Dehydration factor upon activation of building sand by ultraviolet radiation

A N Pavlov, Yu I Gol’Tsov, L R Mailyan, S A Stel’Makh and E M Shcherban

1 Don State Technical University, 1 Gagarin sq., Rostov-on-Don, 344000, Russia

au-geen@mail.ru

Abstract. The analysis of the influence of ultraviolet irradiation of building sand, which is a filler in a concrete mixture, on the dependence of the strength of concrete on the content of the filler. With an increase in the sand content due to the hydrophilicity of the surface of its particles in the mixture, the amount of free water necessary for hydration of the cement and the formation of cement stone decreases. Along with a decrease in the content of binder cement, this factor is an additional reason for the decrease in concrete strength with increasing sand content. Ultraviolet irradiation leads to dehydration of the surface of sand particles and the appearance of hydrophobic centers. With the increase in the hydrophobicity of sand in the concrete mixture, the content of free water available for cement hydration increases, and the strength of the cement stone increases. The change in the hydrophobicity of the surface of sand particles depending on the irradiation time is nonmonotonic. Therefore, there is an optimal ultraviolet activation mode that provides the greatest increase in concrete strength.

1. Introduction

To increase the concrete strength, reduce the cement consumption, and optimize the concrete production technology, ways to improve the properties of construction materials used in the concrete mix have been searched [1-3]. In particular, studies are underway to modify fillers by activation [4-6]. Under the chemical, thermal, mechanical, or electromagnetic effect, the filler particle surface acquires properties contributing to the cement hydration and the formation of cement stone. When the sand and other fillers are used in large amounts to substitute and save cement, the concrete strength reduces with increasing the share of substitutes [2]. However, it turns out that activation may successfully compensate for reducing strength with increasing filler content [4-6]. In [3], data on the change in the concrete strength R with increasing filler content is given (Fig. 1, + signs, where x is the cement/sand substitution ratio).
Figure 1. Dependences of Concrete Strength on the Cement/Sand Substitution Ratio. The + signs correspond to experimental data when using non-activated sand. The signs correspond to experimental data when using sand exposed to UV radiation. The solid curves 1 and 2 represent the theoretical strength calculation results when using not activated sand and that activated by UV radiation.

Substituting a small cement portion leads to some increase in the concrete strength. Further substituting more than 10% of cement with sand causes a linear decrease in strength with increasing sand content. However, ultraviolet (UV) radiation increases strength by almost 10%. The dependence of strength on the radiation time is not uniform and has a maximum [4-6]. Thus, the sand plays a multifaceted role considering its activation. The study objective is to theoretically describe the dependence of concrete strength on the sand content considering its activation by UV radiation.

2. Methods
Hydrophilic adjacent hydrated hydroxyl groups are located on the sand particle surface in an ordinary non-activated state. Water adsorption occurs due to the unused hydrogen bonds in surface hydroxyl groups.
Figure 2. Scheme of Changing the Location of Hydroxyl Groups on Sand Particle Surface [5]: a - adjacent, hydrated, b - adjacent, anhydrous, c - siloxane groups, dehydrated.

Activation causes dehydration and forming hydrophobic adjacent anhydrous hydroxyl groups on the sand particle surface, in which all hydrogen bonds are used (Fig. 2, a, b). Further activation causes dehydroxylation and forming hydrophilic silanol and siloxane groups on the sand particle surface (Fig. 2, b, c). The ease of rehydroxylation on siloxane groups is indicated in [6]. On the other hand, the author of [7] has noted that under the conditions of dehydroxylation, forming strained silicon-oxygen bridges is difficult for structural reasons [7-9]. Therefore, at this activation stage, the surface acquires ionic nature (Fig. 3) and on such a surface, water adsorption will occur by the dissociative mechanism.

Figure 3. Dehydroxylation Scheme with the Formation of Ionic Surface.

In connection with the described mechanism of changes when activating the water-adsorbing properties of the sand particle surface, the correlated behavior of water-need, workability, and the change in the strength of concrete prepared using activated sand with the activation time is not uniform [4-6].

With an increase in the hydrophobicity of the activated filler particle surface, the content of free water in the concrete mix increases, its workability therefore increases, and water-need decreases [10-12]. Herewith, the concrete strength increases due to an increase in the free water content required for cement hydration and the generation of crystalline hydrates forming cement stone from the cement clinker. Alternative model [4-6] of strengthening concrete by the sand activation focuses on an increase in the number of silanol groups leading to an increase in cation exchange according to the Ca ⇌ H scheme and chemical incorporation of sand into the crystal hydrate structure of cement stone.
This does not correlate with the fact that along with an increase in the concrete strength when using activated sand, the workability of the concrete mix, i.e. the free water content increases, while the silanol groups are hydrophilic. Cation exchange, as well as the filling of voids in the sand with cement particles affect the primary tendency of increasing the concrete strength at a low (less than 10 %) cement/sand substitution ratio [3]. Both factors above tend to saturate with increasing sand content. The first factor caused by cation exchange exhausts its effect in connection with the low calcium concentration due to the low solubility of calcium hydrate formed in the course of cement hydration. The second factor has a limited effect due to the full filling of all the cement stone voids. When the described factors are saturated after reaching a certain concentration of sand, the cement stone strength decreases with an increase in the sand content due to a decrease in the amount of binding cement [13-15].

Summarizing the above, it should be noted that the quantitative model (1) describing the dependence of concrete strength on UV activation should reflect four points: 1) the binding cement content, 2) the degree of the sand particle surface hydrophilicity, 3) the effect of cation exchange and the filling of voids in a cement stone, and 4) achieving saturation by the last two factors.

\[ R = A_1(1-x)(1-A_2x+F_y) \]  
(1)

Where \(A_1, A_2, F_y\) are the model parameters. The \((1-x)\) factor reflects the cement content, the \(-A_2x\) summand describes the hydrophilicity effect, and the \(A_2\) factor reflects the hydrophilicity degree. The \(F_y\) parameter is associated with factors increasing strength due to cation exchange and filling of voids with sand; for this parameter, differential relation (2) can be written as follows:

\[ dF_y/dx = (F_{y,\text{max}} - F_y)/A_3 \]  
(2)

Where \(A_3, F_{y,\text{max}}\) are the model parameters. The equation (2) solution has an exponential form.

\[ F_y = F_{y,\text{max}} \left[ 1 - \exp\left( -x/A_3 \right) \right] \]  
(3)

Then, the final equation (4) theoretically describing the concrete strength can be written as follows:

\[ R = A_1(1-x)(1-A_2x+F_{y,\text{max}} \left[ 1 - \exp\left( -x/A_3 \right) \right]) \]  
(4)

3. Results and discussion

The theoretical dependences of concrete strength on the cement/sand substitution ratio obtained by formula (4) are given in Figure 1. Curve 1 describes the dependency of strength on the binding cement content when using inactive sand; the correlation with the experiment is achieved at \(A_1=36.29\) MPa, \(A_2=1.68, A_3=0.025, \) and \(F_{y,\text{max}}=0.36\).

UV radiation of sand changes the surface of its particles. At optimal activation ensuring the maximum concrete strength, this surface becomes mainly hydrophobic due to dehydration followed by dehydroxylation. Although there is a certain number of hydrophilic silanol centers remained, activation greatly reduces the surface hydrophilicity in general. Curve 1 in Figure 1 shows the theoretical dependence of concrete strength on the activated filler content obtained by formula 4 reflecting this tendency. The correlation with the experiment is achieved at \(A_1=36.29\) MPa, \(A_2=0.32, A_3=0.025, \) and \(F_{y,\text{max}}=0.36\). Thus, when moving from a description of using non-activated sand to that for activated sand, the hydrophilicity parameter \(A_2\) significantly decreases.

Based on the equation (4), the change in concrete strength \(\Delta R\) at activation considering the constancy of factors reaching saturation can be described by formula (5).

\[ \Delta R = R_a - R_n = (A_2^n - A_2^a) x(1-x) \]  
(5)

Where, \(R_n\) and \(R_a\) are the strength values of concrete prepared with and without activated sand, \(A_2^n\) and \(A_2^a\) are the hydrophilicity parameters used in the model to describe situations of using non-activated and activated sand.
Figure 4. Change in Experimental (+ Signs) [3] and Theoretical (Solid Line) Dependences of Concrete Strength on the Cement/Sand Substitution Ration when Using Activated Sand.

The change in the theoretical dependence of concrete strength on the cement/sand substitution ratio under UV radiation of sand obtained by formula (5) is shown with a solid line in Fig. 4. The correlation with the experiment is achieved at $A_2^{n}=1.68$, and $A_2^a=0.32$. The data given in Figure 4 shows that concrete strength increases due to the filler activation with the content of the latter.

4. Conclusions

Despite the tendency for concrete strength to decrease with an increase in the cement/filler substitution ratio, when using activated sand, the strength, on the contrary, increases with an increase in the substituting sand content. Therefore, UV radiation of sand weakens the effect of decreasing concrete strength with an increase in the binding cement/filler substitution ratio.

The theoretical description of the change in the dependence of concrete strength on sand content when using sand activated by UV radiation quantitatively confirms the possibility of explaining the strength behavior based on the reduced filler particle surface hydrophilicity, which leads to increased free water content in the cement mortar and improved cement hydration. Several factors affecting the cement stone strength may be considered in a single quantitative model: 1) the binding cement content, 2) the degree of the sand particle surface hydrophilicity, 3) the effect of cation exchange and the filling of voids in a cement stone, and 4) achieving saturation by the last two aspects.
References

[1] Torlina E A, Shuiskii A I, Tkachenko G A, Yavruyan Kh S, Filonov I A and Fesenko D A 2012 *Stroitel'noe materialovedenie* 1 pp 145–153

[2] Pavlov A N, Gol'tsov Yu I, Stel'makh S A and Shcherban' E M 2015 *Nauchnoe obozrenie* 10 pp 147–150

[3] Pavlov A N and Goltsov Yu I 2014 *Nauchnoe obozrenie* 10 pp 711–714

[4] Lotov V A, Sudarev E A and Kutugin V A 2011 *Izvestiya vuzov* 54 11 pp 346–349

[5] Korolev A C and Voloshin E A 2009 *Beton i zhelezobeton* 13 2

[6] Shevchenko A F, Salei A A, Sigunov A A and Peskova N P 2008 *Voprosy khimii i khimicheskoi tekhnologii* 5 pp 129–137

[7] Luginina I G and Afonina I N 2008 *Tsement i ego primenenie* 4 pp 116–117

[8] Yu Ye, Fang Liu, Mengxuan Wang, Lixuan Tai, Kaiyu Cui, Xue Feng, Wei Zhang and Yidong Huang 2019 *OSA Publishing* 6 5 pp 592–597

[9] König S, Bogner S K, Furnstahl R J, More S N and Papenbrock T 2014 *Phys. Rev. C* 90 064007

[10] Hee-Taek Cho, Gyeong-Seo Seo, Ok-Rak Lim, Woojin Shin, Hee-Jin Jang and Tae-Jung Ahn 2018 *OSA Publishing* 2 4 pp 303–307

[11] Srivastava A and Singh S K 2020 *Journal of Cleaner Production* 253 119706

[12] Wang K, Liu G, Li Y, Qin M and Wang G 2019 *Chemical Engineering Research and Design* 151 pp 79–90

[13] Jun Chen and Chi-sun Poon 2009 *Building and Environment* 44 9

[14] Barreira E and de Freitas P V 2007 *Construction and Building Materials* 21 pp 218–224

[15] Kuznik F, Virgone J and Noel J 2008 *Applied Thermal Engineering* 28 pp 11–12