	70.70	Volcanic ash	[83]
0.48	0, 5, 10, 15, 20	7, 28	7, 28	5	22.95, 26.69	Bentonite	[156]
0.30	0, 5, 10, 15, 20	28, 56, 90	28, 56, 90	15	—	Bentonite	[157]
0.50	0, 5, 10, 15, 20	3, 28, 90	90	20	—	Bentonite	[158]
0.40	0, 5, 10, 15, 20, 25, 30	3, 7, 28, 56, 90	28, 56, 90	15	53.2, 70.75, 73.80	Bentonite	[145]

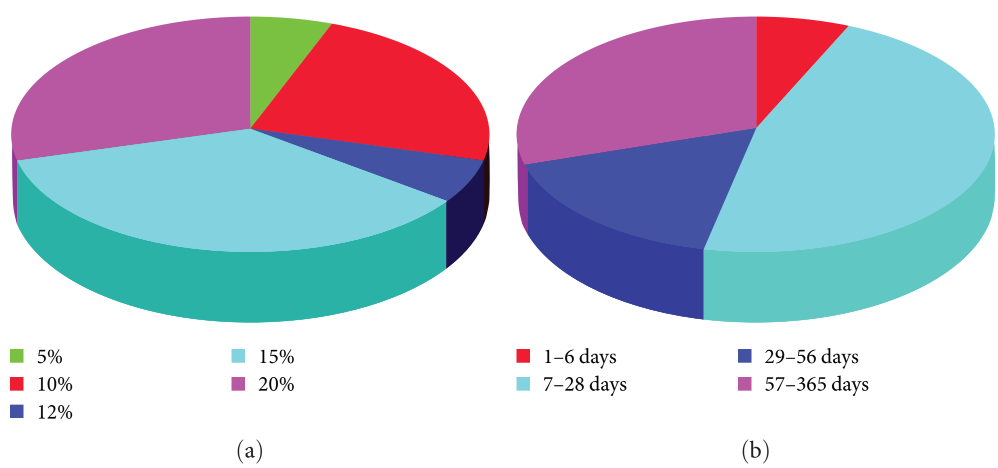

Figure 4: Summary from Table 2: (a) optimum concrete compressive strength achieved by different NP doses and (b) influence of age to give optimum compressive strength.

found that NP specifically meta-kaolin and bentonite clay improves compressive strength which is mainly dependent on the chemical composition and fineness or filling ability of the pozzolana.

Furthermore, Khan et al. [33] reported an improvement of strength by partial replacement of pozzolana in concrete/mortar mostly from (i) cement hydration effect, (ii) pozzolanic reaction effect between amorphous silica and cement hydration product $Ca(OH)_2$, and (iii) filler effect of pozzolanic particles. Hence, all significantly play a crucial role in improving the strength, microstructure, and durability of the concrete.

Therefore, as presented in Table 2, many researchers reported adding NP in concrete increases compressive strength; however, since different doses of NP were taken all have different optimum replacements. Hence, Figure 4(a) reported the summary of the best doses that were reported by many literature in Table 2 which can reflect optimum replacement and found that 5%–20% replacement of volcanic source NP can give good results of compressive strength for concrete having 0.35–0.55 water to cement ratio; specifically, 15% volcanic-based NP by weight of cement replacement in concrete is most governed. Also, as presented in Figure 4(b), the improvement of strength is more visible in a concrete age of 7–28 days. This is mainly due to the consumption of free lime that can form extra C–S–H gel which enhances the strength over a long time by its active pozzolanic reactions. Also, the employment of NP enhances the interface properties by pozzolanic reaction and fills the pores that make the concrete matrix impermeable.

Table 3: Optimum NP dose recorded for improvement of split tensile strength by different researchers.

W/C	Dose range (%)	Curing time (days)	Optimum strength			Type of NP	References
			Age (days)	Dose (%)	Strength (MPa)		
—	0, 5, 10, 15, 20	28	28	15	2.17	Bentonite	[159]
0.40	5, 10, 15, 20, 25	7, 28, 56	7, 28, 56	15	2.8	Bentonite	[160]
—	0, 10, 20, 30, 40, 50	7, 14, 28	7, 28	10	3.4, 3.75	Kaolin	[161]
0.32	0, 5, 10, 15, 20	28	28	15	4.0	Kaolin	[39]
0.53	0, 3, 5, 10	7, 28, 60, 90	7, 28, 60, 90	10	3.4, 4.3, 4.7, 5.0	Kaolin	[162]
—	0, 10, 20, 30	1, 2, 14, 28, 90, 180	14, 28, 90, 180	10	5.56, 5.58, 6.12, 6.22	Volcanic ash	[61]
3.30	0, 5, 10, 15, 20	28, 56, 90	28, 56, 90	15	12.3, 12.6, 13.3	Bentonite	[157]
0.50	0, 10, 15, 20, 25, 30, 35	7, 28, 180	7, 28, 180	15	1.5, 2.39, 2.6	Bentonite	[146]

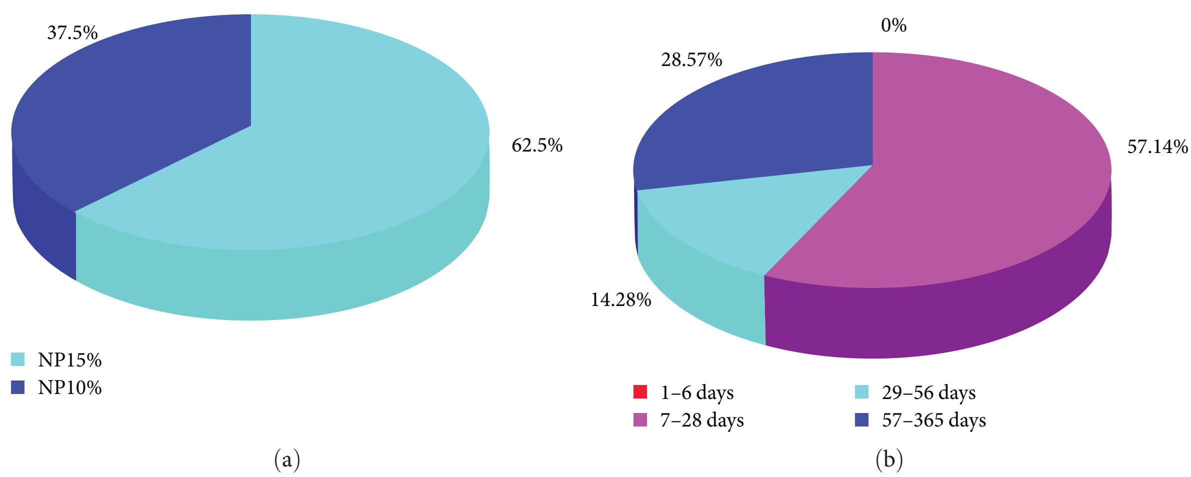

Figure 5: Summary from Table 3: (a) optimum concrete split tensile strength achieved by different NP doses and (b) influence of age to give optimum split tensile strength.

Table 4: Optimum NP dose recorded for improvement of flexural strength by different researchers.

W/C	Dose range (%)	Curing time (days)	Optimum strength			Type of NP	References
			Age (days)	Dose (%)	Strength (MPa)		
0.47	0, 5, 10, 15, 20	7, 28	7, 28	5	3.0, 3.88	Bentonite	[152]
0.40	0, 5, 10, 15, 20	7, 28, 56, 90	56, 90	15	8.90, 8.85	Kaolin	[53]
0.32	0, 5, 10, 15, 20	28	28	15	7.2	Kaolin	[39]
0.48	0, 10, 15, 20, 30	7, 28	28	20	3.86	Kaolin	[155]
0.48	0, 5, 10, 15, 20	7, 28	7, 28	5	17.84, 20.27	Bentonite	[156]
0.30	0, 5, 10, 15, 20	28, 56, 90	28, 56, 90	15	19, 19.5, 20	Bentonite	[157]
—	0, 10, 20, 30	1, 2, 14, 28, 90, 180	28, 90, 180	10	9.65, 10.03, 10.54	Volcanic ash	[61]

The degree of pozzolancity determines the strength development of the cementitious materials blended with NP.

3.2.2. Splitting Tensile Strength. The employment of NP in concrete mixture significantly improves the splitting tensile strength compared to concrete control mixture [156, 159]. As shown in Table 3, a NP that is commonly from volcanic source reported by many researchers as it enhances tensile strength. So, as reported in Figures 5(a) and 5(b) mostly found that 10%–15% employment of NP more significantly improves the splitting tensile strength of concrete, especially many studies found the addition of NP 15% gives the optimum splitting tensile strength than other substitutions, and the improvement is more observed in between 7 to 28 days age. Besides these, it is not reported the improvement of splitting tensile strength at the age from 1 to 6 days, which commonly shows the employment of NP improve strength through long terms by the gradual pozzolanic reactions.

3.2.3. Flexural Strength. Asadollahfardi et al. [163] found that using NP mainly from volcanic deposits in a concrete mixture significantly improves flexural strength compared with the control mixture. The same finding as flexural strength increased by replacing NP in concrete [17, 39, 126]. Also, as presented in Table 4, the flexural strength increased by employing 5%–20% volcanic source NP by the weight of cement in concrete, but

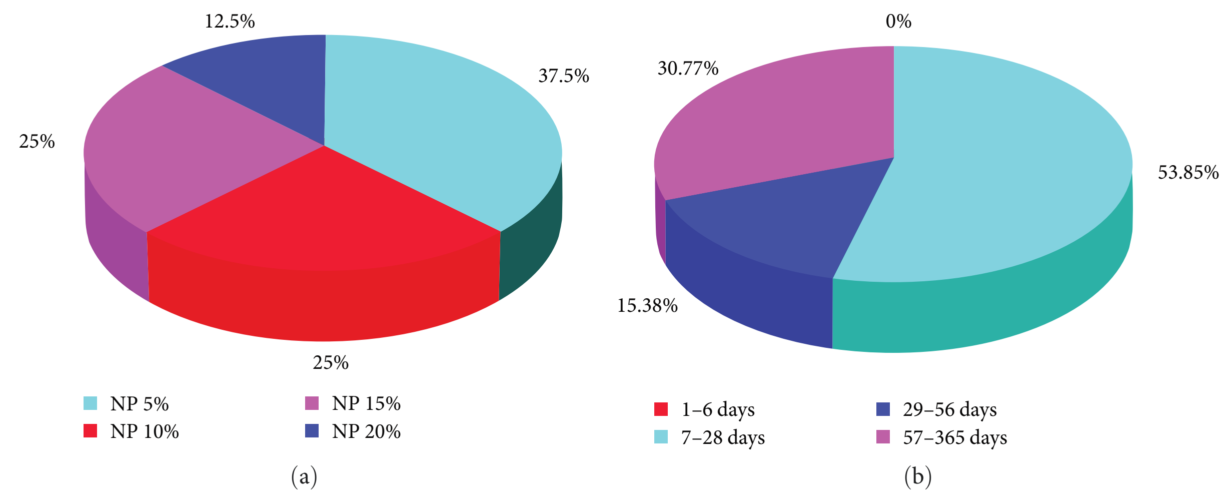

FIGURE 6: Summary from Table 3: (a) optimum concrete flexural strength achieved by different NP doses and (b) influence of age to give optimum flexural strength.

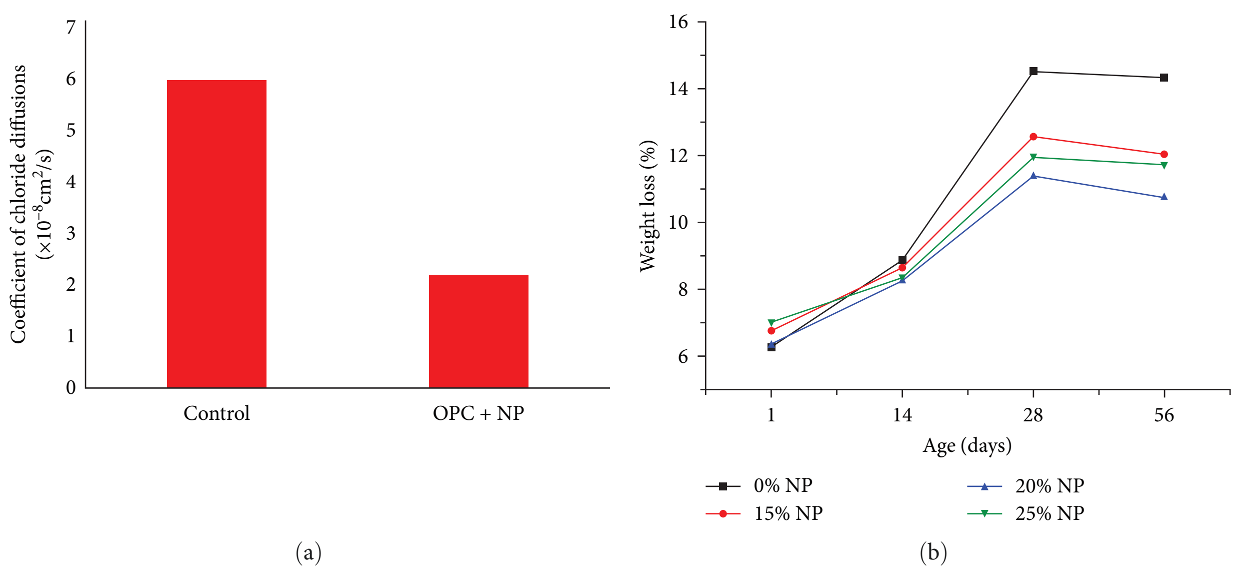

FIGURE 7: Comparison of (a) coefficients of chloride diffusion and (b) weight loss of the concrete mixtures, respectively, from Ahmad et al. [82] permission from Elsevier and Senhadji et al. [99] reproduced.

specifically as presented in Figure 6(a), much of the literature addressed adding 15% of volcanic source NP in concrete was most inclusive to get maximum flexural strength of concrete having 0.30–0.50 water to cement ratio. Besides these, Figure 6(b) presented that flexural strength improvement is more observed between the concrete ages of 7–28 days. Also, it is not reported the improvement of the flexural strength at an early age from 1 to 6 days, which can indicate the replacement of NP cannot improve the early strength compared to the control concrete mixture. This is maybe due to the NP slowly participate in the hydration reaction; however, mostly may depend on the type of NP mineralogical compositions.

3.3. Effects on Durability

3.3.1. Chloride Ion Permeability. The employment of NP in the concrete mixture lowers the chloride permeability than the reference mixture that highly resists chloride ion penetration [27, 29, 145, 151, 158, 164–169]. That is more presented in Figures 7(a) and 7(b), by the coefficient of chloride diffusion and weight loss of concrete after insertion in the chloride ion, which is a concrete sample consisting of NP less affected by chloride ion compared to the reference mixture. Hence, employing NP as a partial replacement of cement in concrete significantly improves the durability of concrete [99, 170]. This is because the pozzolanic reaction between NP and the cement hydration product of portlandite enhances the durability of concrete [15, 171]. In addition to these, blinding of NP in a concrete/mortar can increase durability by reducing the occurrence of corrosion of steel bar by mitigating chloride ion penetration to a concrete matrix [157, 158, 172, 173]. That is mainly due to the microfilling ability of most NP in the concrete matrix which can mitigate the entrance of chloride ions.

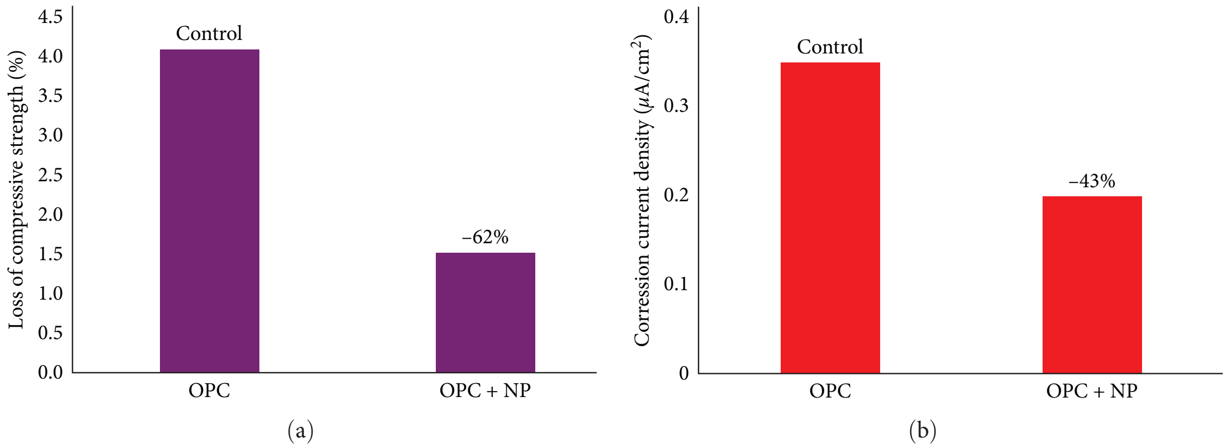

Figure 8: Comparison of concrete with only OPC and OPC + NP on (a) losses of compressive strength due to 1 year of exposure to sulfate and (b) corrosion current densities of steel embedded in concrete from Ahmad et al. [82] reproduced.

3.3.2. Sulfate Attack. The employment of NP is more beneficial in the mitigation of concrete expansion than the conventional concrete mixture [169, 174]. The more expansion observed in the control mixture may be attributed to the small production of secondary ettringite, which is characterized by expansion and cracks. However, by hydration reaction mixed with NP consumes calcium hydroxide; hence, gypsum formed in the reaction between calcium hydroxide and sulfate is responsible for the occurrences of secondary ettringite. Furthermore, the pozzolanic reaction can form a secondary C–S–H gel that is potentially a participant in the densification of the hardened cement paste, since it is collected in the pores and improves the interface of cement paste to aggregate matrix. These effects significantly lessen the diffusion of SiO_2 ions and lower the pozzolanic cement expansion against plain cement [175]. Hence, the concrete produced with the addition of NP is always more sulfuric acid resistant than without NP [91, 147, 176]. In a similar finding, Merida et al. [177] reported that replacing NP with the weight of cement in the mixture of high-performance concrete affect positively the durability of concrete samples cured in the sulfate environment.

Besides these, free CaO and MgO compounds available in cement are responsible for the swelling effect. Therefore, the addition of NP reduces free lime, and hence, can reduce the soundness or expansion of concrete. Especially, more fine NP highly enhances the compressive strength and sulfate attack resistance of concrete [121]. Also, Ahmad et al. [82] investigated the effect of acidic attack on concrete produced from OPC and OPC-NP subjected in a solution made from 5% concentration of mixed sulfate salts: 2.5% of $MgSO_4$ and 2.5% of Na_2SO_4 by immersing in the solutions for 12 months. Hence, as shown in Figures 8(a) and 8(b), the specimen of concrete with OPC-NP reduced compressive strength loss by 62% compared to the control mixture without NP, and the corrosion of steel bar embedded in concrete is also reduced by 43% for concrete having NP. Also, as shown in Figure 9, the concrete cube cast by OPC without the addition of NP cured in 5% hydrochloric acid was much corroded and lost more mass compared to the same sample cured in water; however, the concrete cube casted by OPC-NP was corroded a little and not seen much mass loses for the sample cured in hydrochloric acid for 12 weeks. So, the employment of NP in concrete mixtures is very beneficial in lessening the mass loss due to an acidic environment. Generally, from those results can see that the employment of NP can significantly improve the durability of concrete by improving resistance of acid attack.

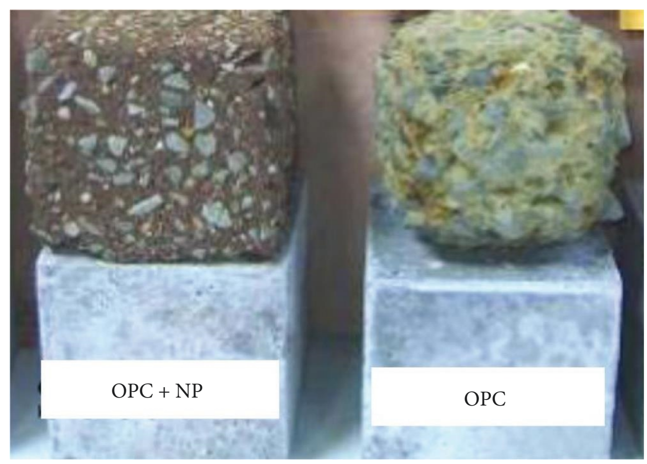

Figure 9: Deterioration of concrete specimens produced from OPC + NP and only by OPC after 12 weeks of immersion in 5% HCl solution from Siad et al. [176].

3.3.3. Water Absorption. Water absorption is the crucial measure of water penetration through concrete pores [158], which can show the existence of pores in the concrete matrix that allow penetration of water and other hazardous chemicals and hence, can cause a reduction of concrete durability. As shown in Figures 10(a) and 10(b), the addition of NP in concrete decreases water absorption [178–180], which is mainly due to pozzolana are finer than cement particle which can make concrete more dense, consequently, improve concrete microstructure [132, 158, 181]. Also, the employment of NP in cement composite enhances the densification of cement slurries that protects the penetration of

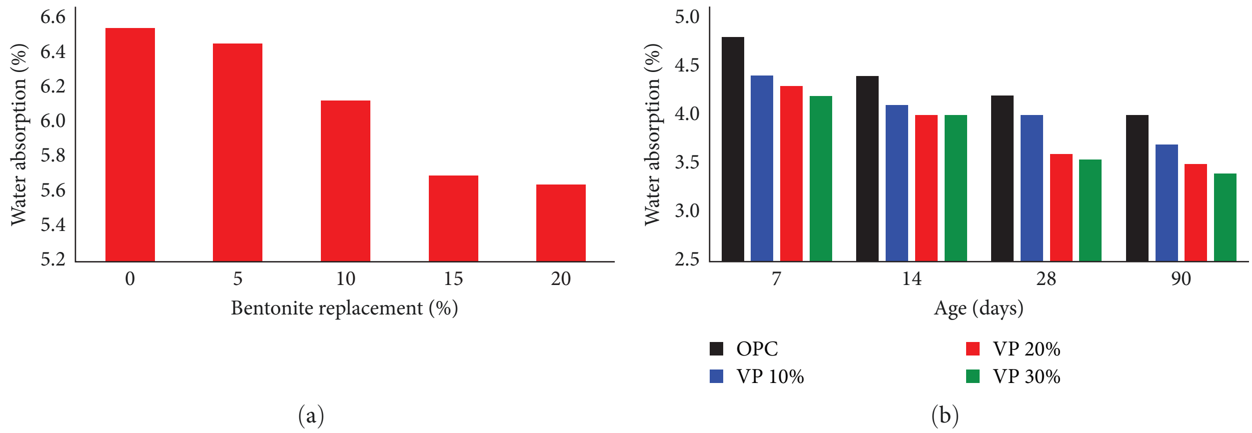

FIGURE 10: (a) Water absorption at 90 days using different doses of bentonite and (b) water absorption at different concrete age using different doses of volcanic pumice respectively from Masood et al. [158] permission from Elsevier and by Zeyad et al. [61] reproduced.

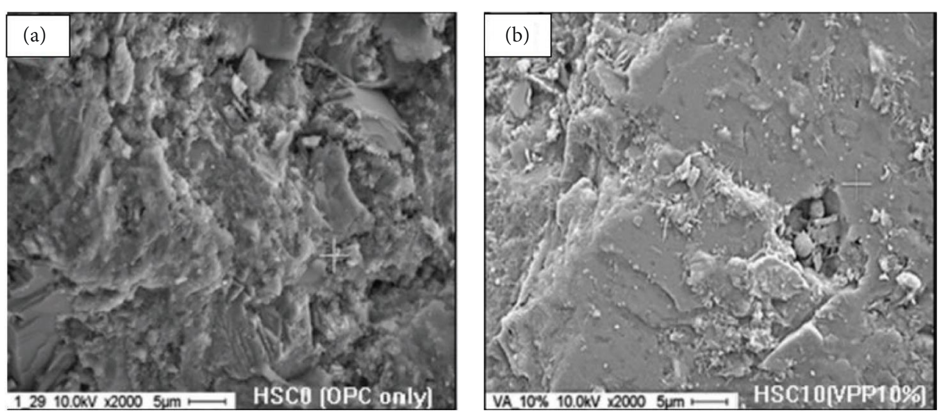

FIGURE 11: Microstructural difference (a) with only OPC and (b) with OPC + NP (volcanic pumice) from Zeyad et al. [61].

water [50, 182]. So, the reduction of water absorption is very crucial for the improvement of the durability of concrete especially for the construction work contact with water like dams, bridges, and culverts.

3.4. Effects on Microstructure. The addition of NP in concrete makes dense microstructure, uniform structural matrix, and very few pores [91, 183]. This is very beneficial for the construction work that needs high-performance cementitious materials. That is more shown in Figures 11(a) and 11(b) as the addition of NP in concrete improves densification and agglomeration of the concrete structures and reduces void compared to the conventional concrete mixture. This is due to the pozzolanic reaction of NP that further promises densification and makes low porosity of the concrete by the formation of C–S–H, which causes a significant improvement of physical and microstructural characteristics of concrete relative to the control concrete mixture [91, 183].

Besides these, Wei and Gencturk [184] reported incorporating NP for the improvement of strength and stability of concrete can be credited mostly to the consumption of free lime during the hydration of pozzolanic reactions to produce secondary C–S–H. This formation of secondary C–S–H is beneficial through improving concrete microstructure by producing a visible densification surrounding natural pozzolanic grains with significantly lessening porosity and permeability of concrete matrix, hence, can greatly improve the durability of the concrete [67, 103, 174, 185, 186].

Also, adding NP in concrete improves the microstructure and strength of concrete/mortar as Morsy et al. [18], hence, any microstructural variation can be observed by hydration products associated with the pozzolanic reaction, which is highly responsible for the strength variation in concrete [187]. The substitution of cement by NP has a beneficial effect on the durability, and thus, contribute to the densification of cement slurries, by consuming portlandite to form a secondary C–S–H and C–A–S–H [50]. Generally, by slowing the hydration reaction, NP can allow to water more participate in cement hydration which forms an adequate reaction of free cement particles [188].

4. Conclusions

The review of the various studies reported the beneficial effects of employing NP in concrete, specifically the following conclusions have been reached.

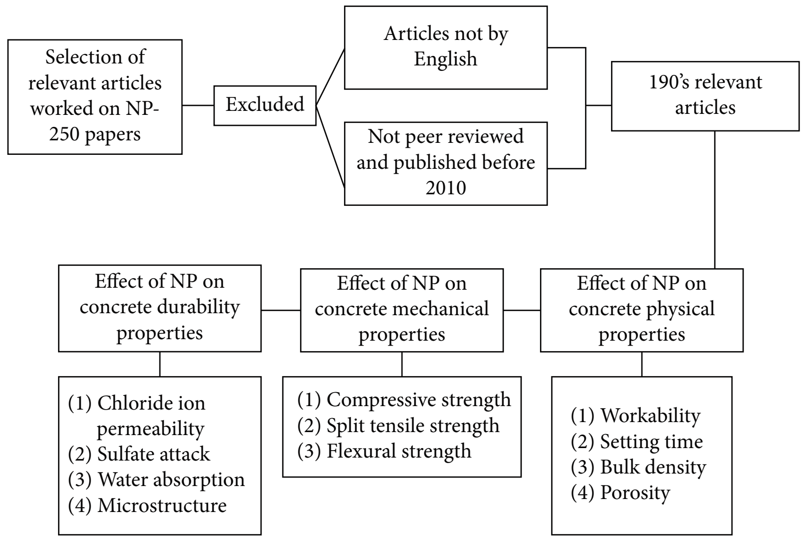

Figure 12: Screening process of used literature.

(i) The employment of NP improves the physical properties of concrete by increasing workability, lengthening the setting time, and reducing bulk density compared to the concrete control mixture. That is due to NP reduces the amount of hydration product that can occur during the early hydration process.

(ii) Furthermore, adding 5%–20% of volcanic base NP in concrete significantly improves compressive and flexural strength, especially as many literature reported that the 15% replacement of volcanic base NP in concrete gives the optimum strength. Also, most of the studies indicated the improvement of the strength was more visible in concrete age of 7–28 days.

(iii) Besides these, the addition of NP in concrete significantly reduces water absorption, and chloride ion migration by blocking capillary voids and making denser concrete microstructure, which is mainly through the pozzolanic reaction of NP and cement composite materials.

(iv) Also, most of the studies found that the addition of NP in concrete decreases porosity; that is mainly due to NP microfilling ability and active reactivity with portlandite to form C–S–H. Hence, C–S–H potentially can participate in the improvement of the strength, durability, and to make dense microstructure of concrete matrix.

Generally, the present review recommends the employment of volcanic base NP by 5%–20% is beneficial through improving durability, physical, mechanical, and microstructural properties of concrete in addition to being economical and environmental pollution protective compared to conventional concrete.

5. Future Perspective

Since NP mostly found in most countries can vary by chemical composition from place to place. This requires deep investigations at every point in different locations of NP for its effective use in every construction industry. Besides these, future research should look into the ways of combining NP with other additives for more improvement of concrete properties.

Another consideration is that the effect of NP depth strata on concrete properties is crucial; however, most studies did not consider the depth variation on the occurrence of NP. So, it is more beneficial to identify the behavioral changes of NP at different strata in the concrete properties.

Generally, around 80% of reviewed literature has not investigated the chloride ion contents in each NP; however, high levels of chloride ions can cause corrosion of steel bars in concrete. So, the authors highly encourage future researchers to consider the effects of chloride ion content in NP on steel-reinforced concrete. Also, the authors recommend future studies to detail investigate the effects of NP on different concrete properties other than the mentioned properties in the present study.

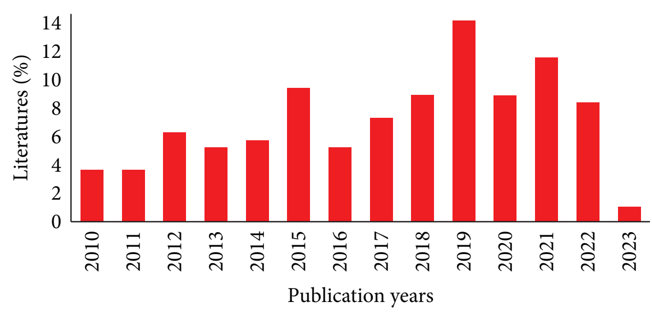

Figure 13: Percentage of used literature versus its publication year.

6. Process of Screened Relevant Papers

The relevant studies on the areas of "employment of NP in different concrete properties" were collected from Google Scholar, and the Nelson Mandela African Institutions of

Science and Technology (NM-AIST) library account database to get published articles, conference papers, case reports, and book sections, hence, screened as shown in Figure 12. Then, the relevant papers very related to the intended work were saved in the Mendeley reference managing system. As presented in Figure 13, the present review paper was deeply reviewed and gave conclusions on the papers related to the present title from the year 2010 to 2023.

Data Availability

All the data are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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