MODIFIED POINT LOAD TEST DETERMINING UNIAXIAL COMPRESSIVE STRENGTH OF INTACT ROCKS

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ABSTRACT: A modified point load (MPL) testing technique is proposed to correlate the results with the uniaxial compressive strength (UCS) of intact rocks. The test apparatus is similar to that of the conventional point load (CPL), except that the loading points are cut flat to have a circular cross-sectional area instead of using a half-spherical shape. The load is applied along the axis of cylindrical (disk) specimens. The results from finite element analysis suggest that the applied stress required to fail the MPL specimen increases logarithmically as the specimen thickness or diameter increases. The maximum tensile stress occurs directly below the loading area with a distance approximately equal to the loading diameter. Over 400 specimens of Saraburi marble have been tested to determine the compressive strength and the MPL and CPL strength index under a variety of specimen sizes and length-to-diameter ratios. The test results suggest that the MPL strength can be correlated with the UCS when the MPL specimens are relatively thin, and can be an indicator of the tensile strength when the specimens are significantly larger than the diameter of the loading points. Even though both MPL and CPL tests overestimate the actual UCS of the rocks, the MPL results yield a better correlation than does the CPL strength index.

1. INTRODUCTION

Conventional point load (CPL) strength index has long been used as an indicator of the uniaxial compressive strength of intact rocks [1-15]. Several investigators have studied the correlation between the CPL strength index and the compressive strength (UCS) for various rock types in an attempt at understanding the true mechanism of failure and the effects of specimen sizes and shapes. The uncertainty of the relationship between CPL index and the compressive strength remains. It has been found that the compressive strength of rocks can vary from 6 to 105 times the CPL index, depending on the rock types [13, 14]. The ASTM standard [1] procedure defines that the rock compressive strength can be calculated as 24 times the CPL strength index (for core size = 54 mm). This calculation is purely empirical, and hence sometimes does not adequate, particularly in term of the reliability, when used in the analysis and design of geological structures. In addition the calculation of the CPL strength index does not have any theoretical support, and does not allow a transition correlation between the CPL index and the compressive strengths of the rock. The curvature of the loading point for the CPL test also has a disadvantage. The contact loading area can increase as the load increases (i.e., the spherical head sinking into the specimen surface). This is due to the deformation of the rock matrix. As a result, the definition of a singular loading point as used in the CPL principle may not be strictly valid.

The objective of this research is to develop a new testing technique, called "modified point load (MPL) test" to obtain an alternative method to estimate the UCS of intact rock. The effort involves laboratory tests and finite element analyses. A series of MPL testing, CPL testing, UCS testing and Brazilian tensile strength testing have been performed on cylindrical specimens with various sizes and length-and-diameter ratios. Saraburi marble has been primarily used as rock specimens. The finite element analyses determine the stress distribution along the loaded axis of the MPL test specimens. The predictive capability of the proposed MPL method has been assessed by comparing its results with the actual UCS for other two rock types.

2. LABORATORY TESTING

2.1. *Modified Point Load Tests*

The test configurations for the proposed MPL technique are similar to those of the CPL, except that the loading points are cut flat to have a circular cross-sectional area instead of using a half-spherical shape. The diameters of loading point (platen) used here vary from 5, 10, 15, 20, 25, to 30 mm. The modification is to ensure that the contact area between the steel platen and the rock surface remains constant as the load increases. The load is applied along the axis of the rock cylinder (or disk). The new loading and boundary conditions also allow a continuous transition between the uniaxial compressive strength test and the MPL strength results. Figure 1 compares the conventional loading point with the modified loading points with the diameters of 5 and 10 mm. Figure 2 shows the loading and boundary conditions of the specimens.

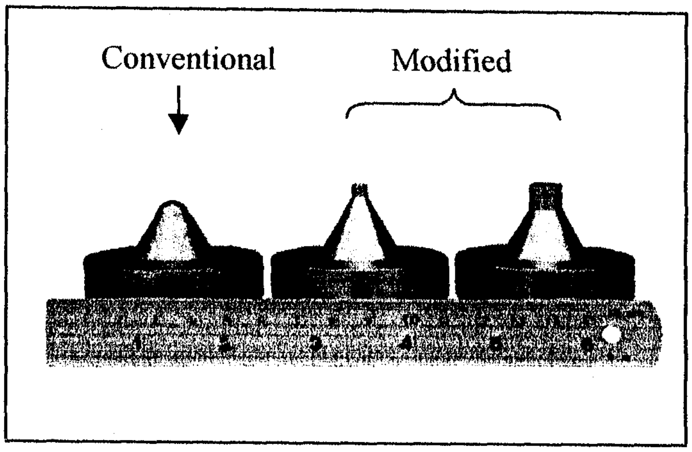

Fig. 1. Conventional and modified loading points.

Saraburi marble has been primarily selected for use as rock specimens due to its uniform texture and availability. The rock is from the quarry in the eastern part of Thailand. Over 200 specimens have been prepared in the laboratory. The specimen thickness (t) is varied from 5 mm to 40 mm. The specimen diameter (D) varies from 20 mm to 100 mm. The specimens are taken as a circular disk. The load is applied along the specimen axis, and is increased until the failure occurs. Digital displacement gauges are used to monitor the deformation of the rock between the loading points as the load increases. Cyclic loading is performed on some specimens in an attempt at separating the elastic from the plastic deformation. This is primarily to detect the development of compressive failure (initiation of micro-cracks) underneath the loading points, as well as the corresponding applied stress. The failure stress (P) is calculated by dividing the failure load by the contact area. Post-failure characteristics are observed and recorded.

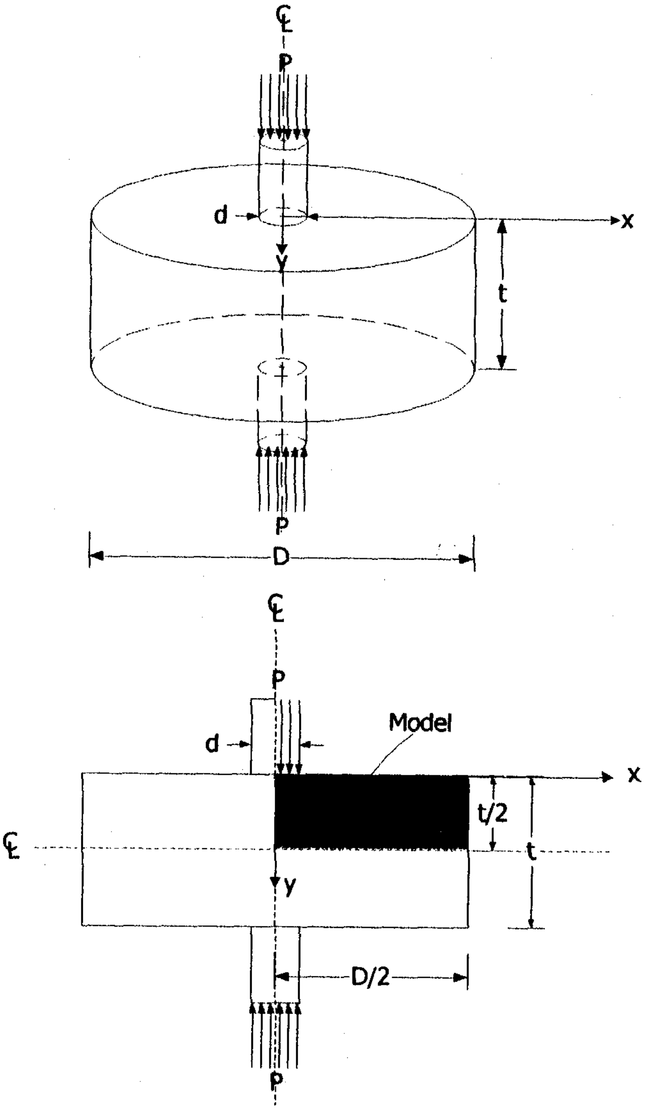

Fig. 2. Configurations of modified point load test specimen.

Figures 3 and 4 show two sets of MPL results by presenting the failure stresses P as a function of specimen diameter and thickness. To isolate the effect of the loading diameter, the specimen diameter and thickness are normalized by the diameter of loading point (d), as shown in the figures. Each data point represents the average values of 5 to 10 specimens. The failure stress P increases exponentially as D/d increases, which can be expressed by a logarithmic equation. The curve fit gives good correlation particularly when t/d is larger than one (Figure 3). The stress P also increases with the ratio t/d which can be best represented by a power equation (Figure 4). Post-tested observations also suggest that shear failure is predominant when the specimen thickness is less than twice the loading diameter while extension failure is predominant when the specimens are thicker than three times the loading diameter. This failure behavior can be clearly observed particularly when the D/d ratio is less than 5. This implies that the MPL strength can be correlated with the compressive strength when the MPL specimens are relatively thin and narrow, and can be an indicator of the tensile strength when the specimen diameter and thickness are significantly larger than the diameter of the loading points. Analysis and applications of the MPL test results will be discussed in section 4.

2.2. Characterization Tests

The objective of the characterization testing is to develop a data basis to compare with the MPL results. Attention is given to the size and shape effects of the specimen on the UCS, tensile strength and CPL strength index. A series of uniaxial compressive strength tests have been conducted on Saraburi marble. The sample preparation and test procedure follow the relevant ASTM standard [16] and ISRM suggested method [17], as much as practical. A total of 280 specimens have been tested under various diameters and L/D ratios. The specimen diameters vary from 22.5, 38.5, 54.0, to 67.4 mm. The length-to-diameter ratio (L/D) varies from 0.25, 0.50, 0.75, 1.0, 1.5, 2.0, to 2.5. All specimens are loaded to failure under a constant loading rate. Post-failure characteristics are observed.

Figure 5 plots the compressive strength as a function of L/D ratio. The results show the end effects of the specimen on the strength values. The strength decreases as the L/D increases. The relationship can be best represented by a power equation. Within the range of sample sizes used here the strength results have not shown the effect of the specimen size. This is probably due to the fact that the size effect pronounces more in tensile failure than does in compressive shear failure. Short specimens (L/D lower than two) tend to fail under the compressive shear failure mode. Extension failure dominates when the L/D ratios are larger than two. In general this finding agrees reasonably well with similar experiments obtained elsewhere [18-23].

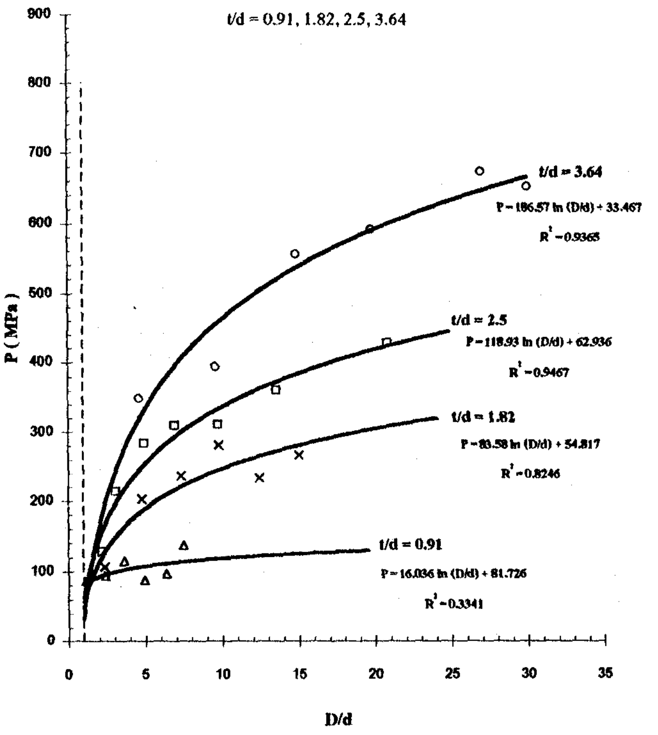

Fig. 3. MPL test results for various t/d ratios.

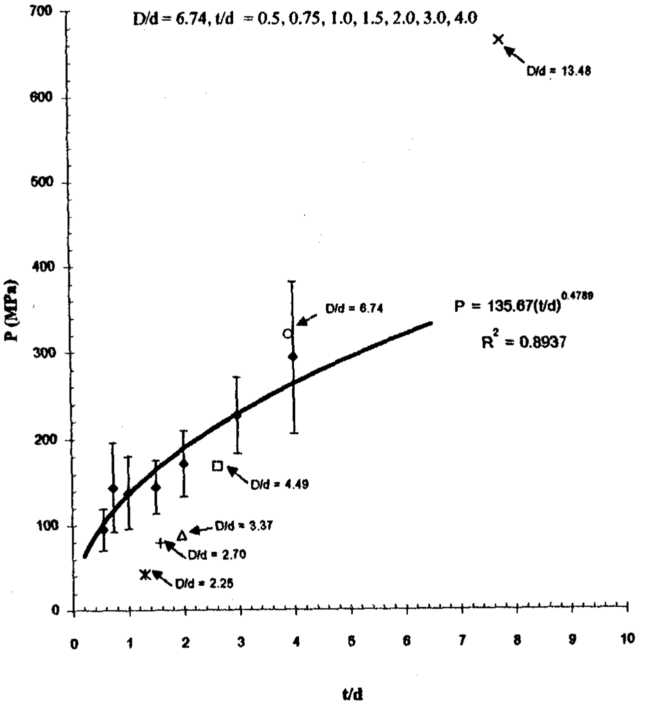

Fig. 4. MPL test results for D/d = 6.74.

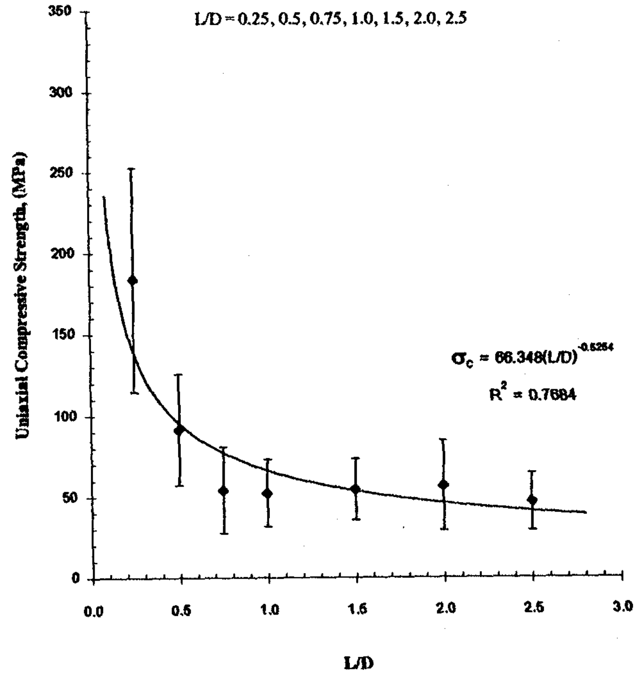

Fig. 5. Uniaxial compressive strength of Saraburi marble.

Brazilian (indirect) tension tests have been performed on the Saraburi marble. The sample preparation and test procedure follow the ASTM standards [24]. Forty specimens have been tested. They have a constant L/D ratio = 0.5, while the specimen diameters vary from 22.5, 38.5, 54.0, to 67.4 mm. The tensile strength tends to decrease as the specimen size increases, and can be expressed by a power equation (Figure 6). This finding agrees with those obtained from similar experiment [25].

The conventional point load (CPL) testing is performed on 70 specimens of Saraburi marble. The test procedure follows the relevant ASTM standard [1]. The specimen diameter is maintained constant at 67.4 mm. The thickness varies from 5.0 to 40.0 mm. The CPL strength index is calculated by dividing the failure load by the specimen thickness and diameter. The strength index results tend to be independent of the specimen dimensions. The point load strength index is averaged as 4.5 MPa (Figure 7).

3. FINITE ELEMENT ANALYSES

A series of finite element analyses have been carried out to compute the stress distribution along the loaded axis of MPL specimens as affected by the specimen diameter and thickness. The results will be specifically used to establish the relationship between failure stress P and the maximum stress induced in the MPL specimens. The analysis is made in axisymmetric, assuming that the material is linearly elastic. A finite element code GEO [26] is used in the simulations. The elastic modulus is defined as 6.75 GPa, and the Poisson's ratio as 0.25 (obtained from the uniaxial compression tests). The specimen diameter (D) and thickness (t) are varied within the range used in the laboratory experiment, and subsequently their effects on the stress distribution can be assessed. A total of 57 specimen models have been constructed. To isolate the impact from the size of loading point, D and t are normalized by the loading diameter (d).

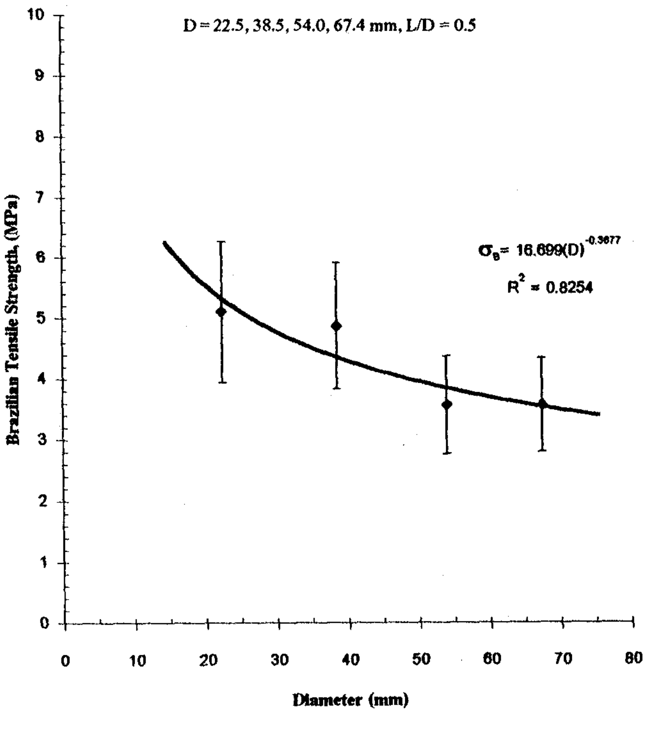

Fig. 6. Brazilian tensile strength of Saraburi marble.

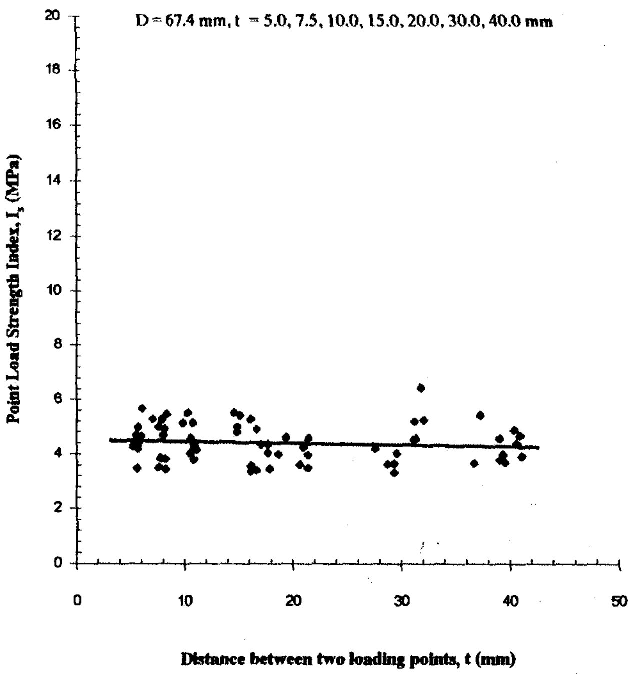

Fig. 7. CPL test results for D = 67.4 mm and t from 5 to 40 mm.

Figure 8 gives an example of the distribution of the minimum principal stresses (σ_2) along the loaded axis for MPL specimen models with a constant D/d ratio (equal to 15), but t/d ratio varying from 1 to 20. These stresses are normal to the loaded axis. It is shown that the largest tensile stress is developed near the loading area. The vertical distance between the contact point and the maximum stress location is about 2-3 times the diameter of the loading platen. The maximum shear stress (½ ($\sigma_1 - \sigma_2$)) also concentrates in this area. It is therefore speculated that this may be the point where the extension failure initiates. Similar findings have been reported by Wei et al. [13] for the CPL test specimens. For t/d equal or larger than two, the magnitude of the largest tensile stress decreases with increasing the t/d ratio. For t/d equal one (very thin specimens), the largest tensile stress becomes smaller. For this case most of the stresses induced along the loaded axis are in compression. This indicates that thin specimens tend to fail under compressive shear failure while thick specimens fail

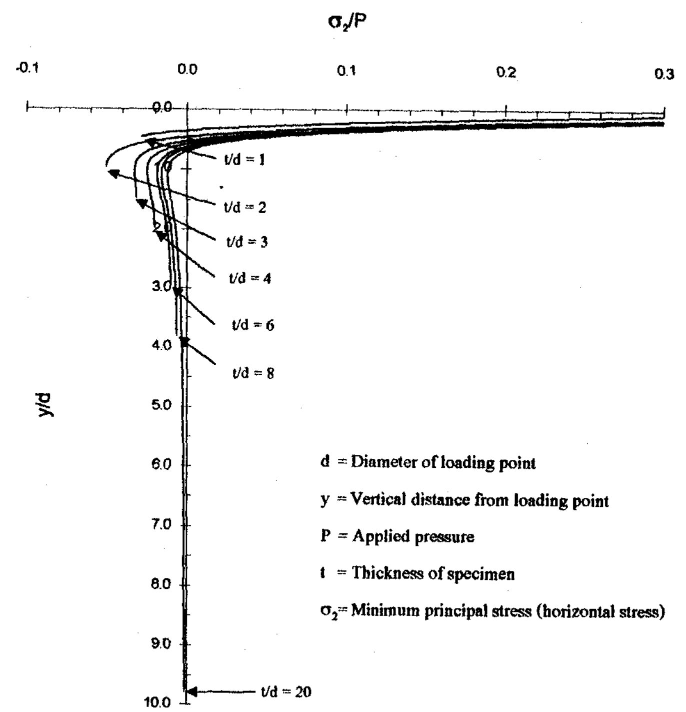

Fig. 8. Distribution of the minimum principal stresses along the loaded axis of MPL specimens. D/d = 15.

under extension failure. This also agrees with the observations on the post-tested specimens. The simulation results also suggest that Poisson's ratio of the rock can affect the magnitude and distribution of the horizontal stresses along the loading axis of the MPL specimen. When the Poisson's ratio approaches 0.5, the induced tensile stress (horizontal stress) tends to be lower and tends to have the maximum value near the middle of the specimen. The Poisson's ratio has no effect on the magnitude and distribution of the vertical stress along the loading axis. For the analysis in this study the Poisson's ratio is taken as a constant at 0.25 which represents the nominal value of the rocks.

The simulations are divided into two cases : 1) no friction at the interface between the loading platen and rock surface, and 2) full friction at the interface (i.e. no lateral movement is allowed at the loading interface). The minimum principal stresses obtained from the full friction case are slightly lower (by 3-5%) than those from the no friction case. It is recognized that the actual friction at the interface will be between those two extreme cases. Since the differences are relatively small, all analyses in this study assume that no friction occurs at the interface.

The results obtained from two series of computer simulations for the case of no friction at the interface are shown in Figures 9 and 10. The applied stress (P) is normalized by the largest values of the tensile stress (T), and are plotted as a function of t/d and D/d. The stress ratio P/T increases logarithmically with t/d and with D/d. These curves can be used to correlate the MPL results with the uniaxial compressive strength of the rock. For example, extrapolation of the curve with t/d = 2.5 (in Figure 9) back to the point where D/d equals to one, will give a stress ratio that can be used to correlate with the UCS valve.

4. COMPARISONS AND VERIFICATIONS

The predictive capability of the CPL and MPL test results has been assessed. The results from both methods are used to predict the uniaxial compressive strength of the marble. The actual UCS of the marble specimens for L/D ratio = 2.5 (satisfy both ASTM and ISRM) can be calculated from Figure 5 as 46.8 MPa.

Using the ASTM recommended calculation, the CPL strength index determines the uniaxial compressive strength of the marble as 108 MPa (24 x 4.5 MPa).

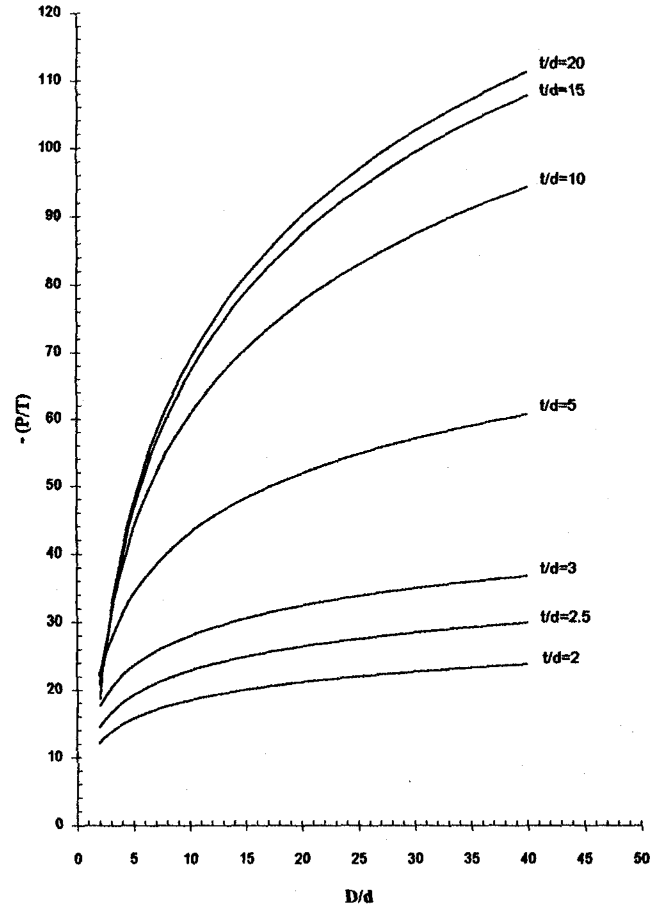

Fig. 9. Normalized failure stress as a function of D/d, obtained from numerical analysis.

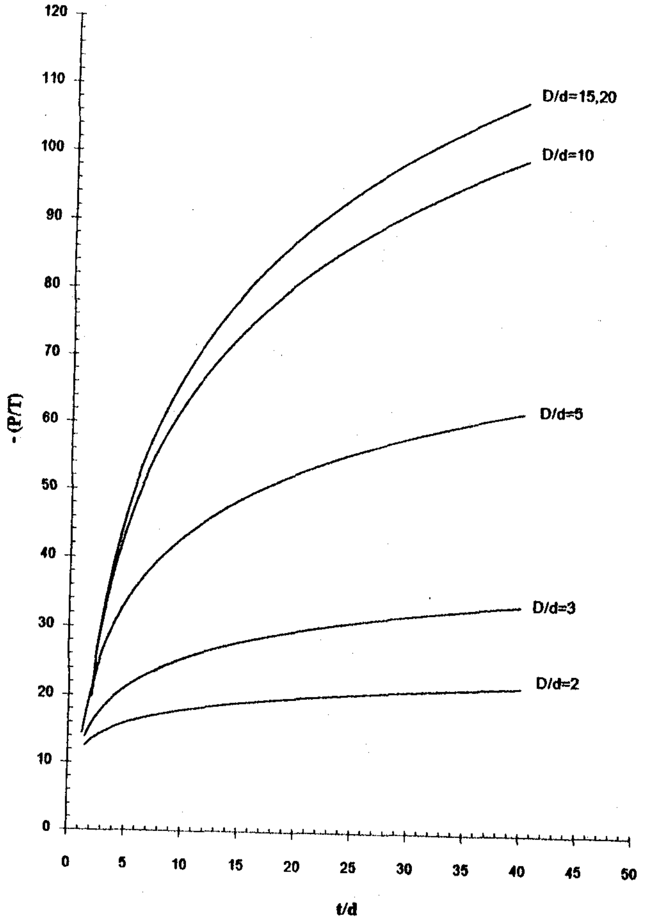

Fig. 10. Normalized failure stress as a function of t/d, obtained from numerical analysis.

Extrapolation of the MPL test result for t/d = 2.5 (in Figure 3) to the failure stress at D/d = 1.0 (uniaxial test condition) yields the uniaxial compressive strength of the marble as 63 MPa. This value can be compared with the uniaxial compressive strength at L/D = 2.5. The actual compressive strength at L/D = 2.5 is 46.8 MPa (calculated from Figure 5).

It should be noted that the CPL test overestimates the actual strength by a factor of 2.3 (or 108/46.8). The MPL test overestimates the actual strength by a factor of 1.4 (or 63/46.8). Since the MPL prediction is based on the actual shape distribution for the strength data, it may be more reliable. The discrepancy is probably due to the non-uniformity of the mechanical response among the marble specimens. Discussion on this issue is given in section 5.

The MPL results can also determine the rock tensile strength by using the relationship given in Figure 9. At D/d = 5 and t/d = 20, the stress ratio -P/T = 52. The t/d = 20 is selected because under this dimension ratio the rock fails in tension mode. Extrapolation of the logarithmic curve in Figure 4 gives the value of P from the experiment equals to 570 MPa. The T value is calculated as 11 MPa. This is the largest tensile stress induced in the specimen at failure, and hence represents the MPL tensile strength of the marble.

The predicted tensile strength by MPL is significantly higher than that obtained from the Brazilian tension test probably because the stress gradient induced along the incipient failure plane of MPL specimens is higher than that of the Brazilian specimens. To further explain the effect of the stress gradient on the strength, ring tension test and four-point bending test [23] have been performed on Saraburi marble. Comparison of the strength results is given in Table 1. The ring tension test specimen poses the largest tensile stress gradient along the plane where the failure is initiated. This leads to the largest tensile strength, as compared with other test methods. The MPL specimen has a higher stress gradient than does the four-point bending specimen, but it has a lower gradient that does the ring test specimen. In summary, the predicted tensile strength by MPL agrees reasonably well with the results obtained from other methods. The effects of the stress gradient on the tensile strength observed here are similar to those observed elsewhere [23].

Table 1. Comparison of the tensile strengths of Saraburi marble for different test methods.

Test Method	Tensile Strength (MPa)
Brazilian tension test	4.0
Four-point bending test	7.5
Modified point load test	11.0
Ring tension test	14.5

The proposed method of predicting UCS has been verified by performing additional tests on different rock types. In the verification process, the MPL, CPL, UCS and Brazilian tests have been carried out on Saraburi limestone and Khao Somphot limestone. Cylindrical (disk) specimens are prepared from Saraburi limestone for use in the MPL and CPL testing. The specimen diameters vary from 22 to 93 mm and the thickness from 27 to 58 mm. For both test methods, the rock cylinders are loaded along its axis until failure. The calculation methods for the rock strengths are identical to those used for the Saraburi marble. Irregular lumps of Khao Somphot limestone are used as specimens for the MPL and CPL tests. The specimen thickness is varied from 34 to 54 mm, and the smallest width from 50 to 100 mm. Comparison of the strength results is given in Table 2. The irregular shaped specimens are carefully selected to allow flat and parallel contacts between the loading platen and the rock surface. The CPL test over-predicts the actual UCS by a factor of 1.6 for Saraburi limestone, and by a factor of 2.8 for Khao Somphot limestone. For both limestones, the MPL method yields a better prediction of the UCS strength than does the CPL method.

Table 2. Comparison of the compressive strength results.

Rock Type	Actual UCS (MPa)	CPL prediction (MPa)	MPL prediction (MPa)
Saraburi marble	46.8 ± 17.96	108.0 (disk)	63.0 (disk)
Saraburi limestone	47.5 ± 15.16	76.8 (disk)	30.9 (disk)
Khao Somphot limestone	43.2 ± 22.30	124.8 (irregular)	48.4 (irregular)

5. DISCUSSIONS

Intrinsic variability or the mechanical non-uniformity among the rock specimens poses some difficulties, particularly in the correlation process. The standard deviations from various tests are relatively high, e.g. 20–30%. Even though the rocks appear to be uniform and homogeneous, the variability might be caused by the relatively large grain (crystal) sizes, as compared with the loading areas. This could cause the discrepancy between the prediction and the actual strength results. The over prediction by the MPL results may also due to the insufficient data in the range between D/d = 1 and D/d = 5. Within this range the stress ratio-diameter ratio curves are highly sensitive (i.e. high gradient) particularly for the low values of thickness ratio (t/d). Therefore, the predictability could be improved by testing more specimens with D/d less than 5.

The proposed MPL test shows a promising trend of predicting the compressive strength of the rock. More MPL test data are needed to further define the effects of the specimen thickness (t/d) and diameter (D/d). Verification of the proposed concept under a wider range of rock types and rock properties is also desirable.

6. CONCLUSIONS

The objective of the present research is to develop a new testing technique, called "modified point load (MPL) test" to obtain an alternative method to determine the compressive and tensile strengths of intact rock. The effort involves laboratory tests and finite element analyses. A series of MPL testing, CPL testing, uniaxial compression testing and Brazilian tension testing are performed on cylindrical specimens with various sizes and shapes. Saraburi marble has been primarily used as rock samples. The finite element analyses determine the stress distribution along the loaded axis of the MPL test specimens. Comparison is made between the compressive strengths predicted by the CPL index and by the MPL results.

The uniaxial test results indicate that the strengths decrease with increasing length-to-diameter ratio. A power law can be used to describe their relationship. The effect of specimen size on the uniaxial compressive strength is obscured by the intrinsic variability of the marble. The Brazilian tensile strengths also decrease as the specimen diameters increase. The results from MPL test agree well with those from the finite element analyses. This suggests that the logarithmic relations between the stress ratio and specimen shape derived by a series of numerical analyses can be used to correlate the MPL strength with the uniaxial compressive strength of the intact rock. Post-tested observations on the specimens also suggest that shear failure is predominant when the specimen thickness is less than twice the loading diameter while extension failure (fracture) is predominant when the specimens are thicker than three times the loading diameter. This can be postulated that the MPL strength can be correlated with the compressive strength when the MPL specimens are relatively thin, and should be an indicator of the tensile strength when the specimens are significantly larger than the diameter of the loading points. For the limestone and marble specimens tested here, the MPL results predict the uniaxial compressive strength of the rock better than does the CPL strength index.

7. ACKNOWLEDGMENTS

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