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The water permeability properties of re-vibrated lightweight concrete

Muayad Mohammed KASSIM

Civil Engineering Department, University of Kirkuk, Al-Wasity street, Kirkuk, 36013, Iraq.

Corresponding author e-mail: moayadmk@uokirkuk.edu.iq

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Abstract

Re-vibration of sequential layers of relatively deep structural members after a particular time harms the strength and water permeability properties of the concrete. The harmful effects can be observed in lightweight concrete due to the floating tendency of lightweight aggregate. In this experimental study, the influence of adding retarder plasticizer and silica fume on water permeability properties of re-vibrated lightweight concrete was investigated. The effects of re-vibration at different time lags on compressive strength and permeable voids ratio were studied. Absorption, sorptivity, and water penetration depth under pressure were also studied. Results show that the addition of a retarder increased the compressive strength and reduced the permeability for all mixes, even though the mixes were re-vibrated before the final set of the cement. Similar effects were found in mixes that contained silica fume as partial replacement of cement, except the sorptivity properties of concrete when compared with the control mixture. A linear relationship between permeable voids and water absorption was set.

1. Introduction

Structural concrete is considered lightweight with low-density aggregate when its air-dry density is ranged from 1440 to 1840 kg·m^{-3} and a 28-day compressive strength not less than 18 MPa [1]. This feature was attained by mixing normal weight fine aggregate with lightweight coarse aggregate. The lightweight aggregate may either be made from the expanded slags, fly ash, clays, and shales or from natural porous volcanic rocks such as pumice or perlite [2,3]. Naturally, these aggregates are different in composition, porosity, and water absorption capacity [4,5,6].

Lightweight concrete (LWC) can be used to reduce the dead loads when produced with high strength. Other benefits of LWC are: i) increases the contact surface between aggregate and the past; ii) improves cement hydration due to internally moist curing by sucking the moisture from the aggregate pores; and iii) leads to less internal microcracks and hence, low permeability [4,5,7].

Penetration of the water or any solution to the concrete causes an aggressive contaminate and accelerates its damage. Therefore, the durability of concrete depends on its water absorption rate, permeability, the existence of excessive cracks, and exposure to deleterious chemical reactions. However, the penetration of the liquids into the concrete can be reduced and the durability can be increased by using a rich cement paste or using normal weight fine aggregate instead of lightweight one [8,9].

Recently, the wide and rapid development of the LWC structure configurations all over the world has not coupled with enough parallel studies on the permeability of this type of concrete. However, Xu *et al.* [10], studied the water permeability of LWC at different layers from the top surface. The authors found that the water permeability coefficient decreases as the tested level are far ahead from the top, because of the high density of the bottom layer and increased trend of floatation of lightweight aggregate. The chloride-ion penetration resistance, water penetration depth under pressure, and sorptivity of LWC were investigated by Liu *et al.* [11]. The experimental results showed that these parameters decrease with the increase in the cumulative LWA, as well as these values were lower compared to the natural weight concrete with similar strength.

The test of a surface zone may be inconvenient to present the permeability of the inside bulk of lightweight concrete due to the floating tendency of lightweight aggregate. Measuring the permeability under pressure may be a solution to test lightweight concrete giving particular attention to determining the permeability at a deeper particle of the composition far from the surface [12,13].

As a matter of fact, the vibration will enhance the quality of the placed concrete. However, the re-vibration effects on strength properties or water permeability of concrete, particularly the LWC were insufficiently investigated. On the other hand, few studies were found about the re-vibration of normal weight concrete (NWC) and the evaluation of its strength properties [14,15]. Kassim [16] found that re-vibration of concrete at a later time before the final set of cement has benefited from liquefying the concrete again, which temporarily breaks down the weaker calcium hydroxide that already formed. This action enhances the compaction of the fresh concrete and produces monolithic concrete. However, if the re-vibration took place at a time closer or after the final setting time, internal micro-cracks may be initiated, which will reduce the strength properties of the hardened concrete. Significant effects of re-vibration

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were found with concrete using lightweight aggregate, blast furnace and fly ash in its composition [15]. Rao *et al.* [17] studied the re-vibration affect strength properties of concrete having a wide range of w/c ratio (0.35-0.7) and re-vibration time varied from 0.5 to 4 h. They concluded that the compressive strength of the tested concretes increases when re-vibration is conducted before initial setting time, then reduces irrespective of the mix type and water-cement ratio.

The main objective of this study reported herein is to evaluate water absorption and permeability of lightweight concrete. The effect of re-vibration was also studied at a particulars time lags after casting various mixes. The opportunity to use the local pumice volcanic crushed rocks called "Bonza" as a lightweight coarse aggregate was attempted in the production of these mixes. The influence of a retarder plasticizer and partial replacement of cement by silica fume was also investigated.

2. Experimental methods

2.1 Materials

In this research, an Ordinary Portland Cement (O.P.C.) type (I) from the Mass Cement Company was used, furthermore, the used cement was partially replaced (10%) by supplementary cementitious Silica Fume (SF). Table 1 and Table 2 shows the chemical and physical properties of the used PC and SF. Natural river sand with a maximum size of 4.75 mm and crushed lightweight pumice rock "Bonza" graduated with a maximum particle size of 20 mm and Loose bulk density 472 $kg\cdot m^{-3}$ were used as fine and coarse aggregate, respectively. The oven dry bulk specific gravity of the fine and coarse aggregates ware 2.61 and 1.86, respectively, and their absorption at 24 h was 0.67% and 48%, respectively. Both coarse and fine aggregates were conforming to the Standards ASTM C 330-04 and BS 882:1992 zone II [19,20]. To minimize the negative effects of re-vibration after the initial set of the cement, a retarder plasticizer was added to the mixes MR and MRS [6,16].

2.2 Mix proportions

Table 3 presents the mix proportions, the control mixture (MC) which does not contain any retarder and silica fume, and a mix with a combination of binary cementitious blends, in which 10% of PC was partially replaced by the SF, is denoted as MS. Adding the setting retarder additive to the control mix, to delay the initial and final set of the cement, is denoted as MR. In addition, the MS with setting retarder additive is denoted as MRS. The mixes were designed to have a fine aggregate-to-total aggregate mass ratio of 0.55 and a total binder content of 480 $kg\cdot m^{-3}$. The water/binder ratio and superplasticizer (HRWR) dosage of 0.25% in these mixes were designed to obtain a slump ranged between 25 and 75 mm. The identification of the specimens was arranged according to the mixture content and re-vibration time. For example (MRS4) denotes the binary mixture containing PC, retarder plasticizer and SF, at 4:30 h:min re-vibration.

Table 1. Mechanical properties and chemical composition of the used OPC. *

Property	Test Result	Standard IQS, No. 5 limits
Fineness (residue on sieve No. 170)	-	Maximum 10%
Specific surface "Blaine" ($m^2\cdot kg^{-1}$)	2630	Minimum 2250
Normal consistency (% by weight)	29	
Initial setting time (min)	190	Minimum 45 min
Final setting time (min)	325	Maximum 10 h.
Compressive strength at 3 days (MPa)	26	15 $MN\cdot m^{-2}$
Compressive strength at 7 days (MPa)	29	23 $MN\cdot m^{-2}$
Compound composition		
C_3A, %	8.34	
C_2S, %	20.84	
C_3S, %	49.66	
C_4AF, %	10.24	
Oxide composition		
Alumina [Al_2O_3 (%)]	5.3	
Silica [SiO_2 (%)]	20.31	
Iron oxide [Fe_2O_3 (%)]	3.37	
Lime [CaO (%)]	61.89	
Sulfate [SO_3 (%)]	2.61	Maximum 2.8%
Magnesia [MgO (%)]	1.99	Maximum 4%

* These test results are from manufacturers' laboratories. IQS = Iraqi Quality Standards.

Table 2. Technical specification of densified micro silica Fume*.

Property	Test results
Colour	grey powder
Bulk density	500-700 $kg\cdot m^{-3}$
Specific gravity	2.10 to 2.40
Silicon Dioxide (SiO_2)	Minimum 85%
Chlorine amount	< 0.1 %
Moisture content (H_2O)	Maximum 3%
Loss of ignition (L.O.I)	Maximum 6%
Blain (fineness)	> 15 $m^2\cdot g^{-1}$
Activity index, 7 days	> 95 %

* Properties as described by the manufacturer CONMIX LTD.

Table 3. Mix proportions of tested mixtures (kg·m^{-3}).

Mixture ID*	Cement	Aggregates (SSD)		Water	SF	Retarder	HRWR	w/b
		Fine	Coarse					
MC	480	662	528	216	-	-	1.2	0.45
MR	480	662	528	202	-	2.4	1.2	0.42
MS	436	662	528	216	43.6	-	1.2	0.45
MRS	436	662	528	202	43.6	2.4	1.2	0.42

*MC- Control mix, MR- Mix containing set retarder additive, MS- Mix containing Silica Fume, and MRS- Mix containing set retarder additive and Silica Fume.

2.3 Casting procedure

To provide efficiency, uniformity, and homogeneity to the mixtures, the same mixing and batching procedure was followed. Therefore, the coarse aggregate was first supplied, then followed by a fine aggregate. The blend was mixed in a pan mixer for 3 min with the addition of the binders. The water-plasticizers solution was added and mixed for an extra 3 min. The overtime mix was prevented to avoid the crushing of lightweight aggregate [15]. A vibrating table was used to vibrate all the concrete specimens. Since the strength properties and absorption of concrete were affected by variant aggregate moisture contents [12,21], all the aggregate (coarse and fine) were immersed in water, then used in a state of saturated surface dry condition (SSD).

Re-vibration of specimens was carried out at time lag intervals 2:50, 4:30, and 5:30 h:min after adding the mix water for 90 seconds extra vibration. According to the author's point of view, the selected time intervals (i.e. just after the initial set, just after the final set, and 1 h after the final set of the cement) were considered critical stages of hardening and strengthing of cement. The cube surface of the re-vibrated specimens did not smoothen and left as it is. These cubes were moisture-cured in a water tank until the testing time.

2.4 Testing procedures

The slump value and density of fresh concrete for each mix were measured immediately at the end of mixing. Compressive strength and splitting tensile strength tests at the age of 28 days were conducted using 150×150×150 mm cubes, following British Standards BS1881: Part 116 and Part 117 respectively [22,23]. To increase the reliability, three specimens were tested and the average was recorded.

The water penetration depth under pressure was executed on 150 mm cube specimens according to the procedure given in TS EN 12390-8 [24]. The procedure states that the specimens are exposed to penetrate drinkable water under 500±50 kPa pressure for a 72-h period as shown in Figure 1. The whole surfaces of the specimens were covered with silicon paint except a particular area before testing to prevent the leakage of the water. At the end of testing time, the tested cubes were split into equal halves according to BS 1881. Part-117B [23], then marked as illustrated in Figure 2, then the maximum water penetration depth was measured. The results represent the average of three specimens.

Figure 1. Water penetration depth test setup.

Figure 2. Water penetration depth in halves cube after the test.

The sorptivity test was performed according to ASTM C 1585 [25]. The absorption rate of water by concrete cubes was measured by determining the increase in the mass of these specimens with time due to immersion the top face of the specimens in water by 20±5 mm depth. During the contact, water will ingress to the dry concrete and dominate by capillary suction. The cumulative water volume absorbed per particular unit area (mm^3·mm^{-2}) was calculated as a function of time. The total water absorption percentage and permeable voids ratio tests were conducted according to ASTM C 642-13 [26]. In this test, the dry mass of specimens (150 mm cube) was measured, then the specimens were immersed in water for 48 h to measure the SSD weight. Specimens were also weighed while immersed in water. All of the permeability tests evaluated at equal ages of specimens for more than 28 days. Three specimens were used to increase the reliability of the results, and the average was recorded

3. Results and discussion

3.1 Strength properties

Table 4 and Figure 3 shows the results of compressive strength at the age of 28-day of all mixes. In general, re-vibration is found to dramatically reduce the strength of the control mix MC by 24% when the re-vibrating process is produced after the final set of cement. This finding on LWC is well agreed with the results of normal weight concrete (NWC) reported by other researchers [16,18,27]. The hydration heat that is generated from the cement when contacts with moisture usually slow by adding the retarder plasticizer to the mix. This will cause a delay in the setting time, hence the positive effect of re-vibration is achieved by extra compacting the concrete and reducing the permeable voids and micro-cracks in the mix structure developed due to bleeding or initial shrinkage of the concrete. On the other hand, the re-vibration process caused a floating movement of the lightweight coarse aggregate. This means that the lightweight aggregate/paste ratio was increased at the top surface, besides the development of micro-cracks, which leads to increase the capillary pores and high ability of water ingress through the unsaturated surface as can be seen on the top feature of the casted cube in Figure 4. This effect seems in strength results of MR specimens even though when re-vibrated in lag time closer to the final set of the cement.

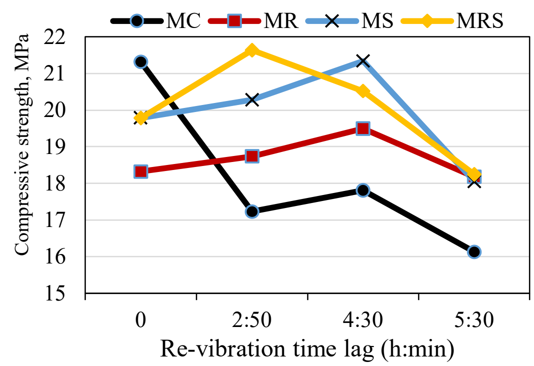

Figure 3. Compressive strength for various mix types versus re-vibration time lag.

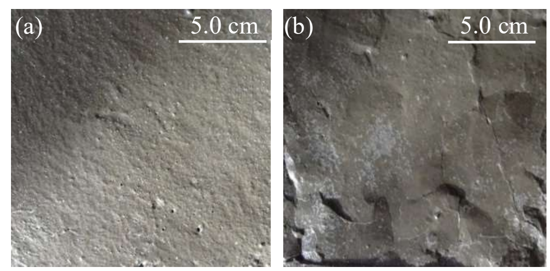

Figure 4. Top surface feature of mixes MR and MRS, (a) before re-vibration, (b) after re-vibration.

Table 4. Strength properties of the tested specimens

Mix ID	Compressive strength, MPa	Splitting tensile strength, MPa	Dry density, kg·m^{-3}	Permeable voids ratio, %	w/b
MC0	21.3	1.98	1543	17.7	0.45
MC2	17.2	2.07	1499	20.9	0.45
MC4	17.8	1.76	1492	20.5	0.45
MC5	16.1	1.70	1534	21.3	0.45
MR0	18.3	2.21	1610	17.4	0.42
MR2	18.7	1.83	1633	15.5	0.42
MR4	19.5	2.16	1628	14.7	0.42
MR5	18.2	2.16	1623	15.6	0.42
MS0	19.8	2.73	1654	13.4	0.45
MS2	20.3	2.79	1677	12.9	0.45
MS4	21.3	2.93	1651	13.6	0.45
MS5	18.1	2.68	1653	13.5	0.45
MRS0	19.8	2.73	1639	15.8	0.42
MRS2	21.6	2.75	1673	14.7	0.42
MRS4	20.5	2.55	1664	14.5	0.42
MRS5	18.3	2.45	1660	14.4	0.42

The positive effect of the addition of SF is significant, as is shown in Table 4. This table shows that there is an increase of 14-25% in the compressive strength of MR and MRS when compared with the control specimens MC. This increase is attributed to the pozzolanic reaction between $Ca(OH)_2$, which is generated from a PC, and SiO_2 of SF, as the increase in strength can be attributed to the fine particles of SF compared to the PC ones.

3.2 Water absorption after immersion

The results of the modified effects of adding the retarder plasticizer or utilizing a binary blend (PC+SF) on total water absorption after immersion are displayed in Figure 5. As shown, the rate of water absorption of the mixture MC is increased by 25% when the re-vibration is taken place before the final setting time and slightly drops to 16% when re-vibration happens after the completion of the final set. On the contrary, the re-vibration has reduced this absorption significantly in mixes MR and MRS and slightly in mix MS by 22%, 12%, and 4%, respectively. This can be explained by the plasticizer action of the retarder that caused to reduce w/b ratio, with the delaying the cement hydration and $Ca(OH)_2$ generation. Furthermore, the re-vibration liquefies the concrete before the final set of the cement, thus closes the air voids left from the bleeding of free water of the concrete mixture. However, while the cement is partially replaced by SF in the mix MS, the pozzolanic action of SF contributes to minimizing the bleeding and decreases the size of air voids between the particles. This action produces a more stable and uniform compacted mixture that is less affected in re-vibration action at a later time. These results, which were obtained from LWC upon using a retarder agent and SF are similarly observed in other works of NWC [6,12,16,28,29].

3.3 Sorptivity

The deviation of sorptivity values for various mixes containing retarder or SF is demonstrated in Figure 6. The test results show that using the retarder or SF separately presents a lower value than the control mix by 12%, and 43%, respectively. However, adding both additives together are found to increase the sorptivity by 17%. These results are similar to the water absorption test result, except for the MRS mixture where its sorptivity increased result can be attributed to the deceleration effect of the retarder to slow the hydration of SF. On the other hand, the re-vibration of the mixes MS and MRS has reduced the sorptivity by 10%, and 9%, respectively when the re-vibration did before the final set (see Figure 7 c and d) [30]. In contrast, the re-vibration is not effective on water sorptivity of the mixture MR (Figure 7 b) and adversely increase by 5% for the mixture MC when it was re-vibrated before the initial set, then it reduces by 13% when re-vibrated closer to the final set (Figure 7 a). The lowest sorptivity reaction, which is 50% of the control mix MC, is observed for the MS mixture when the mix was re-vibrated at 4:30 h:min i.e. before the final set of the cement. Similar behaviors of other permeability test results are observed due to high pozzolanic activity and the effect of the filler of the SF particles at early ages. These results for LWC are well correlated with the findings of other researches of the NWC [12,30,31].

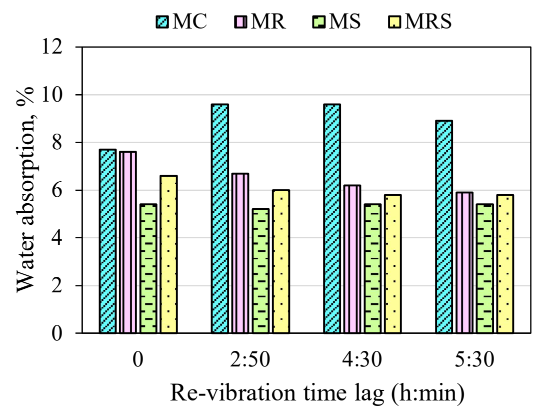

Figure 5. Water absorption versus re-vibration time lag for various mixes.

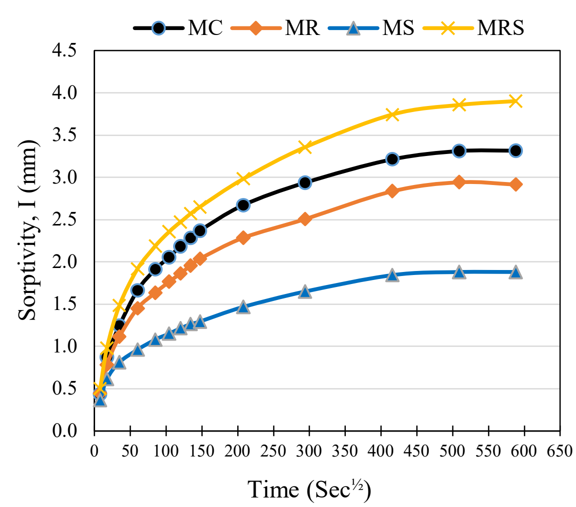

Figure 6. Sorptivity of various mixes at different times.

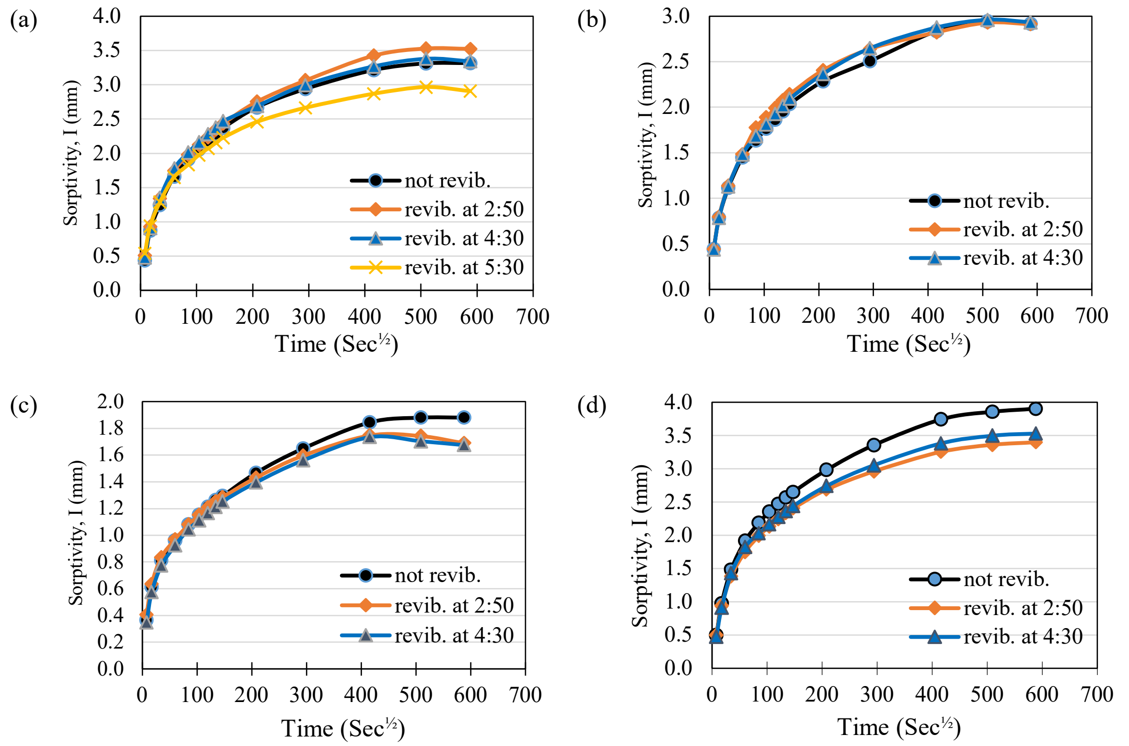

Figure 7. Absorption of the various mixes re-vibrated at different times. Mixes (a) MC, (b) MR, (c) MS, (d) MRS

3.4 Water penetration depth under pressure

The water penetration depth expresses the degree of ease dispersion of a fluid under pressure through a porous medium. The variation of this depth for the re-vibrated different mixtures are shown in Figure 8. The re-vibration is found to reduce the penetration depth under pressure for all mixes MR, MS, and MRS, except the control mixture MC, where it gives an adverse effect when re-vibration is applied after the initial set. Such an increase is attributed to the floating movement of the coarse aggregate (lightweight aggregate) during the re-vibration. This means that the lightweight aggregate/past ratio was increased at the top surface, together with the development of micro-cracks, which leads to the high ability of water to ingress through the capillary pores of an unsaturated surface (see Figure 4). Moreover, the retarder addition to the mixes MR and MRS is inconsistent with water penetration depth when re-vibration is applied at 2:30 or before the initial setting of cement. However, the retarder and SF additives have a significant influence on the penetration depth when the re-vibration is applied before the final set of cement for the mixes MR, MS, and MRS. These depths are found to be 43%, 81%, and 77% of the original mixes depth, respectively [12,32,33,34]. The lowest water penetration depth is found at 41% for the mix MR5 compared to the control mix MC.

3.5 Water absorption, permeable voids, and compressive strength relations

Figure 9 presents the correlation ratio between water absorption and the permeable voids percent in lightweight concrete, with different time lags re-vibration. The figure shows a good correlation of 0.963 between the two parameters, where the absorption is decreased as the voids ratio is decreased. This reduction in the permeable voids ratio is found to be due to reducing in the number and size of capillary pores. Further, possible changing of the types of pores to intermittent pores when the concrete is re-vibrated could be another cause to reduce the permeable voids, besides of the cause of the pozzolanic action of the replaced SF [12,16,31,35].

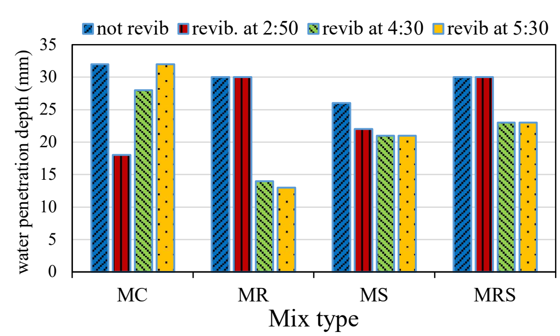

Figure 8. Water penetration depth for various mix types re-vibrated at different times.

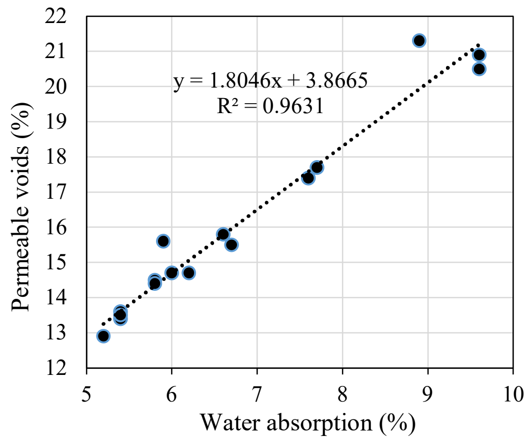

Figure 9. The relation between water absorption and the permeable voids ratio.

The relationship between water absorption percent and compressive strength is illustrated in Figure 10. An inverse linear relation is observed for mix MC; inverse nonlinear for mix MR; and almost straight constant for mixes MS and MRS. Due to the same reasons mentioned above, SF additive may help to reduce the voids ratio even when the water absorption ratio as the compressive strength is increased.

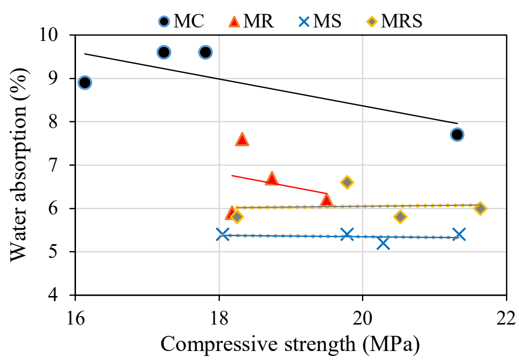

Figure 10. The relation between water absorption and compressive strength.

4. Conclusions

The main conclusions from this work on permeability properties of re-vibrated lightweight concrete are:

1. The compressive strength of lightweight concrete was significantly reduced when re-vibration was applied even before the initial setting time. However, adding the retarder or/ and the pozzolanic material SF to the mixtures has given a positive effect, though re-vibration was started at a time close to the final set.

2. There was a tendency of the lightweight aggregate to float up when re-vibration was carried out. The water absorption rate of the mixture MC was found to increase as re-vibration was applied before the final setting time and slightly dropped thereafter. On the contrary, the re-vibration had significantly reduced the absorption in mix MR which contained the retarder. However, re-vibration had caused a slight reduction in the water absorption of the mixes MS, MS, MRS in which SF was added.

3. The similar behaviors for the water penetration depth under pressure and sorptivity were observed for all mixes which have not been re-vibrated, except the sorptivity of the mixture MRS because it contains the retarder and silica fume together. However, in general, the re-vibration action reduced the sorptivity of all mixes, except the mix MR which was very slightly affected.

4. The absorption was found to reduce when the voids ratio was reduced. A good linear correlation was formulated between the two parameters.

5. For the mixes, MC and MR, a significant reduction in water absorption were observed when their compressive strengths were increased, while by partial replacement of PC by SF in the mixes MS and MRS, the water absorption remained approximately constant even when the compressive strength was changed.

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