Self-compacting lightweight aggregate concrete in Vietnam

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Abstract: Self-Compacting Lightweight Aggregate Concrete (SCLC) is a new building material in Vietnam. The lightweight aggregates (keramsite) produced from expanded clay or slate is used for the SCLC. If dry Keramsite is used in making the concrete mixture, it will partly absorb water from the cement paste, which causes the slump loss of concrete mixture, increasing shrinkage of cement matrix in the concrete. With regard to Self-Compacting Structural Lightweight Aggregate Concrete (SCLC), the cement content used is significant, the ratio of Water to Binder is rather low, and the structure of cement paste is very dense. This does not only increase the autogenous shrinkage of concrete but also have influence on the effectiveness of external curing. Taking advantage of the special structure of Lightweight aggregate as Keramsite, internal curing can be performed in order to improve the quality of SCLC by wetting Keramsite before mixing with suitable water absorption.

This paper presents some research results about SCLC, the incorporation of internal curing with other measures such as the use of dispersal fiber reinforcement, viscous stabilizing admixtures in order to restrain the segregation level of lightweight aggregates, reducing shrinkage and improving mechanical-physical properties of SCLC in the hot-humid climate condition of Vietnam. The research results show that, from selected materials, lightweight concretes with unit weight of 1600 - 1800 kg/m³, compressive strength of 30 - 35 MPa, good workability, capable of self-compacting can be manufactured. The use of pre-wetted lightweight aggregate with suitable humidity for producing SCLC will result in better effectiveness than the use of dry lightweight aggregate, as in reducing restraining shrinkage, improving the strength for SCLC.

Keywords: Lightweight aggregate, Internal Curing, Keramsite, Self-Compacting Lightweight aggregate Concrete, Shrinkage, Compressive Strength

1. Introduction

Since 1990s in Vietnam, Lightweight Aggregates have been produced by rotary kiln from expended clay or slate, which is called “Keramsite” (K) [11]. Since then, Lightweight Aggregate Concrete in general and Self-Compacting Lightweight Aggregate Concrete in particular has been studied and applied. However, it is difficult to produce Self-Compacting Lightweight Aggregate Concrete because the Lightweight Aggregates (LA) easily segregates in the mixture, especially while pumping and compacting. The hot-humid climate in Viet Nam is rather advantageous for cement concretes. However, quality of the concrete is strongly influenced by the curing process, especially with regard to Lightweight Aggregate Concrete. If the concrete mixture is transported by pump, due to the pump pressure, water from cement paste may continue to be transferred to LA. After being discharged from
pump’s pipe, concrete mixture is released from the pumping pressure, and the water from LA tends to be bleeding on particle surfaces. According to some authors [2, 3, 4], the water absorption by LA may weaken the bond between LA surfaces and cement paste, due to the formation of air bubbles or cracks in the interface transfer zone.

To prevent the segregation, pre-wetted LA could be used [3]. This solution not only to reduce segregation and slump loss of concrete mixture but also to cure concrete from the inside, due to internal water being supplied via reservoir such as pre-wetted LA. Therefore, this action is called “Internal Curing” (IC) [4, 5, 6]. The important matter of IC technique is to determine the initial stored water content in LA, the water absorption of LA and the transferability of absorbed water content by LA to the cement paste surrounding it. In SCLC, if the water absorption of LA is too high, the bleeding on LA surfaces is very likely to take place during the setting process of concrete, reducing concrete strength and its waterproofing capacity

The essence of IC is to supply water to concrete through reservoir materials, such as Keramsite. The Keramsite contains microscopic, which holds water and, over time, supplies it to the concrete as needed. This amount of water, though not included in the total volume of concrete mixing water, can be transferred to the surrounding binders’ paste to compensate for the chemical shrinkage and maintain the humidity saturation in the porous system of the concrete.

2. Theoretical analysis

2.1. Segregation of lightweight aggregate concretes

The sedimentation of relative more heavy particles and the emersion of relative lighter particles is a self-happened process. Movement velocity of the particles depends on the viscosity and rheology of concrete mixture, grain sizes, parameters of grain state and structure. The movement rate of spherical grains with different particle density in the concrete mixture complies with Stocke equation [2, 9] as follows:

\[ v = 2r^2 \Delta \rho g/9\eta \] (1)

Where:
- \( r \) (m) - radius of grains;
- \( \Delta \rho = \rho_m - \rho_h / \rho_m - \rho_h \);
- \( \rho_m \) (kg/m\(^3\)) - unit weight of cement paste or mortar;
- \( \rho_h \) (kg/m\(^3\)) - particle density of aggregate;
- \( g \) (m/s\(^2\)) - acceleration of gravity;
- \( \eta \) (Ns/m\(^2\)) - dynamic viscosity of cement paste or mortar.

On the basis of analyzing (1), some methods for limiting segregation of aggregates in SCLC may be proposed as follows: 1- Reducing grain sizes of porous aggregates; 2- Reducing the difference between unit weight of aggregate particles and that of cementitious paste, \( \Delta \rho = \rho_m - \rho_h / \rho_m - \rho_h \); 3- Increasing viscosity of cement mortar/paste.

If using LA with small size particles but their unit weight is big, the difference of \( \Delta \rho \) will be limited. However, this causes increase of unit density of the concrete. An effective method for increase unit weight of particles without increase significantly unit weight of SCLC is to soak LA in water before mixing concrete.

In producing self-leveling concrete in general and producing SCLC in particular, the adjustment of dynamic viscosity of cement paste within a certain limit is very important. Chemical admixtures in combination with adjustment of the ratio of water - binder(s) may be applied. Dispersal fibers should also be used as a technological admixture to prevent the emersion of LA particles [3].
2.2. **Internal Curing and water absorption of Keramsite**

The volume of internal water needed to compensate for the chemical shrinkage of the binder (in concrete) can be determined according to the formula by Bentz D.P. and Snyder K.A. as follows:

\[
V_w = B \cdot CS \cdot \alpha_{\text{max}} / \rho_n
\]  

(2)

Where:
- \( V_w \) (m\(^3\)/m\(^3\) concrete) - The volume of the internal water volume;
- \( B \) (kg/m\(^3\) concrete) - The content of the cementitious material (Binder);
- \( CS \) (g water/1g binder) - Chemical shrinkage due to hydration by binder(s), (≈ 0.06 - 0.07);
- \( \rho_n \) (g/cm\(^3\)) - Specific gravity of water, (≈1.0);
- \( \alpha_{\text{max}} \) - Maximum degree of hydration of cementitious material; And:
  - \( \alpha_{\text{max}} = 1.0 \) when \( W/B > 0.36 \);
  - \( \alpha_{\text{max}} = (W/B)/0.36 \) when \( W/B \leq 0.36 \)

\( W \) (kg/m\(^3\) concrete) - The content of mixing water in the concrete;

Assume that \( CS = 0.065 \) and \( W/B \leq 0.36 \), we have:

\[
\frac{W_{IC}}{B} \approx 0.18 \frac{W}{B}
\]  

(3)

Where:
- \( W_{IC} \) (kg) - The amount of internal water to completely perform internal curing;
- \( B \) (kg) - Binder(s) content in concrete.

Suppose that the water content lost or received from the environment is negligible (disregarded). The water absorption by weight of LA will be calculated according to the following formula:

\[
W_{IC} = H_{\text{LWA}} \cdot S \cdot K = 0.18B \left( \frac{W}{B} \right)
\]  

(4)

Where:
- \( H_{\text{LWA}} \) - The water absorption by weight of LA;
- \( K \) (kg/m\(^3\) concrete) - The content of the LA (as Keramsites);
- \( S \) - The maximum water transferring factor from LA to cementitious paste (Consider: \( S \approx 1.0 \)).

2.3. **Influence of temperature and relative humidity (RH) on the shrinkage of concrete**

In the cement stone and lightweight aggregate of concrete has a system of pores storing water (moisture) connecting together. According Kelvin \([9]\), due to wetting phenomena, the vapor pressure of the liquid above curvature surface (\( p_r \)) of capillary pore depend on the temperature of the following equation:

\[
\ln \left( \frac{p_r}{p_s} \right) = \ln \left( \text{RH} \right) = - \frac{2\sigma \cdot \cos \varphi \cdot V_m}{r(t)RT}
\]  

(5)

Where:
- \( p_r \) - Vapor pressure on the curved surface of the fluid in the capillary;
- \( p_s \) - Saturation vapor pressure of the liquid in the capillary;
- \( \sigma \) - Surface tension of the liquid in the pores;
- \( \varphi \) - Wetting angle;
- \( V_m \) - Molar volume of the liquid;
- \( R \) - Gas constant; \( T \) - Absolute temperature;
- \( \text{RH} = p_r / p_s \) - The relative humidity in the pore.
On the basis of Mackenzie equation the shrinkage of solid materials containing partial saturated pore systems due to capillary attraction, can set equation 6:\(^{\text{[10]}}\):

\[
\varepsilon = -\frac{S \cdot R.T. \ln(RH)}{3W_m}(E^{-1} - E_s^{-1})
\]

Where:
- \(\varepsilon\) - Shrinkage of cement matrix in concrete;
- \(S\) - Coefficient of capillary saturation or partial volume of water in the capillary;
- \(E\) - ELAtic modulus of cement stone containing pore system;
- \(E_s\) - ELAtic modulus of dense completely cement stone material.

Evidently, with enough reservoir of liquid, if the temperature increases to a sufficient value: \(T \rightarrow T_{\text{max}}\), \(p_s\) will achieve to \(p_r\), and RH achieves to 100%, thus \(\varepsilon \rightarrow 0\). Thus from (5) and (6) shows that, if the temperature of the system increases, the relative humidity RH in capillary pore will achieves saturated value, cause decreasing of shrinkage. On the other hand, the effect of thermal factors - humidity also increases the structural strength of the cement stone (increasing of \(E\) and \(E_s\)), thus limiting the shrinkage of the concrete. These conclusions are the basis of the theory to explain the obtained experimental results.

3. Experimental results

3.1. Cementitious material: Cement (C) and Mineral admixtures - Fly Ash (FA)
Cement PCB40 Chinfon is produced according to Vietnam standard, TCVN 6260-2009. Fine mineral admixture is fly ash, floated from Phalai thermo-electric plant’s coal ash, F type according to ASTM C618, replacing 25% cement content (by weight). To increase the fine powder content in SCLC and increase the density of aggregates, 15% yellow sand was replaced with the same type of fly ash.

3.2. Fine aggregates - Sand (S)
Sand (S) from the Lo River (Vietnam), according to standard TCVN 7570-2006, is used.

3.3. Lightweight Aggregates - Keramsite (K) and Slender Fibers
Lightweight Aggregates used for these researches are Keramsite with grain sizes: 5 - 10 mm, meeting ASTM C330\(^{[11]}\). Mechanical-physical properties of Keramsite are shown in Table 1. Polypropylene fiber (PP) and alkali-resistant gLas fiber (ARG) were used as technology admixtures. The properties of slender fibers are shown in Table 2.

**Table 1. Properties of Keramsite**

| Physical properties          | Keramsite 5 - 10 (mm) |
|------------------------------|-----------------------|
| Bulk density, kg/m³          | 710                   |
| Specific density, g/cm³      | 2.65                  |
| Compressive strength, MPa    | 6.5                   |
| Particle density, kg/m³      | 1030                  |
| Water absorption, %:         |                       |
| Hp1 (1 hour)                 | 9.6                   |
| Hp24 (24 hours)              | 13.0                  |
| Hps (Saturated)              | 24.5                  |

**Table 2. Properties of fibers**

| Physical properties          | PP fiber | ARG fiber |
|------------------------------|----------|-----------|
| Specific density, g/cm³      | 0.91     | 2.70      |
| Average diameter, µm         | 40 - 60  | 13 - 15   |
| Average length, mm           | 20       | 15 - 17   |
| ELAtic modulus, GPa          | 3.5      | 72        |
3.4. Superplasticizer (SP) and Viscosity Stabilizing Admixture (VSA)
The SP is Glenium ACE388 based on polycarboxylate ether, cLAs F according to ASTM C949. Its specific weight is 1.1÷1.2 g/cm$^3$.
The VSA is COMBIZELL produced by Hurcules Asia Pacific. It is the derivative of Methylcellululoses. Characteristic properties of COMBIZELL are: soluble in cold water; increasing water-retaining capacity; stabilizing the suspension state of cement paste.

3.5. Compositions of Concrete mixtures
Experimental study was performed on 7 groups of sample, using different materials. Symbols of concrete samples studied are shown in Table 3.

| No. | Description                      | Symbol | Notes               |
|-----|----------------------------------|--------|---------------------|
| 1   | Use of dry Keramsite             | Kd     |                     |
| 2   | Use of dry Keramsite and ARG fibers | Kdg    | ARG fibers         |
| 3   | Use of wet Keramsite             | Kw     | $H_p$ = 8 - 10%     |
| 4   | Use of wet Keramsite and ARG fibers | Kwg    | ARG fibers         |
| 5   | Use of wet Keramsite and PP fibers | Kwp    | PP fibers          |
| 6   | Use of wet Keramsite and VSA     | Kwv    | VSA                |
| 7   | Use of Normal-weight Aggregate   | NA     | Grade M30          |

Based on the grading design that obtains the maximum density, together with the research results by experimental planning method, after solving the optimum problem and adjusting results experimentally, the compositions of SCLC mixtures, with grade of M30 and dry unit weight of 1600-1800 kg/m$^3$, are described in Table 4.

| Symbol | Cement (kg) | Sand (kg) | FA (kg) | Water (kg) | NA (kg) | LA (kg) | SP (l) | Fiber (g) | VSA (g) |
|--------|-------------|-----------|---------|------------|---------|---------|--------|-----------|--------|
| Kd     | 420         | 570       | 180     | 195        | 0       | 410     | 3.3    | 0         | 0      |
| Kdg    | 420         | 570       | 180     | 195        | 0       | 410     | 3.3    | 0         | 700    |
| Kw     | 420         | 570       | 180     | 195        | 0       | 410     | 3.3    | 0         | 0      |
| Kwp    | 420         | 570       | 180     | 195        | 0       | 410     | 3.3    | 570       | 0      |
| Kwg    | 420         | 570       | 180     | 195        | 0       | 410     | 3.3    | 0         | 850    |
| Kwv    | 420         | 570       | 180     | 195        | 0       | 410     | 3.3    | 0         | 170    |
| NA     | 300         | 830       | 240     | 173        | 880     | 0       | 3.0    | 0         | 0      |

The composition of Kw is similar to that of Kd, however, its mixing water content is reduced of about 10-11kg/m$^3$ concrete to keep the flowability of concrete mixture unchanged. The content of fibers and the content of viscosity stabilizing admixture in Kwv were determined experimentally, based on the investigation of concrete mixture flowability vs. the admixture content. For the comparison purpose, in this study, self-compacting heavy concrete with compressive grade of M30 (symbolized as composition of NA) was also tested.

The calculation results of required water absorption of Keramsite: $H_p$ = 8 - 10%, to gain this water absorption, Keramsite should only be submerged in water or sprinkled during some 1 - 2 hours [4].
3.6. Workability of concrete mixture

3.6.1. Flowability and loss of flowability of concrete mixture

Measuring results of flowability of concrete mixture right after mixing and at different time intervals are illustrated in Figures of 1; 2 and 3.

![Figure 1. Flowability Do and loss of flowability](image1)

![Figure 2. Flowability Dj and loss flowability](image2)

![Figure 3. Photos of tests on flowability Do and flowability Dj of concrete mixture](image3)

3.6.2. Segregation of concrete mixtures

The segregation of concrete mixture is determined according to the method for determining segregation of Polystyron concrete mixture of based on the standard GOST P 51263-99. Vibrator was not used in the tests. Measuring results of segregation of Light Concrete mixtures (LC) is illustrated in Figure 4.

![Figure 4. Segregation of Concrete mixture](image4)
We can see, from the measuring results of segregation of aggregates, that the homogeneity of concrete samples using waterlogged LA is significantly higher than that of samples using dry LA. Super-slender fiber reinforcement plays the role as a network preventing the emersion of LA. Due to the big length-to-diameter ratio and the compatibility with cement paste, the anti-segregation of ARG fibers was better promoted than that was promoted by PP fibers. The samples using waterlogged LA in combination with either gLAs fibers or viscous admixture give a very good effectiveness, reducing some 50% the segregation of aggregate if compared to that of the sample using dry LA without fibers.

3.6.3. Self-compacting capacity of concrete mixtures

The high flowable potential of concrete mixture was determined based on the test using J-ring according to ASTM C1666M – 2007 [12] and ASTM C1611M [13]. In addition, the flowable time of concrete mixture via the V-funnel and the passing ability in the L-box were also determined. Test results are illustrated in Figure 5.

![Figure 5. Self-compacting capacity of concrete mixtures](image)

Test results show that, for the mixtures using dry lightweight aggregate (Kd), the loss of flowability over time is very big, due to the strong absorption by LA in cement paste. In this composition, the mixing water is higher than that of other compositions so the concrete mixture tends to segregate the aggregate and strongly laminate the mortar, resulting in a bad flowability. For the mixtures using LA waterlogged before mixing (Kw), the mixing water content can be reduced. This prevents the aggregates from freely absorbing water in cement paste, significantly reducing the loss of flowability of concrete mixture. At the same time, the segregation of mortar and that of lightweight aggregates are also reduced. Flowability and loss of flowability of lightweight concrete mixtures is equivalent to that of heavy concrete mixture having the same compressive grade. The use of viscosity-stabilizing admixture (for the composition of Kwv) with a very small content (0.03 - 0.05% the weight of binder) has overcome this disadvantage.

When keeping the mixing water unchanged, the presence of fibers has made the flowability of concrete considerably reduced if compared to the flowability of the mixture concrete without fibers. With regard to ARG fibers, this effect is stronger. This can be explained that, though ARG fibers and PP fibers are slender fibers with big ratio of length-to-diameter, gLAs fibers are much more slender and much more compatible and adherent to the cement paste than PP fibers so they have made the viscosity of concrete mixture increased and the flowability of that reduced.

The self-compacting capacity of concrete mixture can be assessed according to the flowability Do and the flowability by J-ring Dj, and then we calculate the value of (Do - Dj). It can also be assessed via the flowability Do and result of L-box test [3].
3.7. Plastic shrinkage of SCLC
To study the influence of the waterlogged levels on plastic shrinkage and to determine the suitable water-logged level for LA, the authors have investigated plastic shrinkage and measured the relative humidity (RH) inside concrete using LA with different initial water-logged levels. The tests have been performed on summer hot days in Hanoi. The results are shown in Figures 6 – 9.

The results show that in the same test condition, plastic shrinkage of SCLC reduces as the initial waterlogged levels increase. When using water-saturated LA (H_p = 23%) plastic expansion has been appeared when drying up concrete samples. This might be the consequence of a water content added from LA and the influence of heat absorption from the ambient environment that makes the relative humidity in the material always saturated.

The results show that during the initial 1 – 8 hours, the shrinkage of samples is big and then it is gradually stabilized. The shrinkage of sample Kd is the biggest, plastic shrinkage of this sample is much higher than that of other samples. This is because the mixing water of composition Kd is more than that of other compositions and, as a result, the chemical shrinkage and autogenous shrinkage will be bigger. On the other hand, because LA is in dry state before mixing, it will absorb much more water from cement mortar so the shrinkage of concrete will be increased, particularly plastic shrinkage. With regard to compositions using LA water-logged before mixing, their plastic shrinkages are very small.

Therefore, LA waterlogged before mixing in combination with the use of dispersal fiber not only can restrain considerably the segregation of concrete mixture but also reduce effectively shrinkages of Concrete. To achieve this purpose, gLAs fibers should be preferred to PP fibers.
3.8. Strength and strength development of SCLC

Test results of compressive strength at the age of 3, 7, 28, 90, 120 and 180 days are shown in Figure 10.

![Figure 10. Development of strength of SCLC over times](image)

The experiments show the compressive strength and increase of the concretes significantly differ, depending on the ages of concrete. The increment of strength of SCLC was rather quick (3 days: more than 50%, 7 days: more than 75% of that at 28 days). However at the long-term ages, increment of the compressive strength of the concrete using waterlogged LA is much more than the concrete using dry LA.

The concretes contain PP fibers (Kwp) and viscous admixture VSA (Kwv) give strengths lower than the other concretes. However, at the age of 180 days, owing to the effect of self-curing by internal water from LA, compressive strength of them equal to that of Kd and Kdg.

4. Conclusions

From the theoretical and experimental research results, the following conclusions can be drawn:

From selected materials, lightweight concretes with unit weight of 1600 - 1800 kg/m³, compressive strength of 30 - 35 MPa, good workability and capable of self-compacting can be manufactured.

In the production technology for SCLC, LA waterlogged before mixing should be used. The initial water absorption of LA depends on the structure of its porous system, the density of LA in concrete as well as the cementitious volume and ratio water - binder(s). If producing SCLC with the use of keramsite, the initial water absorption of them can be: \( H_p = 8 - 10\% \)

The use of suitable pre-wetted LA for SCLC has resulted in better effectiveness than the use of dry LA with the following advantages:

Reduce segregation and increase the workability of fresh concretes; Reduce plastic shrinkage (up to 90%) and dry shrinkage (40 - 50%); Increase the strength of the concrete.

The use of ARG fibers or PP fibers, in combination with LA water-logged before mixing will result in not only a high effectiveness in anti-segregation, restraining shrinkages but also improving the mechanical-physical properties for SCLC. The effectiveness of ARG fibers is better than that of PP fibers.

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