HBRC Journal (2016) 12, 1–12

Housing and Building National Research Center

HBRC Journal

http://ees.elsevier.com/hbrcj

Evaluation of consistency properties of freshly mixed concrete by cone penetration test

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Received 20 June 2014; accepted 29 September 2014

KEYWORDS

Fresh concrete;
Consistency;
Workability;
Rheology;
Cone penetration

Abstract This study is directed to evaluate the ability of using cone penetration test as a simple method to investigate the consistency level of fresh concrete. A cone of 30° apex angle attached with different load values was used. Eighteen concrete mixes divided into three groups were conducted. Three types of coarse aggregate were tried. Crushed dolomite, round gravel, and crushed basalt all of 20 mm maximum grain size were investigated. For each type of coarse aggregate, six levels of concrete consistency calibrated by standard slump test were tried. For the investigated mixes and at a specified consistency level, the displaced volume values were directly proportional to the applied load. The inclination of this relation is termed as the displaced volume rate (D.V). The results of cone penetration were analyzed and compared to the corresponding slump test values. The displaced volume per unit mass, bearing strength, as well as shear yield strength were the evaluated properties. The results introduce the cone penetration test as a simple instrument that could be adopted either at a laboratory or at site to evaluate fresh concrete workability. Moreover, it is being more sensitive compared to the well known slump test. It can simply and clearly distinguish between stiff mixes as well as floppy ones. Very useful numerical limits for the evaluated properties controlling the workability levels of very low, low, medium, high and very high were proposed.

Introduction

Fresh concrete is being a transit stage. The importance of this stage comes from the fact that the concrete strength is very seriously affected by the degree of its compaction. Moreover, ease of placement, consolidation and durability depend on the flow properties of concrete. Concrete that is not properly consolidated may have defects like honey combs, air voids, and aggregate segregation.

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Peer review under responsibility of Housing and Building National Research Center.

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http://dx.doi.org/10.1016/j.hbrcj.2014.09.001

Historical development of existing workability test methods

The concrete industry has recognized the importance to monitor concrete workability since the early 20th century [1]. The American concrete industry at the beginning of 1900s had no standard test methods to measure workability. Instead, subjective, qualitative descriptions of "consistency" were typically given. While recognizing that concrete consistency was of utmost importance, Taylor and Thompson [2] divided concrete consistency into three simplistic and vague categories: "dry" consistency, "medium" or "quaking" consistency, and "wet a mushy" consistency.

In 1918, the concrete industry took a dramatic step forward as a result of Duff Abrams's [3] work in the field of design concrete mixture, in which he showed that concrete strength was directly related to the ratio of water-to-cement what Abrams called the water ratio. Whereas, other mixture proportioning procedures of that time focused mainly on achieving an optimum packing of aggregates and considered the water content to be subordinate, Abrams showed that the water-to-cement ratio was the most important parameter in developing mixture proportions and that it should be set as low as possible on the condition that proper workability could be achieved.

To define workability, Abrams [3] suggested the slump test method to evaluate the relative consistency of concrete mix. Although the slump test was quickly accepted due to its simplicity, the concrete industry immediately recognized that the slump test was in adequate for fully properly characterizing workability.

Since the introduction of the slump test, a myriad of workability test methods have been developed. Workability tests for concrete workability have attempted to simulate actual field conditions to develop an index expressing particular aspect of workability. On the other hand, rheology-based approaches attempt to measure the fundamental rheological parameters of concrete, which can then be related to practical construction requirements. Workability tests can generally be split into five broad categories, free flow tests, confined flow tests, vibration tests, rotational rheometers, and tests for very dry concrete.

Free flow tests

Common free flow tests include slump test, Kelly ball test, modified slump test etc. [1].

Free flow tests measure either the penetration resistance of concrete or the ability of concrete to flow under its own weight. Such tests are simple to perform and provide a direct result without calculations. The results of free flow test methods are typically closely related to yield stress. The slump test is the best known of the free flow test methods.

In addition to the slump test, several free flow test methods have been improved to also measure plastic viscosity. For instance, the modified slump test [4]. In the Kelly ball test, which is the best known penetration resistance test, the depth of penetration of a ball is measured and then related to slump [1].

Confined flow tests

Common confined flow tests include the compaction factor test beside the free orifice (Orimet) test, L-shaped boxes which are commonly used for self-compacting concrete [1].

In these tests, concrete flows through a narrow orifice either under its own weight or under an applied pressure. Confined flow tests are simple to perform and provide a direct result; however, they do not give a direct indication of yield stress and plastic viscosity [1].

Generally, confined flow tests are not suitable for low to moderate slump concretes, which are not sufficiently fluid to readily flow under confined flow conditions and produce meaningful results.

Vibration tests

Many test methods are used to measure the flow of concrete under vibration due to the wide use of vibration in placing concrete. Vibration tests are important in measuring the flow properties of low to moderate slump concretes that are commonly vibrated in the field. VeBe test and flow table test are examples of vibration tests that measure the ability of concrete to remold from one shape to another under applied vibration [1].

Rotational rheometers

Rotational rheometers for concrete apply shear stress to concrete at different shear rates to measure yield stress and plastic viscosity. Rotational rheometers are typically used exclusively in the laboratory. Although some rotational have been designed to be sufficiently small and rugged for use on jobsites, the limited availability and high cost of these devices made them impractical for regular field use. Different rotational rheometers measure different ranges of workability. Coaxial cylinders, impeller and parallel plate are some common geometries of concrete rotational rheometers [1]. Modified vane shear test was used to measure the shear yield strength of the fresh concrete [5].

Very dry concrete tests

For very dry concrete mixtures, compaction tests are used due to unsuitability of flow and other tests. The proctor test for soils can be used for very dry concrete mixtures. With the exception of the widely used slump test, the few methods that have been studied extensively have generally failed to gain widespread acceptance [1].

Compaction factor test was developed in Britain in the late 1940s and has been standardized as British standard 1881–103. Although this test gives more information than the slump test due its dynamic nature and its large and bulk nature reduce its usefulness in the field moreover, it is not suitable for harsh concrete mixes [1].

The slump test is the most well-known and widely used test method to characterize the workability of fresh concrete. An inexpensive test, which measures consistency, is used on job sites to determine rapidly whether a concrete batch should be accepted or rejected. The test method is widely standardized throughout the world, including ASTM C 143 and EN 12350-2. Although this test is the most widely used worldwide, concretes with the same slump can exhibit different behavior when tapped with a tamping rod. Moreover, the slump test is less relevant for newer advanced concrete mixes than for more conventional mixes [1].

The Kelly ball test was developed in the 1950s in the United States as a fast alternative to the slump test. The simple and inexpensive test can be quickly performed on in-place concrete and the results can be corrected to slump. The results of this test are related to slump test results [1]. The VeBe consistometer measures the remolding ability of concrete under vibration. The test results reflect the amount of energy required to remold a quantity of concrete under given vibration conditions. The VeBe consistometer is applicable to concrete with slumps less than 2 in. This test is suitable for low slump concretes [1].

The focus of workability measurement has changed many times over the years. Generally, the used method for measuring the workability of concrete cloud be classified as one of the three classes given in Table 1 [6].

According to the flow produced during the test, the national institute of standards and technology (NIST) divided existing rheology test methods into four broad categories [7]. The definitions of the four categories are given in Table 2.

Many attempts have been made either to improve the efficiency of existing method or to introduce new methods in the field of concrete workability. Modified slump test is an example of the research effort to measure both the plastic viscosity and yield stresses of concrete mixtures [4].

The use of K-slump tester [8] is being an example of the methods introduced simply to concrete to quickly measure its workability neglecting the influence of coarse aggregate contained in the concrete mixture.

On the other hand, a modification was introduced to vane shear test to enhance its applicability to measure yield stresses of concrete mixtures [5] A cone penetration test was developed to measure the workability of fiber reinforced concrete [9]. The developer of the test optimized the value of both apex angle and the cone weight to 30° and 4 kg, respectively. The depth of penetration is measured as an indication of workability.

In view of the above, concrete industry still needs simple or enhanced field test methods able to evaluate accurately the concrete workability. So this study is directed to investigate the ability and accuracy of using a cone penetration test to measure concrete workability.

Experimental program

The ability of using the cone penetration test was investigated in this experimental study. The program included eighteen concrete mixes with different coarse aggregate type and different consistency levels. The consistency levels for the conducted concrete mixes were evaluated by performing the well known slump test. The main parameters of this study comprise;

– Type of coarse aggregate (crushed dolomite, round gravel and crushed basalt).
– Different levels of workability and consistency that are governed through varying water to cement ratio (0.4–0.7).
– The applied load attached to the cone under penetration.

Table 1 Classes of workability measurement [6].

Class I Qualitative Workability, flow ability, compact ability, pump ability.	To be used only in a general descriptive way without any attempt to quantify
Class II Quantitative Empirical Slump, compacting factor, VeBe time, flow table spread, etc	To be used as a simple quantitative statement of behavior in a particular set of circumstances
Class III Quantitative fundamental Viscosity, mobility, fluidity, yield value, etc	To be used strictly in conformity with standard definitions

Table 2 NIST categorization of concrete rheology test methods [7].

Category	Definition
Confined flow tests	The material flows under its own weight or under an applied pressure through a narrow orifice
Free flow tests	The material either flows under its own weight, without any confinement or an object penetrates the material by gravitational setting
Vibration tests	The material flows under the influence of applied vibration. The vibration is applied by using a vibrating table, dropping the base supporting the material, an external (vibrator, or an internal vibrator)
Rotational rheometers	The material is sheared between two parallel surfaces, one or both of which are rotating

Materials

Cement

Ordinary Portland cement of grade 42.5 N was used in this investigation. Eighty minutes and two hundred and seventy minutes were the initial and finial setting times, respectively. The used cement is conformed to the requirements of the Egyptian standard specifications ES (4746-1/2005).

Fine aggregate

Medium well-graded sand of fineness modulus 2.79 was used.

Coarse aggregate

Three types of coarse aggregates were used in this study. Crushed dolomite, round gravel and crushed basalt all of 20 mm maximum grain size. Both fine and coarse aggregates are conformed to the requirements of the Egyptian standard specifications ESS (1101-2002). Table 3 presents the properties of the used aggregates.

Water

Clean water from water supplier tap was used in this study.

Concrete mixes

Eight concrete mixes for each type of coarse aggregate were investigated in fresh state. A total of eighteen concrete mixes were conducted for the three used coarse aggregate types in fresh state. The details of the conducted concrete mixes are given in Table 4.

Methodology

Eighteen concrete mixes divided into three groups as presented in Table 4 were prepared and tested. The concrete mixes were mixed in a portable concrete mixer with a maximum capacity of 100 L. The water and cementitious materials were mixed for

Table 3 Properties of the used materials.

Material type		Sand	Crushed dolomite	Round gravel	Crushed basalt
Property	Sieve size, mm	Grading (% passing)			
Grading	19.5	100	99	96	97
	9.5	100	55	48	37
	4.75	96	8	6	5
	2.8	84	–	–	–
	1.4	75	–	–	–
	0.71	50	–	–	–
	0.30	14	–	–	–
	0.15	2	–	–	–
Maximum grain size, mm		–	20	20	20
Unit weight, kg/m^3		1580	1570	1610	1630
Specific gravity		2.62	2.65	2.70	2.72
Fineness modulus		2.79	6.38	6.5	6.61

half a minute to ensure the uniformity of the constituents. Sand was simultaneously charged into the mixer and the mixing process was continued for half a minute and then coarse aggregate was added. After that, the total content was mixed for a period of 2 min. After mixing, the standard slump test according to the procedure described in Egyptian code ECP 203:2009 and ASTM C143 standard was conducted. At the same time, a concrete sample was discharged into a bucket of 500 mm diameter. The concrete depth was kept as 100 mm greater than the used cone depth. The concrete is leveled horizontally then the cone instrument with its adjusting frame was resisted on the concrete surface. The cone attached with the applied load was lowered slowly till it touched the concrete surface. Then it was left to fall freely to statically penetrate the investigated concrete. The penetration depth was recorded as shown in Fig. 1. After that, the instrument was shifted to another position and the attached load was increased and the penetration depth was to be measured. Different load values were used for each concrete mix and the corresponding penetration depths were measured. Based on the measured penetration depths and the corresponding load values, the displaced volume rate (D.V) cm^3/kg, the bearing strength (σ_b) MPa, and the shear yield strength (σ_{sh}) MPa were calculated according to the Eqs. (1)–(3) respectively that are derived in the following sections. Fig. 2 shows the acting forces on the cone at the end of penetration process.

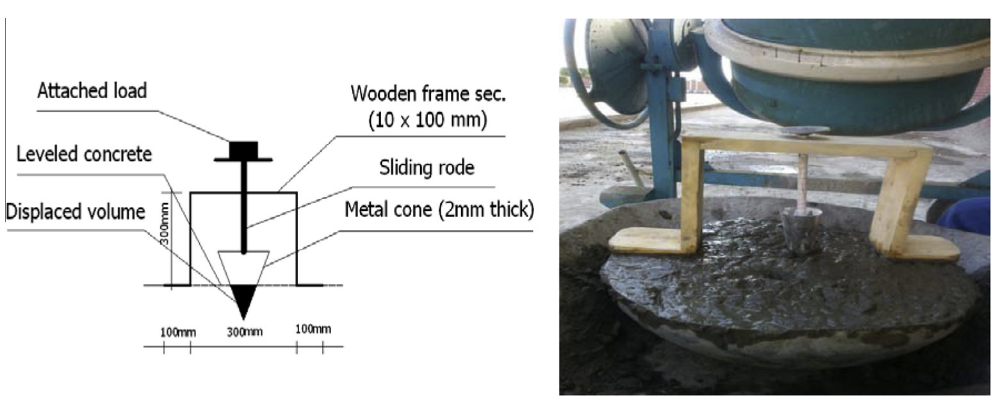
Derivation of the displaced volume rate (D.V)

In this study, the used cone attached with the applied mass is gently lowered to touch the flat surface of the freshly mixed concrete then it is left to freely penetrate the tested concrete under its own weight plus the attached load. The penetration

Table 4 Concrete mix compositions (ratios by weight).

Type of coarse aggregate	Coarse aggregate	Fine aggregate	Cement[a]	w/c	Mix code[b]
Crushed dolomite (D)	2.625	1.5	1	0.45–0.7	D_x
Round gravel (G)	2.625	1.5	1	0.4–0.6	G_x
Crushed basalt (B)	2.625	1.5	1	0.43–0.6	B_x

[a] Cement content 400 kg/m^3.
[b] D_x: D denotes dolomite and x denotes slump.



a- Cone penetration instrument b- Cone penetration test in progress

Fig. 1 Setup of the cone penetration test.

depth (h) is measured at which a case of equilibrium is reached. At that state, the total applied load (W) is in equilibrium with the vertical component of the shear resistance of the tested concrete.

The displaced volume could be calculated from Eq. (1):

$$v = \frac{1}{3}\pi h^3 \tan^2 15^\circ \quad (1)$$

where v: is the displaced volume, cm^3 and, h: is the penetration depth, cm.

Derivation of both bearing (σ_b) and shear yield (σ_{sh}) strengths

The penetration of the cone into the investigated concrete mix is stopped when the applied force resisted by equal one in the upward direction. This may be regarded to the vertical component of the resistant shear force for which the following Eq. (2) could be applied;

$$\sigma_{sh} = \frac{w}{A\cos\theta} \quad (2)$$

where w: is the total applied load kg, A: is the penetrated side area of the used cone, σ_{sh}: is shear stress (MPa) along the side area of the cone and, θ: is half the cone apex angle (15° for the used cone in this study).

The equilibrium state after the penetration may be regarded as the equilibrium of the applied force (downward) and the resistance of σ_b applied on the horizontal plan of the surface area of the used cone from that the following Eq. (3):

$$\sigma_b = \frac{W}{\pi h^2 \tan^2\theta} \quad (3)$$

Test results and analysis

The present experimental program was conducted to investigate the ability of using cone penetration test to evaluate the consistency properties of freshly mixed concrete. Three main groups containing eighteen concrete mixes were conducted. The studied parameters included coarse aggregate types namely; crushed dolomite, round gravel and crushed basalt. Beside the three types of coarse aggregates, six levels of consistency for each coarse aggregate type pre evaluated by the well known standard slump test were investigated. For each mix, penetration tests were performed using a cone of 30° as an apex angle with different weights. The results of the penetration are explained as a rate of D.V (cm^3/kg), σ_b as well as σ_{sh} at balanced state.

Results and analysis of the displaced volume of cone penetration test

Fig. 3 presents the relationship between the applied load (W) versus the displaced volume for six concrete mixes containing crushed dolomite as a coarse aggregate at different consistency levels. At each consistency level evaluated by standard slump test, increase in the applied load results in an increase in the displaced volume. For each mix, the applied load versus the displaced volume could be represented by a linear relation from which the rate of the displaced volume per unit mass could be estimated. The displaced volume rates were 15.63, 72.92, 123.52, 310.45, 373.08 and 766.15 cm^3/kg for mixes D_{10}, D_{15}, D_{80}, D_{120}, D_{170} and D_{220}, respectively. The displaced volume rates are plotted and presented in Fig. 4 versus the corresponding slump values for the investigated mixes. A linear correlation coefficient between slump values and the displaced volume rates is shown in Fig. 4 with a correlation coefficient of 0.91. Workability levels that could be approximately evaluated by slump test as presented in Table 5 could be related to the displaced volume rates. According to that and for very low, low, medium, high and very high workability level the displaced volume rates are as; 0–6.05, 6.05–95.28, 95.28–278.3, 278.3–568.7 and more than 568.7 cm^3/kg, respectively.

The relationship between the applied load (W) and the displaced volume for mixes containing round gravel as coarse aggregates is presented in Fig. 5.

For each consistency level evaluated by standard slump test, increase in the applied load results in an increase in the displaced volume. For each mix, the applied load versus the displaced volume could be represented by a linear relation from which the rate of the displaced volume per unit mass could be estimated. The displaced volume rates were 20.18, 95.77, 185.47, 452.65, 534.12 and 691.33 cm^3/kg for mixes G_{15}, G_{50}, G_{95}, G_{165}, G_{195} and G_{230}, respectively. The displaced volume rates are plotted and presented in Fig. 6 versus the corresponding slump values for the investigated mixes. A linear correlation coefficient between slump values and the displaced volume rates is shown in Fig. 6 with a correlation coefficient of 0.99. Workability levels that could be approximately evaluated by slump test as presented in Table 5 could be related to the

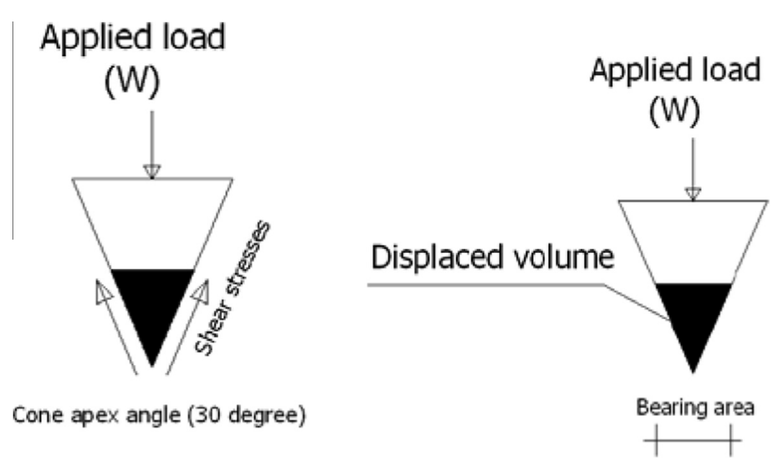


Fig. 2 Acting forces on the cone at the end of penetration process.

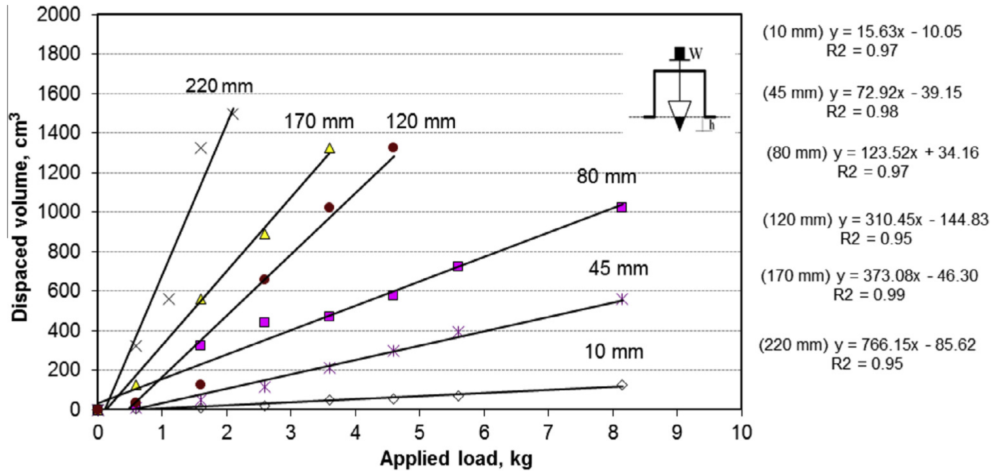


Fig. 3 Applied load versus displaced volume for concrete mixes containing 20 mm dolomite aggregate.

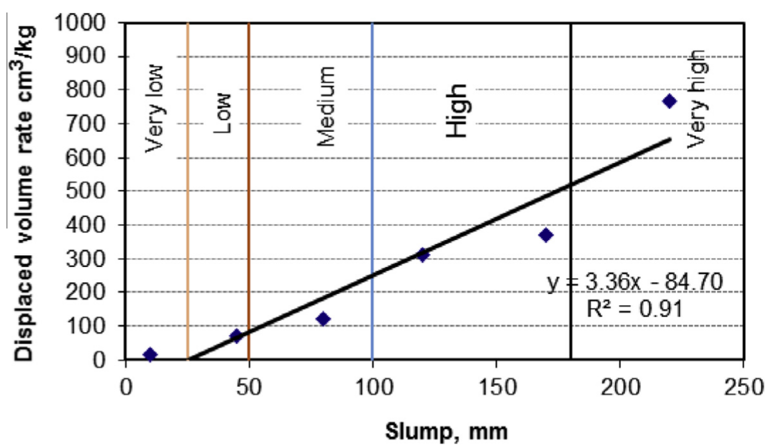


Fig. 4 Slump versus displaced volume rate concrete mixes containing 20 mm dolomite aggregate.

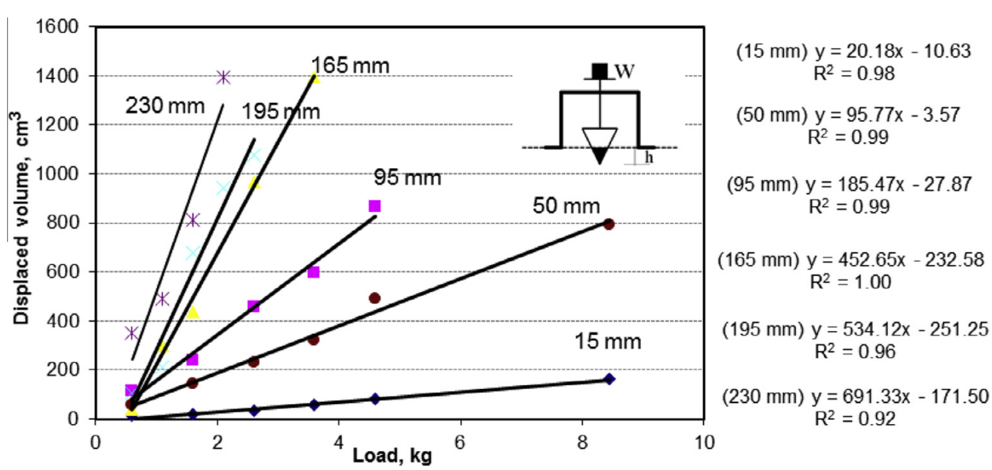


Fig. 5 Applied load versus displaced volume for concrete mixes containing 20 mm gravel aggregate.

displaced volume rates. According to that and for very low, low, medium, high and very high workability level the displaced volume rates are as; 0–17.03, 17.03–95.28, 95.28–251.78, 251.78–502.1 and more than 502.1 cm^3/kg, respectively.

On the other hand, Fig. 7 presents the relationship between the applied load (W) versus the displaced volume for six concrete mixes containing crushed basalt as a coarse aggregate at different consistency levels. At each consistency level evaluated by standard slump test, increasing the applied load results in

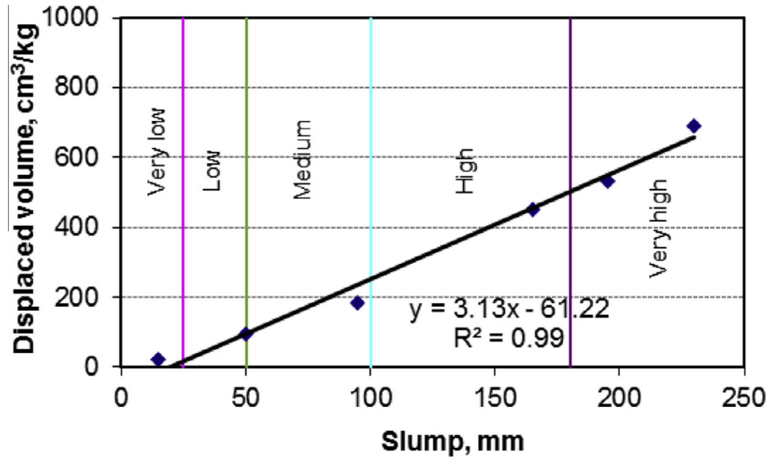


Fig. 6 Slump versus displaced volume rate for concrete mixes containing 20 mm gravel aggregate.

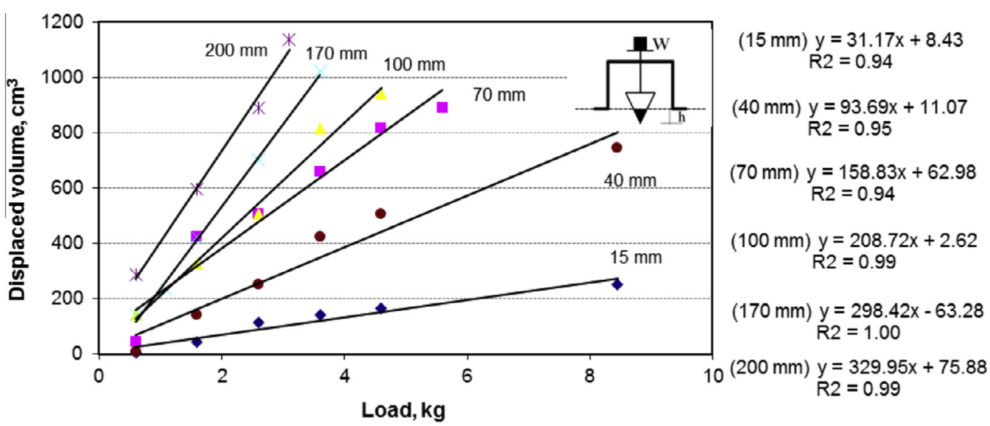


Fig. 7 Applied load versus displaced volume for concrete mixes containing 20 mm crushed basalt.

an increase in the displaced volume. For each mix, the applied load versus the displaced volume could be represented by a linear relation from which the rate of the displaced volume per unit mass could be estimated. The displaced volume rates were 31.17, 93.69, 158.83, 208.72, 298.42 and 329.95 cm^3/kg for mixes B_{15}, B_{40}, B_{70}, B_{100}, B_{170} and B_{200}, respectively. The displaced volume rates are plotted and presented in Fig. 8 versus the corresponding slump values for the investigated mixes. A linear correlation coefficient between slump values and the displaced volume rates is shown in Fig. 8 with a correlation coefficient of 0.98. Workability levels that could be approximately evaluated by slump test as presented in Table 5 could be related to the displaced volume rates. According to that and for very low, low, medium, high and very high workability

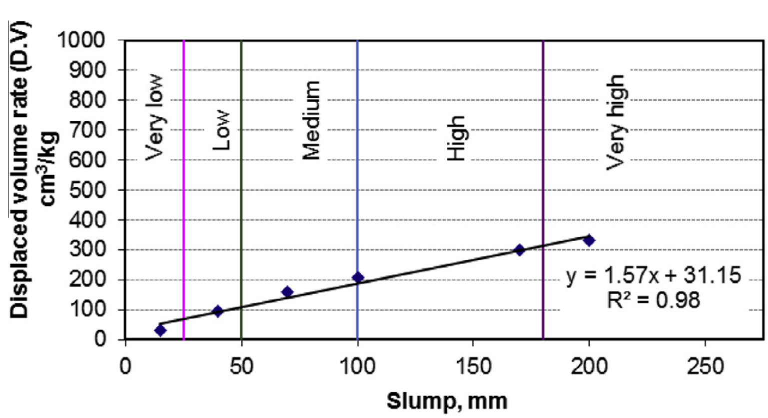


Fig. 8 Slump versus displaced volume rate for concrete mixes containing 20 mm crushed basalt.

Table 5 Experimental results as extracted from the corresponding curves.

Type of coarse aggregate	Workability level					
	Type Slump, mm	Very low 0–25	Low 25–50	Medium 50–100	High 100–180	Very high More than 180
D	D.V, cm^3/kg	0–6.05	6.05–95.28	95.28–278.3	278.3–568.7	> 568.7
	σ_b, MPa	12.11–0.58	0.58–0.31	0.31–0.16	0.16–0.09	< 0.09
	σ_{sh}, MPa	33.18–1.61	1.61–0.84	0.84–0.44	0.44–0.25	< 0.25
G	D.V, cm^3/kg	0–17.03	17.03–95.28	95.28–251.78	251.78–502.1	> 502.1
	σ_b, MPa	8.68–0.51	0.51–0.28	0.28–0.15	0.15–0.09	< 0.09
	σ_{sh}, MPa	23.78–1.4	1.4–0.76	0.76–0.41	0.41–0.25	< 0.25
B	D.V, cm^3/kg	0–70.4	70.4–109.65	109.65–188.15	188.15–313.75	> 313.75
	σ_b, MPa	5.03–0.42	0.42–0.25	0.25–0.15	0.145–0.09	< 0.092
	σ_{sh}, MPa	13.79–1.16	1.16–0.68	0.68–0.4	0.4–0.25	< 0.25

level the displaced volume rates are as; 0–70.4, 70.4–109.65, 109.65–188.15, 188.15–313.75 and more than 313.75 cm^3/kg, respectively.

The results of the rate of the displaced volume values versus the corresponding slump values for the eighteen conducted concrete mixes are presented in Fig. 9. A regression line of a correlation coefficient approaching 0.87 is drawn between slump values and the corresponding displaced volume rates for all the investigated mixes. The displaced volume rates for the workability levels evaluated by slump test are given in Table 5. According to the presented values and for very low, low, medium, high and very high workability levels, the corresponding values for the displaced volumes per unit mass are 0–25, 25–100, 100–250, 250–500 and more than 500 cm^3/kg, respectively.

Results and analysis of bearing stresses (σ_b) associated with cone penetration

For cone penetration test and after penetration is being stable, the stresses that are generated as a reaction for the applied load (W) are balanced with the external load. The result of the

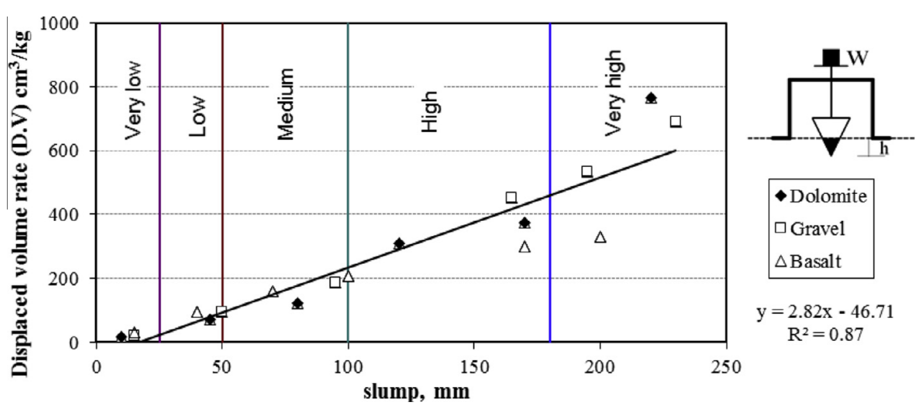


Fig. 9 Slump versus displaced volume rate (D.V) for the conducted concrete mixes containing different coarse aggregates.

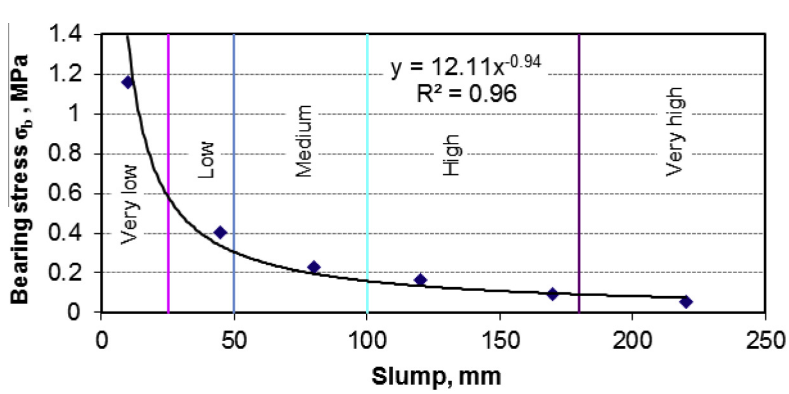


Fig. 10 Slump versus bearing stresses for concrete mixes containing 20 mm dolomite aggregate.

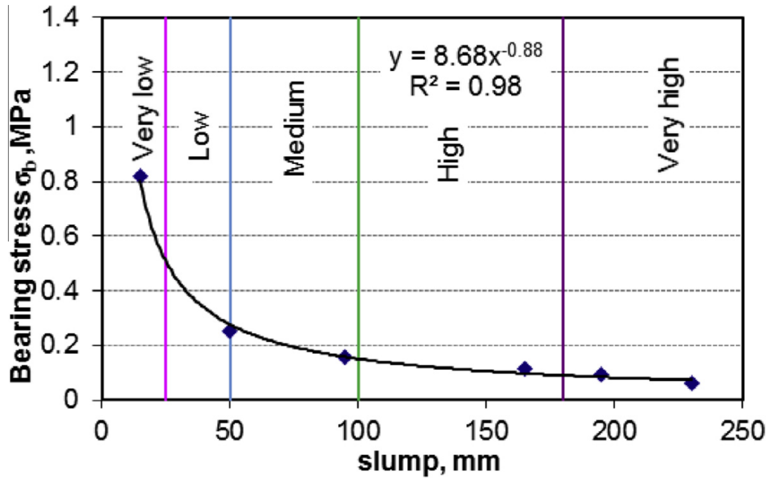


Fig. 11 Slump versus bearing stresses for concrete mixes containing 20 mm gravel aggregate.

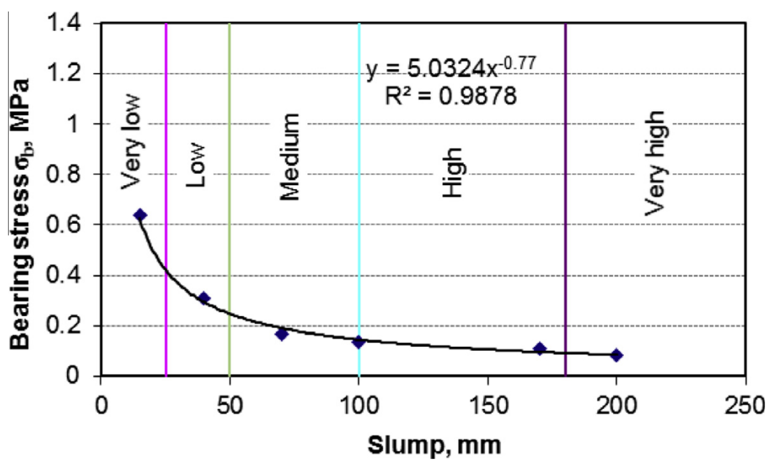


Fig. 12 Slump versus bearing stresses for concrete mixes containing 20 mm basalt aggregate.

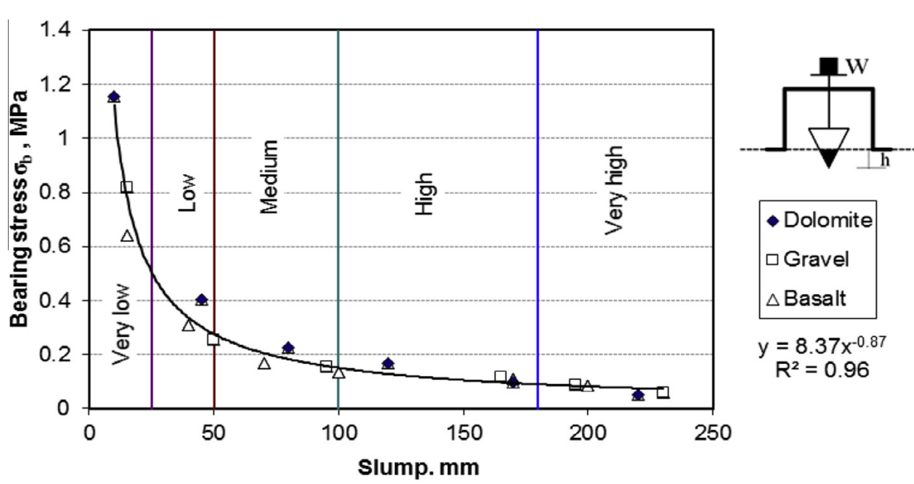


Fig. 13 Slump versus bearing stresses for concrete mixes containing different coarse aggregates.

applied load divided by the horizontal projection area of the penetrated cone is mentioned here as the bearing stresses.

The results of the calculated bearing stresses versus the slump cone values are presented in Figs. 10–12 for concrete mixes containing crushed dolomite, round gravel and crushed basalt, respectively. For the conducted mixes, the bearing stress values seem to be decreased with increasing the consistency level as evaluated by standard slump test.

Table 6 Estimated experimental values for consistency levels and proposed limits.

Measured and proposed limits		Workability level				
		Very low 0–25	Low 25–50	Medium 50–100	High 100–180	Very high More than 180
D.V rate cm^3/kg	Eq. (1)	0–23.79	23.79–94.29	94.29–235.29	235.29–460.9	> 460.9
	Proposed	0–25	25–100	100–250	250–500	> 500
σ_b, MPa	Eq. (3)	8.37–0.51	0.51–0.28	0.28–0.15	0.15–0.09	< 0.09
	Proposed	> 0.50	0.50–0.28	0.28–0.15	0.15–0.09	< 0.09
σ_{sh}, MPa	Eq. (2)	22.93–1.38	1.38–0.76	0.76–0.41	0.41–0.25	< 0.25
	Proposed	> 1.4	1.4–0.75	0.75–0.40	0.40–0.25	< 0.25

The bearing stress values versus the slump for the eighteen conducted concrete mixes containing different coarse aggregate type is presented in Fig. 13. From Fig. 13, it can be noticed that as concrete slump increases, the associated bearing stress values balanced with cone penetration are remarkably reduced. A classification of concrete workability (flow ability) based on the bearing stress capacities is presented in Table 5. For mixes having, very low, low, medium, high and very high workability level, the corresponding bearing stress values are given as, more than 0.5, 0.5–0.28, 0.28–0.15, 0.15–0.09 and less than 0.09 MPa, respectively. The results indicate the ability to evaluate the consistency degrees of the concrete based on the bearing stresses calculated from cone penetration test (see Table 6).

Results and analysis of shear yield stresses (σ_{sh}) associated with cone penetration

As a cone penetrates a fresh concrete mix, a resistance forced preventing the cone to penetrate the concrete acts upward.

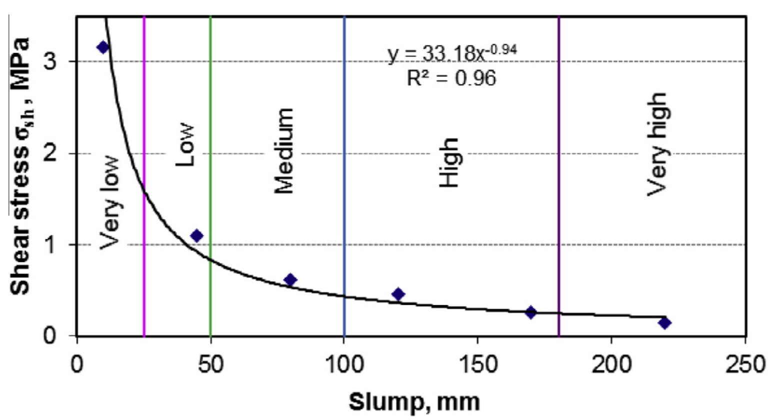


Fig. 14 Slump versus shear yield stress for concrete mixes containing 20 mm dolomite aggregate.

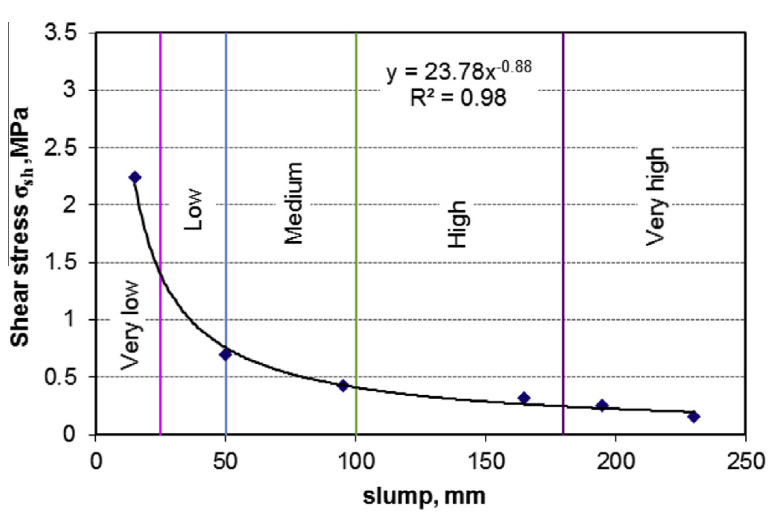


Fig. 15 Slump versus shear yield stresses for concrete mixes containing 20 mm gravel aggregate.

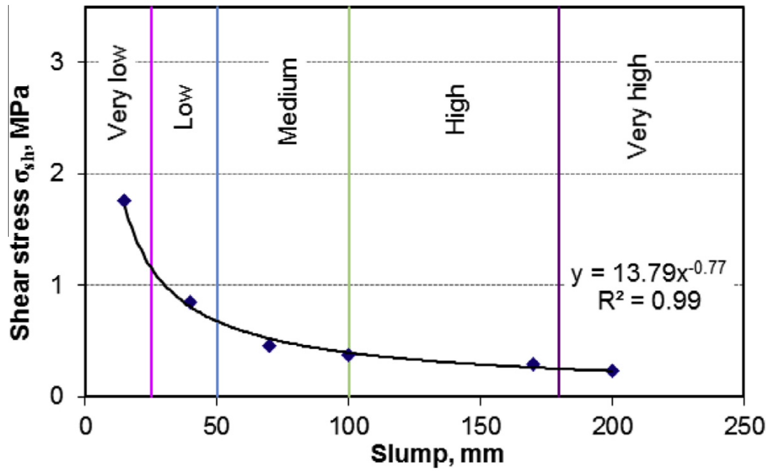


Fig. 16 Slump versus shear yield stresses for concrete mixes containing 20 mm basalt aggregate.

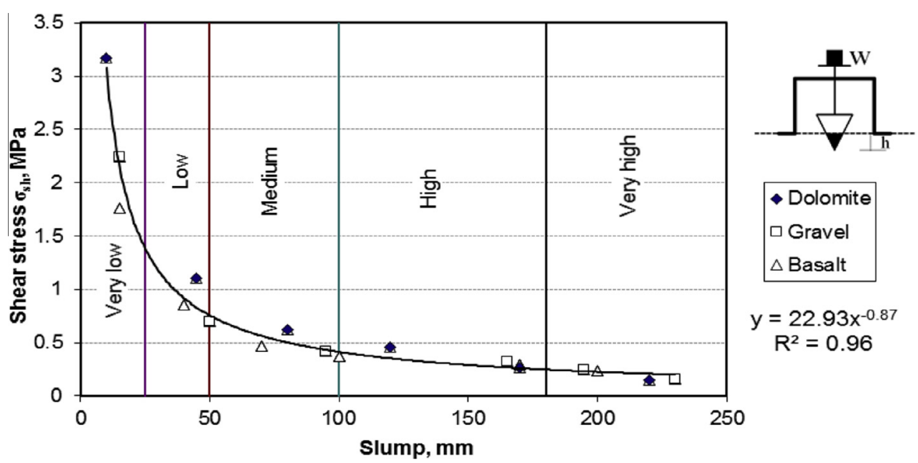


Fig. 17 Slump versus shear yield stresses for concrete mixes containing different coarse aggregates.

This resistance force is due to the shear stresses. This stress is called yield stress at balanced stage. The calculated shear yield stress values are plotted against slump in Figs. 14–16. For mixes containing crushed dolomite, round gravel, and crushed basalt as a coarse aggregate types, it could be noticed that, with the increase of the consistency level, a noticeable decrease in the calculated shear yield stresses are recorded.

On the other hand, the values of the shear yield stresses for the eighteen investigated concrete mixes containing different coarse aggregate types as well as with different consistency level versus the slump values are plotted in Fig. 17. As the slump value increases, the corresponding shear yield stress remarkably decreases which is course due to the high flow ability of the concrete mix. The workability levels are plotted in Fig. 17 for comparison. For workability levels very low, low, medium, high and very high, the corresponding shear yield stress values are more than 1.4, 1.4–0.75, 0.75–0.4, 0.4–0.25 and less than 0.25 MPa, respectively.

These results indicate the ability to measure the consistency levels of concrete based on the shear yield stresses measured from cone penetration test.

Conclusions

Based on the results of this experimental investigation, the following conclusions could be drawn;

- The cone penetration test device of an apex angle of 30° with different weight values could be simply used to evaluate concrete consistency level not only at laboratory but also at site location and directly in the actually cast concrete element provided that no constraints to penetration are exist.
- The displaced volume is directly proportional to the applied load for the investigated concrete mixes.
- The rate of the displaced volume per unit mass (cm^3/kg) could be a specific property for the conducted concrete mixes containing different coarse aggregate types at different consistency levels.
- The rate of the displaced volume is more sensitive to the variation in the fresh concrete mix compared to the value of slump.

- Cone penetration test can differentiate between stiff mixes as well as floppy ones that could not be achieved by the well-known slump test.
- Cone penetration test can simply evaluate all ranges of concrete consistency from stiff to floppy.
- The bearing stresses calculated at balanced state of cone penetration could be used as a measure for consistency level for fresh concrete mix.
- The shear yield stresses calculated at balanced state of cone penetration could be considered as a measure for concrete consistency level for fresh concrete mix.

Conflict of interest

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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