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Journal of Materials Processing Technology 113 (2001) 238–244

Journal of Materials Processing Technology

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The flowability of bentonite bonded green molding sand

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Abstract

This paper investigates the properties of green molding sands, and a new model to evaluate the flowability of sand compact is developed. Controlling the flowability of the molding sand is extremely important in the sand casting process. Although several flowability indices have been proposed to measure this property, none of them has been universally adopted as a reliable indicator of the flowability. In this study, experimental results are presented to show how the flowability of silica sand is affected by water content, bentonite and sea-coal content.

The equation proposed by Shapiro and Kolthoff can well fit the relationship between the compacting pressure and the relative density. The coefficients of S–K equation were substituted into the strength equation proposed by Sheppard and McShane. The S–M equation matches the green compaction strength data, with an error less than 5%. The model reported here correlates a one-dimensional compaction model with the S–M and S–K equations, and derives the relative density difference and the compression strength difference of the compact. The experimental results showed that the green strength reached the maximum at the ratio of moisture-to-bentonite of around 0.33. The hardness deviation on the central plane of the compact was taken as the reference to test the estimated strength difference. The results indicated that the flowability increased as the water content decreased. The model can explain the experimental results and directly predicts the uniformity of the compact. The estimated relative density difference ΔD_r can be a new index of the flowability. For lowest ΔD_r, the best water content occurs at around w% = 3.0.

Keywords: Green molding sand; Flowability; Granular material compaction; Hardness

1. Introduction

Controlling the properties of green molding sand in a suitable range is the most important task for a modern automatic molding line. The water activated bentonite bonds the sand particles together and develops the strength needed to sustain the geometry of the sand mold. Because a non-uniform green sand mold will lead to serious casting defects, most researchers have recognized that the best water content of green sand is not only determined by the strength of the green sand but even more seriously by the plastic behavior, or flowability, during the molding process.

The problem of the flowability, sometime called moldability, of molding sand has been studied by researchers over the past 50 years. Most of the researchers took flowability as an independent plastic property, such as the internal friction angle, of molding sand. At greater ease to flow, the sand will form a more uniform mold surface. Control the water content to develop the best flowability is extremely important in a modern automatic foundry.

Dietert proposed the sand movement method for flowability measurement in 1934. He used the amount of compaction of a standard AFS $\phi 50 \times H50$ mm specimen between the fourth and fifth rams on the standard AFS rammer as an index for flowability. A few years later, Dietert et al. [1] proposed another rotating screen method to evaluate the flowability of green molding sand but they named it the moldability test. After Dietert's work much work were put forward to find the index of the flowability. More than 12 different methods for measuring the index of flowability were proposed. Generally they can be classified into three broad categories: hardness gradient, compaction vs. deformation, and the stress–stain curve methods.

In the hardness gradient method, a standard AFS 2 in. specimen holder split down the center is used and the flowability is expressed in %. The flowability is equal to the hardness at the top divided by the hardness at the bottom.

Because the permeability is sensitive to the geometry of the voids in a porous media, Moore [2] suggested that the sum of the averaged green compression strength increment (i.e., bondability) and the averaged permeability increment (i.e., ventability) could be used to represent the flowability. He reported that the flowability increased as the water

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0924-0136/01/$ – see front matter
PII: S0924-0136(01)00639-2

Nomenclature

A, B	constants in the Shapiro and Kolthoff equation
Ben%	bentonite content percentage
C_s	constants in Sheppard and Mcshane equation
d	diameter of the compact
D_r	relative density
H	height of the compact
k	proportional constant, $k = \sigma_3/\sigma_1 = (1 + \sin\phi)/(1 - \sin\phi)$
P	compaction pressure
SC%	sea-coal content percentage
w%	water-content percentage
z	distance below the punch end

Greek letters

Δ	maximum difference of a property in the compact
μ	surface friction factor
σ_c, σ_t	green compaction strength and green tensile strength
ϕ	internal friction angle of Mohr–Coulomb yield criterion

addition increased and that inflection zone of the curve showed the best water level range. However he did not explore in his studies the physical meaning of the bondability and ventability. Hofmann and Dietert [3] investigated the volumetric deformation of several green sand samples under squeeze compaction and proposed a compactability test to measure the moldability of molding sand. They pointed out that the best water content was at a compactability of 45%, which was practically independent of sand composition. Although the criterion they proposed was based on the experience of hand molders only, most researchers, Shih [4] and Heine [5] now adopt this compactability test. Strobl and Schuster [6] observed the stress–strain curves of standard AFS cylindrical test specimens under continuous uni-axial compressive loading, and suggested that the flowability index could be expressed as the falling slope of the curve divided by green compression strength. Their experimental results showed that dryer sand flowed more easily than one that contains more water. Some flowability indices mentioned above are compared in Fig. 1.

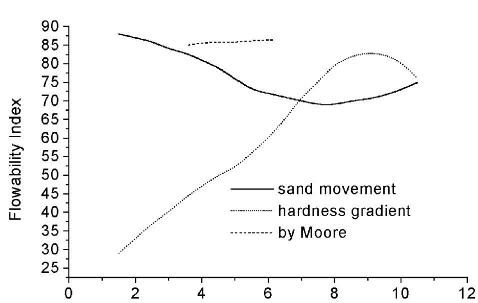


Fig. 1. Flowability indices with different definitions, after [2].

These curves have completely different relationships with respect to the water content and it is difficult to determine the best water content by these curves. This inconsistency in the water-content effect is one of the reasons why none of these methods have been universally accepted as a reliable indicator of flowability.

Although many different indices were proposed, the definition about the flowability and the inconsistent statements about the effect of water content on the flowability are ambiguous still. The purpose of this paper is to investigate the water-content effects of bentonite-bonded green molding sand, and a new model will be developed to evaluate the flowability of the green molding sand.

2. One-dimension model to estimate uniformity of the compact

Consider a cylindrical green sand compact of diameter ϕd and height H such as shown in Fig. 2. A compacting pressure P_0 is applied on top of the compact and friction force is exerted on the peripheral surface of the cylinder. Assuming all properties are homogeneous in the radius direction, the equilibrium equation of a thin sectional element of height dz can be expressed as

$$[P - (P + \mathrm{d}P)]\frac{1}{4}\pi d^2 = \pi\,\mathrm{d}\tau\,\mathrm{d}z, \tag{1}$$

where $\tau = \mu P_n = \mu k P$. τ is the friction shear exerted on the outer surface of the element, μ is a friction factor and k a proportionality constant between vertical pressure $P(z)$ and horizontal pressure P_n. If the plastic behavior of the green sand follows the Mohr–Coulomb yield criterion, then the constant k can be expressed as $k = \sigma_3/\sigma_1 = (1 + \sin\phi)/(1 - \sin\phi)$, where ϕ is the angle of internal friction, and σ_3 and σ_1 are principal stresses. Solving Eq. (1) for the pressure difference between the top and bottom of the element dP,

$$\mathrm{d}P = -4\mu k P \frac{\mathrm{d}z}{d}. \tag{2}$$

Integration of the pressure term with respect to the compact height gives the pressure at any position z below the punch,

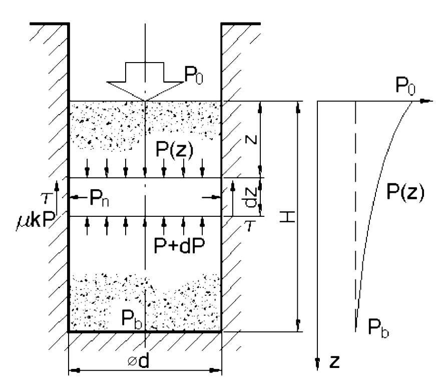


Fig. 2. Scheme of the compaction model.

as follows:

$$P(z) = P_0 \exp\left(-4\mu \frac{kz}{d}\right). \tag{3}$$

Assume the relationship between compaction pressure P and relative density D_r can be represented by the most widely used compaction equation proposed by Shapiro and Kolthoff [7], which has the form:

$$P = A + B \ln \frac{1}{1 - D_r}. \tag{4}$$

Substituting this equation into Eq. (3) and solving for D_r gives an expression of the relative density distribution D_r along the z direction as follows:

$$D_r(z) = 1 - \exp\left[\frac{A - P(z)}{B}\right]. \tag{5}$$

Hence, the maximum relative density difference across the section of the sand compact can be calculated by

$$\Delta D_r = D_{r,top} - D_{r,bottom} = D_r(0) - D_r(H). \tag{6}$$

If the constants in Eqs. (3) and (4) are found by experiment, the value of ΔD_r can be determined and be used as an indicator for measuring the uniformity of relative density inside the compact.

Sheppard and Mcshane [8] investigated the relationships between compact pressure, compact density, and compact strength. They proposed a strength equation for cold-pressed compacts as follows:

$$\sigma_t = C_1 - C_2\left(\exp\frac{P}{B} - \exp\frac{A}{B}\right)^{-2/3}, \tag{7}$$

where σ_t is the tensile strength of the compact, and C_s are constants of the material. Substitution of Eq. (3) into the strength equation gives an expression for σ_t in the z direction, below the punch end of the compact. However, the tensile test is difficult to conduct with many granular materials such as green sand. Hence, this study adopted the compression test as the strength test. In order to compare with data from experiments, it is assumed that the green compression strength σ_c is proportional to the tensile strength σ_t, so that Eq. (7) can be used to express σ_c. Therefore, the maximum green compression strength difference $\Delta\sigma_c$ of the compact can be expressed as

$$\Delta\sigma_c = \sigma_{c,top} - \sigma_{c,bottom} = \sigma_c(0) - \sigma_c(H). \tag{8}$$

$\Delta\sigma_c$ is an indicator for uniformity of the strength of the sand compact. For an ideal homogeneous compact, $\Delta\sigma_c$ and ΔD_r must be zero. Hence, $\Delta\sigma_c$ and ΔD_r can be used to evaluate the flowability of the green sand.

3. Methods and materials

Most green sand is mainly comprised of silica sand, bentonite, water, and flammable additives, such as sea-coal.

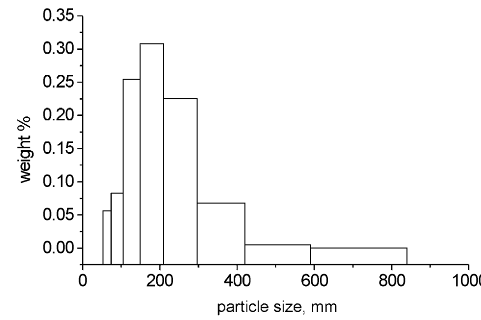


Fig. 3. Sieve analysis results of the silica sand used in this study.

Fig. 3 shows the riddle analysis result of the sand used in the experiments of this study. The GFN number of the sand was 52.4. The additives of the green sand are bentonite, water, sea-coal (i.e., fine coal powder), and dextrin. Table 1 lists the composition of the green sand. All numbers, except for water, listed in Table 1 are weight percent with respect to 100% weight sand. The water content is measured with respect to the total weight of the sand mixture. Usually the cyclically used system sand will not contain sea-coal to more than 5%. The compositions No. 5 and 6 listed in Table 1 are prepared to simulate poorly maintained system sand that may contain too many fine particles. In order to avoid agglomeration the mulling process was divided into two stages. At first stage, 5 kg of clean silica sand with water were poured into a small Simpson type Muller and mixed for 60 s. Then all other additives were added into the mixture and mulled for 4.5 min. When the mixing process was finished, the sand mixture was sieved with a 6″ mesh screen. An infrared moisture meter tested the water content of the sand mixture. If the level of water content was not in the desired target region, the sand mixture would not be considered. The sand mixture compact specimen was made using a specially designed sand press, of which the compact pressure and loading time were adjustable. The compact pressures were adjusted to 0.98, 1.96, and 2.45 MPa, and the loading time was constantly settled at 15 s. The green sand mixture was compacted into an AFS standard cylindrical specimen ($\phi 50 \times H50$ mm). The green compaction strength σ_c and the permeability were tested using a standard AFS instrument supplied by Dietert.

For granular materials, most of the properties, such as the density, are difficult to measure inside the specimen. Hence,

Table 1
List of green sand compositions (baseline condition: No. 1, dextrin = 0.08%, Ben: bentonite%, SC: sea-coal%)

No.	Ben (%)	SC (%)	Water (%)
1	10	3	2.3, 3.0, 4.4, 5.0
2	8	3	2.3, 3.0, 3.6
3	12	3	2.6, 3.0, 3.9, 5.0
4	10	0	2.5, 3.0, 4.0
5	10	6	2.8, 3.1, 4.5
6	12	6	3.5, 4.5

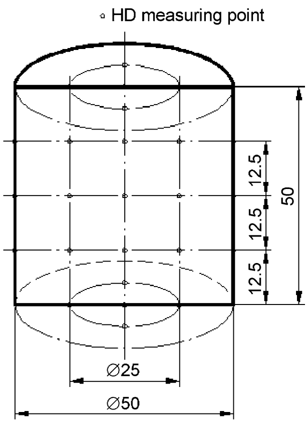


Fig. 4. Hardness measuring points.

the deviation of the hardness distribution on the central section of a sand specimen was adapted as an indicator for a uniform check of the specimen. The dimensions of the locations for hardness measurement are depicted in Fig. 4.

The internal friction angle ϕ from the Mohr–Coulomb equation of the green sand mixture was measured by the ASTM standard direct shear test. Each kind of the experiments in this investigation were conducted at least five times. The results that are shown in this report are averaged values.

4. Result and discussion

4.1. Green compression strength and bulk relative density

The green strength increased when the bentonite content was increased, as shown in Fig. 5. Most of the curves ($SC\% < 6\%$) shown in this figure have peaks located at $w\% = 0.3{-}0.4\%$. Over this region, the green strength decreased slowly as the water content increased. If the w% was divided by Ben%, the peaks of strength were located around $w\%/Ben\% = 0.3$. For the green sand with $SC\% = 6\%$, an inflection of the strength occurred at $w\% = 0.3$, but no maximum strength was observed. Because of the high green strength at this water content, most foundries take $w\% = 3.0$ as the target of the water-

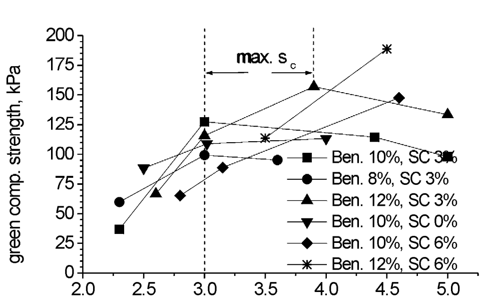


Fig. 5. Green compression strength of the green sands with different compositions ($P = 2.48$ MPa).

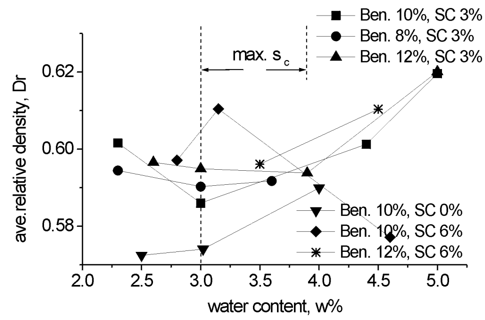


Fig. 6. Relative density vs. water content ($P = 2.45$ MPa).

adding process, whereas many researchers have suggested that controlling the w% to reach the desired compactability (38–45%) is more important than that of the maximum strength. However, they did not give the answer about what is the best w% and explain how to determine the best compactability [3,9,10].

The relative density curves with $SC\% < 6$ is always at the minimum values in the maximum σ_c water-content region, as shown in Fig. 6. The inflection of the curve may express that the state of the sand-grains arrangement translates from a pattern of dryer sand to a different pattern of wetted sand.

The equation that was proposed by Shapiro and Kolthoff can fit the relative density data well, as shown in Fig. 7. The maximum error of the fitted data was less than 3%. Fig. 8 shows a set of green strength data fitted with the Sheppard and Mcshane equation. The maximum error of the S–M

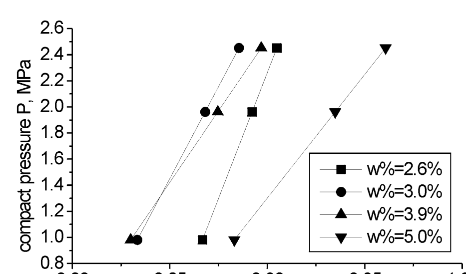


Fig. 7. Relative density vs. compaction pressure ($P = 2.45$ MPa, $Ben\% = 10, SC\% = 3$).

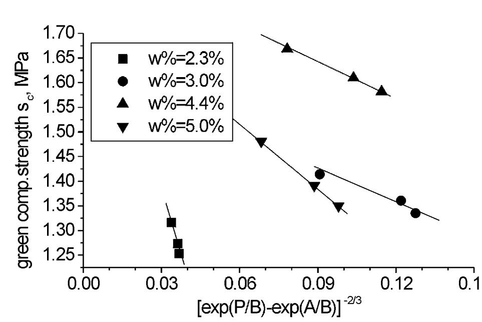


Fig. 8. Green compression strength vs. the factor derived from the S–M equation ($P = 2.45$ MPa, $Ben\% = 10, SC\% = 3$).

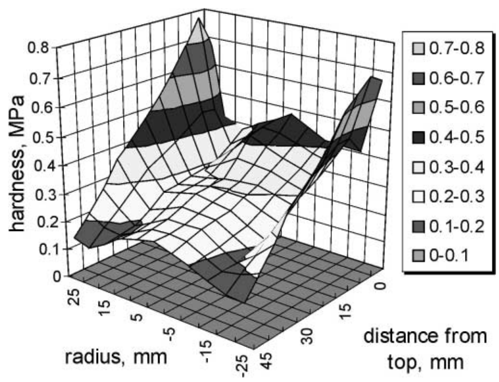


Fig. 9. Average hardness distribution on the central plane ($P = 0.98$ MPa, Ben% = 10, SC% = 1, w% = 3).

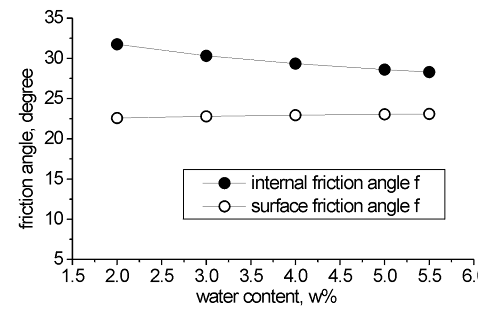


Fig. 11. Internal friction angle and surface friction angle (w% = 3.0, Ben% = 10, SC% = 3).

equation was less than 5%. The highly accurate fitting data may help to improve the assurance of the estimation by the model mentioned above.

4.2. Hardness distribution on centric plane section

A typical hardness distribution profile is depicted in Fig. 9. The maximum hardness on the central section is at the outer edge of punch end of the sand compact. The hardness decreased as the distance from the punch end increased. In order to compare the hardness data with the green strength tested under the same conditions, all hardness data were converted from hardness degree, 0–100, to a kPa scale by applying the equation used to convert hardness data as proposed by Kupczuns and Szreniawski [11]. The relationship between average hardness and water content was the same as that of green strength and water content but much greater than the latter, as shown in Fig. 10. This phenomenon is due to the different load conditions. With a water content higher than the maximum green strength region, the hardness was 2.8–4 times greater than the green strength. When the water content is below that region, the hardness drops to 0.6 times the green strength. The hardness drop can be attributed to brittleness of dry sand. The unstable hardness test result arises from the brittleness of the dry sand surface, as it is too fragile to sustain the penetrating force acting on it by the indenter of the hardness meter. Moreover, the hardness degree on the standard AFS hardness meter is more sensitive on the low hardness scale than that it is on the higher hardness scale. Therefore, these two conditions may lead to a result that dryer sand has lower flowability by the hardness gradient method with a low compaction pressure.

4.3. Green compression strength difference $\Delta\sigma_c$ and relative density difference ΔD_r

A set of typical internal friction angles and surface friction angles with respect to water content are shown in Fig. 11. The internal friction angle decreased as the water content increased, whereas the surface friction angle increased slowly as the water content increased. Within the water content range of this study, the range of internal friction angle was about 27–32° and that of surface friction factor was about 0.415–0.43. From the aspect of friction angle, the green sand with higher w% should be the easier to be stuck on the mold surface than that for a lower w% under the same compressive stress conditions.

Fig. 12 compares tested hardness difference results with the correspondence strength difference $\Delta\sigma_c$ estimated by the use of Eq. (8). The data of $\Delta\sigma_c$ and ΔD_r shown in Fig. 12 are normalized by the corresponding green compressive strength and average hardness, respectively, in order to compare with each other without bias from the magnitudes of them. At this low compact pressure condition, $P = 0.98$ MPa, the hardness deviation decreased as the

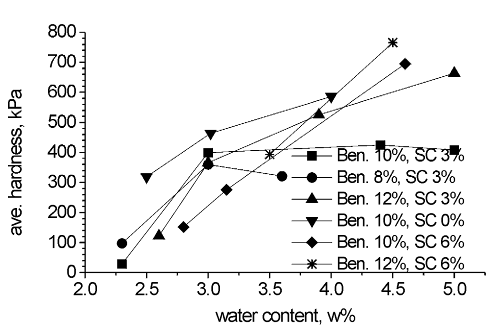


Fig. 10. Average hardness vs. water content ($P = 2.48$ MPa).

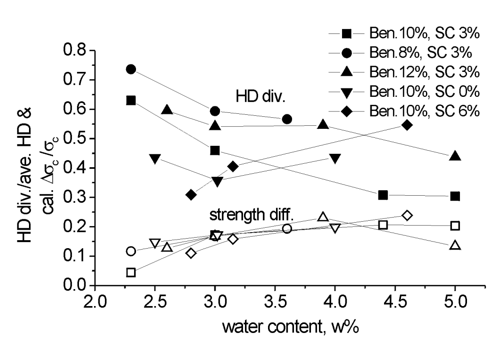
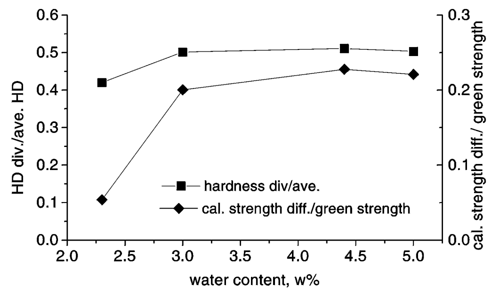
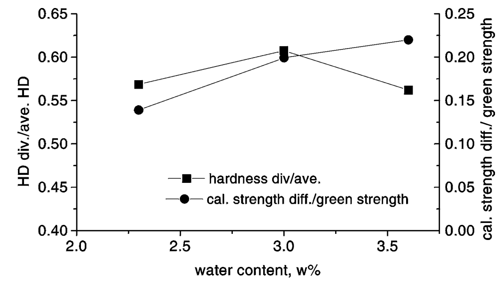


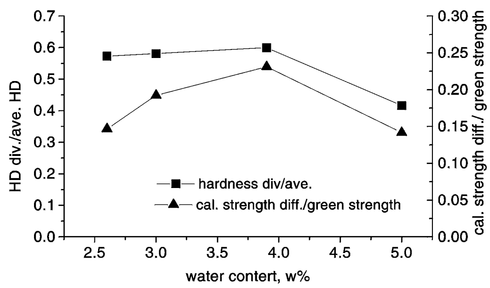
Fig. 12. The estimated $\Delta\sigma_c$ compared with hardness difference at $P = 0.98$ MPa.



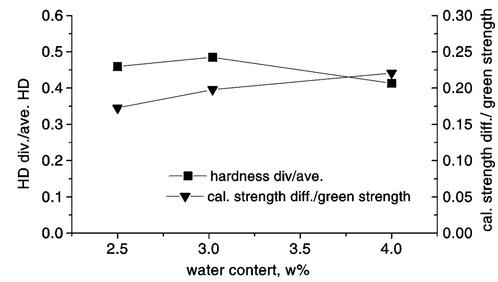
(a) Ben%=10, SC%=3.



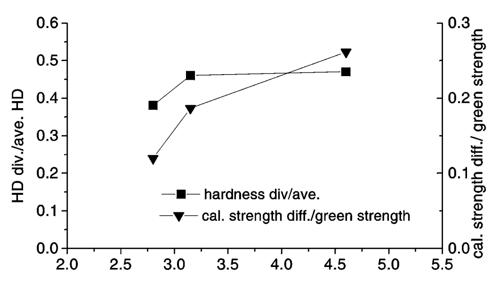
(b) Ben%=8, SC%=3.



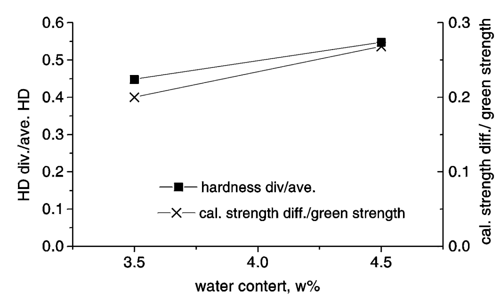
(c) Ben%=12, SC%=3.



(d) Ben%=10, SC%=0.



(e) Ben%=10, SC%=6.



(f) Ben%=12, SC%=6.

Fig. 13. The estimated $\Delta\sigma_c$ compared with hardness difference at $P = 2.45$ MPa.

water content increased. This phenomenon was similar to the results obtained by hardness gradient method such as shown in Fig. 1. The estimated $\Delta\sigma_c$ increased, i.e., more water added decreased the flowability. The estimated $\Delta\sigma_c$ agrees well with the friction angle results and the results presented by Strobl and Schuster [5]. When the compaction pressure was increased, the behavior of the hardness deviation with respect to w% was getting close to that of the estimated $\Delta\sigma_c$, as shown in Fig. 13(a)–(f). The normalized estimated $\Delta\sigma_c$ can be correlated to the normalized hardness deviation with a constant of about 2.5. The inconsistency at low pressure may due to the brittleness of the dry sand and the uneven scale of the hardness meter. The estimated relative density difference is shown in Fig. 14. The density difference increased as the water content increased. When $SC\%/Ben\% > 3.7$, the minimum ΔD_r occurs at around $w\% = 3.0$. For relative higher Ben% conditions, a minimum did not occur. This phenomenon may be due to the relative larger amount of fine sea-coal particles being filled into the voids between the sand particles, thus decreasing the relative density difference of the compact. The peak of the relative density curve in that condition shown in Fig. 6 supports the above suggestion. The $\Delta\sigma_c$ curve drops slowly in the high

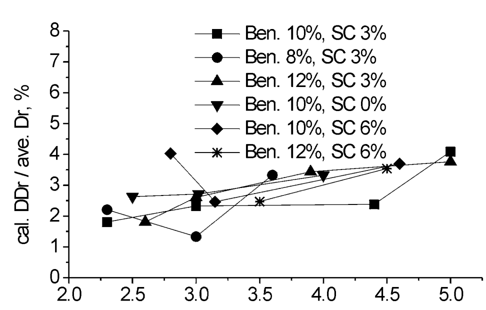


Fig. 14. Estimated relative density difference ΔD_r.

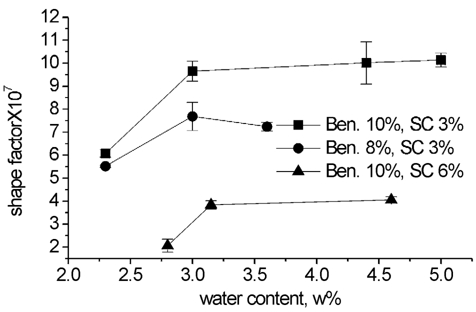


Fig. 15. Shape factor vs. water content.

water-content zone, whereas the ΔD_r curve continuously increased as the water content is increased. This difference between them may indicate the phenomenon that bentonite activation is gradually saturated with increasing water content. Thus the low $\Delta\sigma_c$ in the high water-content region may explain why the existing hardness gradient method always yield high flowability in the high water-content region.

4.4. Flowability and the best water content

Most of the indices for flowability are defined based on the consideration of the uniformity of the compact. However, none of them can directly inspect the uniformity of the compact. The sand movement method and the compactability method are equivalent relationship between relative density and compaction pressure that may closely relate Eq. (4). Nevertheless, the deficit between the compactability and the two friction angles, i.e. Eq. (6) needs to be supplemented by the experience of the foundryman. The results obtained by the hardness gradient method may be affected by the brittleness of the dry sand. The method proposed by Strobl and Schuster [5] is only an indirect way to conduct the direct shear test without consideration of the surface friction effect and the relative density change such as Eq. (4).

The model proposed in this research synthesizes important parameters on compaction in a simple way. Therefore, the estimated results can match the experimental data well. Both the density difference ΔD_r and the strength difference $\Delta\sigma_c$ proposed in this report are direct indicators about the uniformity of the compact. The ΔD_r may be even more suitable to the flowability index than that of the $\Delta\sigma_c$ because of the relative low sensitivity of the latter.

The best uniform compact occurs at the lowest ΔD_r condition. Therefore the water content should be determined at this condition. In this study, the best water content was around $w\% = 3.0$, or accurately around $SC\%/Ben\% = 3.3$. In order to understand why ΔD_r occurs at this point, these minimum densities were compared with the corresponding shape factors shown in Fig. 15. The shape factor is derived from the hydraulic conductivity, i.e. permeability. It is a sensitive factor about the geometry of voids inside porous medium. It was found that all these minimum values coincided with the inflections of the shape factor curves, as shown in Fig. 15. This evidence supports the statements about the aforementioned arrangement-translation statements that were made in the above.

5. Conclusions

The existing flowability indices, such as compactability, slope of the stress–strain curve, and hardness gradient, cannot totally agree with experimental results. The inconsistency of these indices with respect to water content leads to a fuzzy condition in the determination of the best water content.

The relationship of the properties of green molding sand with respect to water content was fully investigated in this paper. A new model to estimate the uniformity in strength and relative density of the cylindrical compact has been developed. The model correlates a one-dimensional compaction model and two empirical equations to derive the relative density difference and the green compression strength difference of the sand compact. The experimental hardness deviation was used to examine the performance of the model. This model can be used to evaluate the performance of green molding sand. For lowest ΔD_r, the best water content may be around $w\% = 3.0$. The estimated relative density difference ΔD_r can be a new index of flowability.

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