Effect of Incorporation of Nano-Silica on Mechanical Properties of Mortar and Concrete

Patel Karan and Thakkar Sonal

Abstract There are a number of applications of nanotechnology, particularly in concrete. The addition of nano-silica improves both the mechanical and durability properties of concrete. During the hydration process, the reaction of nano-silica with calcium hydroxide creates an additional calcium silicate hydrate bond, which improves the mechanical characteristics of concrete. The effect of the inclusion of nano-silica on the mechanical properties of paste, mortar and concrete is investigated in this study. Nano-silica was introduced as a replacement of cement from 1 to 5% with an increase of 1%. Various mechanical properties and setting time of different mixes were evaluated and compared with the control mix. The cement paste's consistency increased while the setting time of the paste was reduced by 8 and 47%, respectively, due to the inclusion of nano-silica. The optimum dosage of the addition of nano-silica was 3%. At 3% of nano-silica, the compressive strength of the mortar specimen was higher than control mortar by 15 and 28% at 7 and 28 days, respectively. Above three percentages of nano-silica, the strength will be reduced. Similarly, in concrete, the inclusion of nano-silica by 3% led to an increase in compressive strength by 15 and 20%, respectively, at 7 days and 28 days over control concrete. Flexural and split tensile strength was also increased by 3% nano-silica by 15 and 22%, respectively. Nano-silica did not produce a significant change in the modulus of elasticity of concrete.

Keywords Nano-silica · Compressive strength · Tensile strength · Split tensile strength

P. Karan (✉) · T. Sonal
Civil Engineering Department, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India
e-mail: karanpatel520163@gmail.com

T. Sonal
e-mail: sonal.thakkar@nirmauni.ac.in

D. Patel et al. (eds.), *Innovation in Smart and Sustainable Infrastructure*, Lecture Notes in Civil Engineering 364, https://doi.org/10.1007/978-981-99-3557-4_28

1 Introduction

ISO defines nanomaterials as any material having internal or outward dimensions in the nanoscale. Nanomaterials are widely used in various areas, including the medical, pharmaceutical and construction industries. There are many ways of modifying concrete properties and one of the ways is to add nanomaterials to it. Nanomaterials like nano-titania, nano-silica, nano-alumina, nano-zirconium dioxide, carbon nanotubes and carbon nanofibers are widely used. These materials have a very high surface area which is directly related to high reactivity.

Carbon nanotubes have the ability to improve ductility and resist the formation of cracks at the nanoscale, while graphene nano-platelet's inclusion lowers the permeability of water and chloride ions. Nano-kaolinite has anti-microbial and self-cleaning properties when incorporated into concrete (Abhilash et al. 2021; Singh et al. 2013).

Nanomaterials have shown a remarkable effect on cement hydration through a nucleation process that acts as a seed for calcium silicate hydrate hydration. As nano-silica has a high surface area, hydration process gets accelerated resulting in a more compact microstructure and denser mixture. The addition of nano-silica in concrete reduces water absorption, permeability and chloride penetration due to dense packing (Abhilash et al. 2021; Singh et al. 2013). Rupasinghe et al. (2017) observed that 8% nano-silica incorporated cement paste gives higher strength by 18% compared with control cement paste. The incorporation of nano-silica in mortar showed a high torque value during the testing period because of increasing plastic viscosity and yield stress. 2.5% dosage of nano-silica reduces the spread of mortar on the flow table and reduces the setting time of the paste (Senff et al. 2009). Ng et al. (2020) suggested that 3% of nano-silica gives maximum positive results in cement mortar. In twenty-eight days, compressive and flexural strength increased by 38 and 18%, respectively. 20% compressive strength increased with 3% nano-silica, and 50% cement was replaced with GGBS (Said et al. 2021). Total porosity was reduced for all concentrations of nano-SiO_2 concerning the control mix (without nano-SiO_2). 2% containing nano-SiO_2 mix shows the lowest porosity (Ng et al. 2020). Isfahani et al. (2016) observed that the concrete consisting of 1.5% NS developed 20% more compressive strength compared to concrete without nanomaterial at 0.5 water to binder ratio.

According to the authors (Mukharjee et al. 2020), as nano-SiO_2 has very high specific area, pozzolanic activity increases at early age resulting in early strength in cement. Therefore, even a small amount of nano-silica significantly increased the compressive strength. However, the maximum compressive strength at 28 days was obtained at 2 to 3% dosage of nano-silica, indicating that the nano-silica's optimum dosage was within this range (Behzadian and Shahrajabian 2019; Elkady et al. 2013; Kumar et al. 2019). Compressive strength reduces at higher dosages of nano-silica due to more voids and agglomeration (Elkady et al. 2013). 3% of nano-silica replacement led to increased flexural strength due to less void and the formation of the greater interfacial transition zone in the concrete matrix. The addition of 3% nano-silica increased flexural strength by 15% in both recycled and natural aggregate concrete

Table 1 Cement's physical properties

Consistency	Setting time (min)		Specific gravity	Fineness (m^2/kg)
	Initial	Final		
28	80	170	3.12	290.5

(Mukharjee et al. 2020). Kumar et al. 2019 reported that 3% nano-silica improves the tensile strength of concrete by 22%.

Materials like nano-silica redefine the fresh and hardened properties of concrete and also help in enhancing the durability of concrete. Therefore, the use of nanomaterials is likely to revolutionize bulk material properties by controlling the properties at the nano-level by providing an accelerated hydration mechanism and reducing the porosity of concrete. Nano-silica when used in concrete will give high strength, better durability and sustainability and will be an environmentally friendly cementitious composite. As nanomaterial is costly, it is to be used in judicious quantity since an excess of nanomaterials incorporated in concrete does not produce the desired effect; hence, experimental investigation was performed to determine the percentage of nano-silica to be incorporated and its effect on mechanical properties of concrete.

A small increase in initial cost will avoid undue distress in the structure due to particle packing and increase the durability leading to lesser repair and maintenance costs to users of the structures (Rupasinghe et al. 2017).

2 Materials and Methods

2.1 Materials

Ordinary Portland Cement used was OPC 53, as classified by the IS 269:2015 standard (IS: 12269 2013). Table 1 shows the physical properties of cement (Indian Standard: IS 4031–5 1988): Methods of Physical Tests for Hydraulic Cement of Indian Standards. Nano-silica (NS) particles have an average size of 12 nm. Specification of nano-silica is given in Table 2. Fine aggregate (FA) consisted of river sand. Results of tests conducted on fine and coarse aggregate (CA) are illustrated in Table 3 (IS 2386 (PartIII) 1963b; of Indian Standards). BASF Master Polyheed 8305 superplasticizer (SP) was used, and the specific gravity is 1.07.

2.2 Mortar Specimen Preparation

Mortars specimens were prepared with one part cement to two-part aggregate (1:2) ratio and a water/cement ratio of 0.4. Nano-silica was added in various proportions of 0, 1, 2, 3 and 5% by weight of cement. Superplasticizer named BASF Master

Table 2 Specification of nano-silica

Specific surface area (m^2/g)	175–225
Avg. particle size (Nm)	12
Tamped density (g/l)	Approx. 50
Specific gravity	2.2
Moisture (Wt%.)	≤ 1.5
pH	3.7–4.5
Purity (Wt%.)	> 99.8

Table 3 Properties of aggregates

Aggregates	Specific gravity	Water absorption (Wt%.)	Fineness modulus
Fine aggregate	2.6	0.4	2.74
Coarse aggregate (10 mm)	2.6	0.81	6.028
Coarse aggregate (20 mm)	2.77	0.74	7.378

Polyheed 8305 was used in a range of 0.7 to 1%. For each type of mortar mixture, three samples of 75 mm × 75 mm × 75 mm were cast for the compressive strength test. Mortar specimens were prepared by the following procedure: (1) weighing of the dry materials, (2) mixing of cement and sand for one minute, (3) adding nano-silica and superplasticizer in water, (4) adding the solid materials into water and mixing for 3 min. Once the uniform mortar mixture was achieved, take out the mortar to the bowl. A vibrator was used for the compaction of the mortar. Oiled moulds were kept on the vibrator and filled the mould. Because of the less w/c ratio, continuous vibration was given till the finishing of the moulds. After 24 h demoulding was carried out and the mortar cubes were water cured. The mixture design of mortar is shown in Table 4.

Table 4 Mortar formulations

Mix	Cement (g)	Nano-silica (g)	Sand (g)	Water (ml)	*SP (ml)
Control	200	0	600	80	0
NS1	198	2	600	80	1.2
NS2	196	4	600	80	1.3
NS3	194	6	600	80	1.5
NS5	190	10	600	80	1.6

* SP: superplasticize

Table 5 Concrete mixture designs (kg/m^3)

Mix	Cement	NS	FA	CA	Water	SP
*CO	380	0	790	1197	152	3.8
NS3	369	11.4	790	1197	152	3.8
NS4	365	15.2	790	1197	152	3.8

* CO: control

2.3 Concrete Specimen Preparation

This experimental work used a mixture design of M30 grade concrete. Two dosages of nano-silica of 3 and 4% are considered as cement replacement by weight. Table 5 shows the mixture proportion of concrete mixes. Compressive strength was evaluated on a 150 mm cube specimen. Beams size of 100 mm × 100 mm × 500 mm were used for evaluation of flexural strength while for split tensile test and also for modulus of elasticity 150 mm dia. and 300 mm height cylinders were cast. First, all the dry materials were weighed, and then NS was stirred manually after adding to water. Then superplasticizer was added to the combination. A mixture of cement and aggregates was then added to it.

2.4 Test Methods

Compressive Strength

The compressive strength (C) test was performed according to (IS 516 1959) on mortar and concrete cubes at an age of 7, 14 and 28 days. All the compression tests are performed using a compression testing machine (CTM). An average of three samples for each combination gave compressive strength of mortar and concrete mix.

$$\text{Compressive strength (MPa)} = P/A \quad (1)$$

where

P Peak load (N).
A Contact surface area (mm^2).

Flexural Strength

The test procedure was used to evaluate flexural strength (IS 516 1959). Concrete specimens were tested at 28 days. A flexural testing machine was used for testing concrete specimens.

$$\text{Flexural strength (MPa)} = (P \times L) \big/ \left(B \times D^2\right) \quad (2)$$

where

P Maximum load (N).
B, D Lateral dimension of the specimen (mm).
L Length of span on which the specimen is supported (mm).

Split Tensile Strength
IS 516 (1959) was used to evaluate the split tensile strength. The peak load has been considered as a failure load for the cylinder.

$$\text{Split tensile strength (MPa)} = 2P \big/ \pi l d \quad (3)$$

where

P Maximum load applied on specimen (N).
l Length of cylinder (mm).
d c/s dim. of cylindrical specimen (mm).

Modulus of Elasticity
IS 516 has been used to measure the modulus of elasticity of concrete. In this method, the extensometer is attached to the cylinder and placed in UTM, and the load is applied. The load on the cylinder increased to 1/3 of the cube strength. Now, this load is maintained for 1 min. After one minute, the load is gradually released. The extensometer reading is noted and reloaded in the second step until the load reaches 1/3 of the cube strength. The reading from the extensometer is noted, and the load is slowly released.

3 Results and Discussion

3.1 Compressive Strength

Figure 1 shows the control concrete and cubes with nano-silica.

Table 6 showed the average compressive strength of mortar. It was observed that there was an increase in the compressive strength of mortar with an increase in the dosage of nano-silica up to 3% (NS3) and at 3% maximum strength was observed. For 5% nano-silica (NS5), there is a reduction in compressive strength due to the high surface energy of NS particles causing accumulation and uneven dispersion in the mortar matrix which results in a decrease in strength. Figure 2 shows the compressive

a) Control Concrete b) Cubes with 3% Nano Silica

Fig. 1 **a** Control concrete; **b** Cubes with 3% nano-silica

Table 6 Average compressive strength of mortar

Mixture	Compressive strength (MPa)		
	7 days	14 days	28 days
Control	35.23	45.83	54.2
NS1	38.13	50.56	56.5
NS2	38.43	52.2	59.04
NS3	41	52.8	69.23
NS5	35.7	48.3	57.33

strength comparison at 7, 14 and 28 days for mortars. The optimum dosage of nano-silica for concrete is also 3%. Table 7 shows the compressive strength of concrete. For a greater nano-silica dose, it was difficult to produce uniform dispersion of nano-silica particles in water, which results in a decrease in the compressive strength of mortar and concrete at larger nano-silica dosages. Figure 3 shows comparison of compressive strength of concrete at different curing age.

3.2 Flexural Strength

Figure 4 shows the beams of control concrete and mixture incorporating 3% nano-silica.

Test results show that NS3 concrete has higher flexural strength than control concrete. Further increasing the dosage of nano-silica flexural strength was reduced. The flexural strength of NS4 concrete is nearly similar to that of control concrete. The average 28-day flexural strength of concrete mixtures is shown in Table 8. Figure 5 shows the comparison of the flexural strength of concrete.

Fig. 2 Compressive strength of mortar

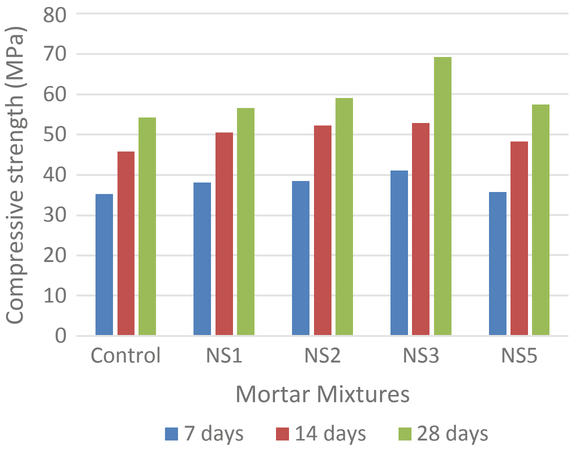
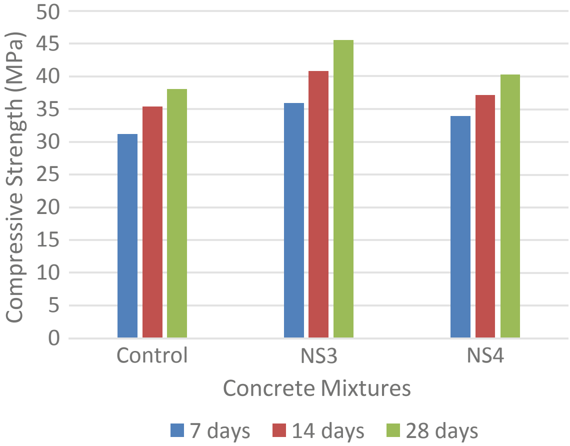


Table 7 Average compressive strength of concrete

Mixture	Compressive strength (MPa)		
	7 days	14 days	28 days
Control	31.2	35.4	38.06
NS3	35.92	40.86	45.53
NS4	33.9	37.1	40.23

Fig. 3 Compressive strength of concrete



3.3 Split Tensile Strength

At 3% dosage of NS, maximum split tensile strength is obtained. The split tensile strength of concrete mixtures is given in Table 8. Above 3% nano-silica split tensile

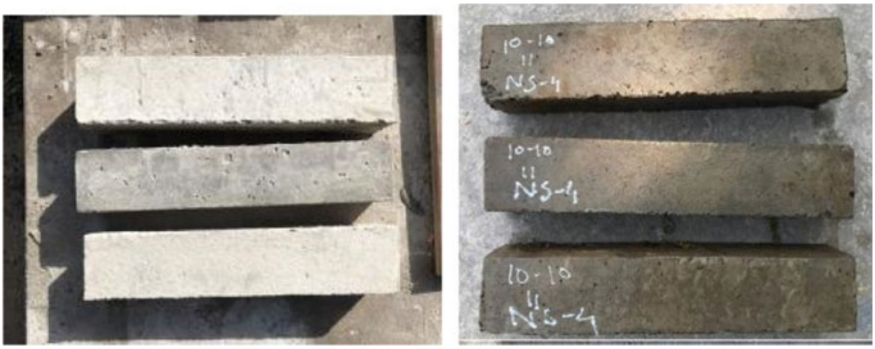


Fig. 4 Control and 3% nano-silica beams for flexure

Table 8 Average flexural and split tensile strength of concrete

Mixture	Flexural strength (MPa)	Split tensile strength (MPa)
	28 days	28 days
Control	4.6	2.38
NS3	5.26	2.9
NS4	4.93	2.35

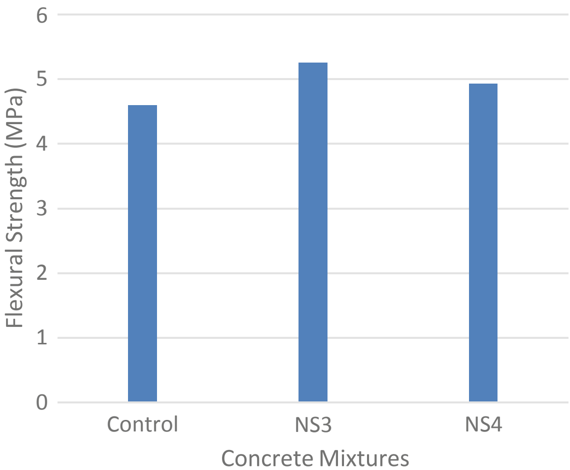


Fig. 5 Flexural strength of concrete

strength was decreased. NS4 concrete shows lower 28 days split tensile strength than the control concrete. A comparison of split tensile strength is mentioned in Fig. 6.

Fig. 6 Split tensile strength of concrete

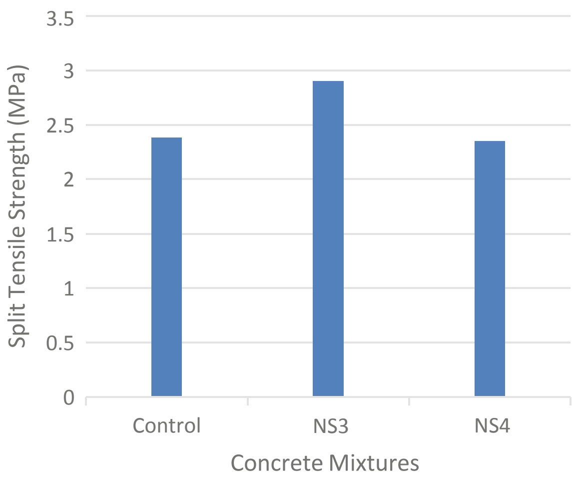


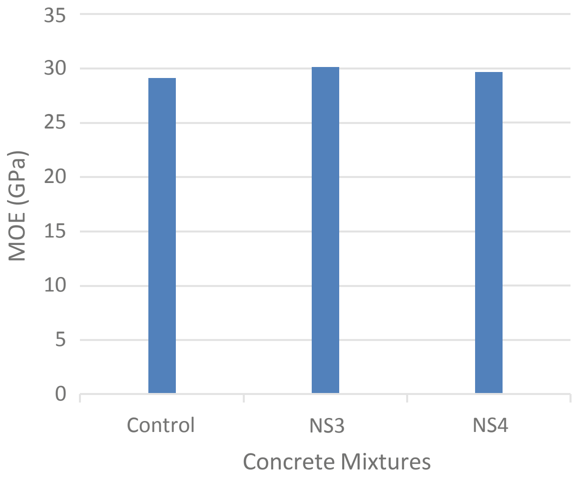
Table 9 Average MOE of concrete mixtures

Mixture	Modulus of elasticity (GPa)
	28 days
Control	29.102
NS3	30.13
NS4	29.639

3.4 Modulus of Elasticity

Table 9 shows the average 28 days modulus of elasticity of concrete. It was observed that there was a slight increase in the modulus of elasticity of NS3 concrete. Figure 7 mentioned a comparison of the MOE of concrete.

Fig. 7 Modulus of elasticity



4 Conclusion

The current study's findings have led to the following conclusions.

- The setting time of cement was decreased with increasing nano-silica dosage. This is because of nano-silica has a very fine particle size so, it has large specific surface area and required more water for wetting.
- It was observed that by incorporating 3% nano-silica in mortar mix, the compressive strength increased by 28%. In concrete incorporating 3% nano-SiO_2 in concrete mix, the compressive strength increased by 20%.
- Above the optimum dosage, the compressive strength was decreased; this may be due to uneven dispersion of nanoparticles and agglomeration leads to weak zone in concrete matrix.
- Flexural strength test reveals that 3% nano-silica increased the flexural strength by 15%.
- Split tensile strength was also increased by 22% for 3% nano-silica.
- The addition of nano-silica did not significantly alter the concrete's modulus of elasticity. It was noticed that the elastic modulus of concrete had slightly increased.

Thus, it can be observed that inclusion of 3% of nano-silica in concrete will lead to 20% increase in compressive strength, 15% increase in flexural strength and 22% increase in split tensile strength. Besides this due to dense particle packing durability of material also increases. Thus, for high rise buildings, we can optimize the use of materials by using nano-silica. Thus, overall entire construction industry will be benefited and saving of materials can be done. Nanomaterials will lead to sustainable and durable structures.

Initial cost of incorporation of nanomaterials may be higher, which may hinder into application at large scale level. Durability properties can be evaluated in future to highlight more benefits of use of nano-silica.

Acknowledgements Authors would like to thank Nirma University and Civil Department for providing with funds and facilities to carry out the work.

References

Abhilash PP, Nayak DK, Sangoju B, Kumar R, Kumar V (2021) Effect of nano-silica in concrete: a review. Constr Build Mater 278:122347. Elsevier Ltd. https://doi.org/10.1016/j.conbuildmat.2021.122347

Behzadian R, Shahrajabian H (2019) Experimental study of the effect of nano-silica on the mechanical properties of concrete/PET composites. KSCE J Civ Eng 23(8):3660–3668. https://doi.org/10.1007/s12205-019-2440-9

Elkady H, Serag MI, Elfeky MS (2013) Effect of nano silica de-agglomeration, and methods of adding super-plasticizer on the compressive strength, and workability of nano silica concrete. Civ Environ Res 3(2):21–34. ISSN 2222-1719 (Paper) ISSN 2222-2863 (Online). Available at www. iiste.org

IS 516 (1959) Methods of tests for strength of concrete

IS 2386–1 (1963a) Methods of test for aggregates for concrete. Part I: particle size and shape

IS 2386–3 (1963b) Methods of test for aggregates for concrete. Part 3: specific gravity, density, voids, absorption and bulking

IS 4031–4 (1988) Methods of physical tests for hydraulic cement. Part 4: determination of consistency of standard cement paste

IS 4031–5 (1988) Methods of physical tests for hydraulic cement. Part 5: determination of initial and final setting times

IS 4031–2 (1999) Methods of physical tests for hydraulic cement. Part 2: determination of fineness by specific surface by Blaine air permeability method

IS 12269 (2013) 53 grade ordinary Portland cement

Isfahani FT, Redaelli E, Lollini F, Li W, Bertolini L (2016) Effects of nanosilica on compressive strength and durability properties of concrete with different water to binder ratios. Adv Mater Sci Eng 2016(8453567):1–16. https://doi.org/10.1155/2016/8453567

Kumar S, Kumar A, Kujur J (2019) Influence of nanosilica on mechanical and durability properties of concrete. Proc Inst Civ Eng Struct Build 172(11):781–788. https://doi.org/10.1680/jstbu.18.00080

Mukharjee BB, Barai SV (2020) Influence of incorporation of colloidal nano-silica on behaviour of concrete. Iran J Sci Technol Trans Civ Eng 44(2):657–668. https://doi.org/10.1007/s40996-020-00382-0

Ng DS, Paul SC, Anggraini V, Kong SY, Qureshi TS, Rodriguez CR, Liu Q-feng, Šavija B (2020) Influence of SiO_2, TiO_2 and Fe_2O_3 nanoparticles on the properties of fly ash blended cement mortars. Constr Build Mater 258:119627. https://doi.org/10.1016/j.conbuildmat.2020.119627

Rupasinghe M, Nicolas RS, Mendis P, Sofi M, Ngo T (2017) Investigation of strength and hydration characteristics in nano-silica incorporated cement paste. Cement Concr Compos 80:17–30. https://doi.org/10.1016/j.cemconcomp.2017.02.011

Said AM, Islam MS, Zeidan MS, Mahgoub M (2021) Effect of nano-silica on the properties of concrete and its interaction with slag. Transp Res Rec 2675(9):47–55. SAGE Publications Ltd. https://doi.org/10.1177/0361198120943196

Senff L, Labrincha JA, Ferreira VM, Hotza D, Repette WL (2009) Effect of nano-silica on rheology and fresh properties of cement pastes and mortars. Constr Build Mater 23(7):2487–2491. https://doi.org/10.1016/j.conbuildmat.2009.02.005

Singh LP, Karade SR, Bhattacharyya SK, Yousuf MM, Ahalawat S (2013) Beneficial role of nanosilica in cement-based materials—a review. Constr Build Mater 47:1069–1077. https://doi.org/10.1016/j.conbuildmat.2013.05.052